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Taras Shevchenko National University of Kyiv**

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STRATEGIC MINERALS OF UKRAINE AND THEIR INVESTMENT ATTRACTIVENESS

MONOGRAPH



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Abstract

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The role of Ukraine's inventory of strategic mineral in the total known global supply of critical raw materials is addressed, and strategic mineral raw materials of Ukraine, the state and problems of the mineral resource base (MRB) of Ukraine, the systematic analysis of MRB of strategic minerals of Ukraine and the ranking of MRB of Ukraine by investment attractiveness was conducted. According to the degree of investment attractiveness, four types of raw materials have been identified for metallic and non-metallic minerals: traditional (iron, manganese, titanium, uranium, kaolin, foundry sands, building and facing stones, refractory clay); highly promising (rare earths, zirconium and hafnium, lithium, scandium, germanium, graphite, potassium salts, abrasive raw materials (garnet), quartz raw materials, piezooptical raw materials); promising (nickel, cobalt, chromium, aluminum, copper, tantalum and niobium, beryllium, gold, phosphorites, apatite, fluorspar, glauconite, flux limestones and dolomites, limestones for the sugar industry, bentonite clays, raw stone, field); with unclear prospects (vanadium, lead and zinc, tungsten, molybdenum, platinum and platinum, strontium, magnesium, arsenic, rubidium, cesium, barite, boron, dawsonite, bromine and iodine, mineral sorbents, high alumina raw materials, diamond, raw materials for production of mineral paints, fluorine, sulphur).

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CONTENTS

List of Figures	8
List of Tables	11
Gallery	15
Foreword	18
Introduction	21
This Book: Its Purpose, Contents and Intended Audience	21
The Research Scope of This Book	22
What Conventions are Used in This Book?	25
Geography and Proper Names	25
Mineral Reserves and Resources	27
Stratigraphy	30
Units	30
Glossary	31
List of Other Abbreviations	32
Executive Summary	33
Acknowledgements	35
 Chapter 1. A European Perspective	 38
1.1. Brief Overview of European Raw Materials History	38
1.2. Challenges as Drivers for EU Policies and Actions	39
1.2.1. The EU, a Society in a State of Constant Developments	42
1.3. Research and Innovation to Support Europe's Ambitions	47
1.3.1. Bonds and Relationships	48
1.3.2. Europe's Raw Materials	51
1.3.3. Ukraine is a Partner in the European Community of Geological Survey Organisations	54
1.4. Outlook – Recommendations for Future Cooperation, Impact on the Ukraine Reconstruction	57
 Chapter 2. Overview of the Economic Geology, Mineral Resource Base and Strategic Mineral Resources of Ukraine	 59
2.1. Economic Geology of Ukraine	59
2.2. Overview of the Mineral Resource Base of Ukraine	62
2.2.1. Metallic Minerals	62
2.2.2. Non-Metallic Minerals	64
2.2.3. Hydrocarbons	64
2.2.4. Coal	66
2.2.5. Summary of Ukraine's Mineral Resources	67
2.3. The Concept of Strategic Minerals in Ukraine	71
2.4. Mineral Resource Base of Ukraine: Status and Challenges	73
2.5. The Place and Role of Ukraine in World Mining	74

Chapter 3. Factors and Criteria Affecting Investment Attractiveness of Mineral Resource Base of Ukraine	79
3.1. Basic Regulations of Ukraine in the Field of Subsurface Use	79
3.1.1. Basic Laws in the Field of Subsurface Use	79
3.1.2. The Rights to Use Subsurface	82
3.1.3. Assessment of Mineral Reserves and Resources	94
3.2. The Main Factors and Criteria of Investment Attractiveness of Mineral Resource Base of Ukraine	99
3.3. Availability and Accessibility of Mineral Data of Ukraine	101
3.3.1. Geological Mapping Data	101
3.3.2. Sources and Delivery of Geoscientific Data	103
3.4. Derivation of a Ranking Method for Relative Investment Attractiveness with Rules of Thumb	106
3.4.1. Revenue Data	108
3.4.2. Cost Data	109
3.4.3. Economic Calculations	113
3.4.4. The Final Establishment of a Merit Order of Attractiveness for Projects with Very Different Stages of Knowledge	114
3.5. From Prospective Geology to an Active Mine	115
3.6. Ranking of Mineral Resource Base of Ukraine by Investment Attractiveness	118
 Chapter 4. Metallic Minerals	121
4.1. Traditional Raw Materials	121
4.1.1. Iron	121
4.1.2. Manganese	132
4.1.3. Titanium	139
4.1.4. Uranium	146
4.2. Highly Promising Types of Raw Materials	153
4.2.1. Rare Earths	154
4.2.2. Zirconium	165
4.2.3. Hafnium	168
4.2.4. Lithium	169
4.2.5. Scandium	178
4.2.6. Germanium	181
4.3. Promising Types of Raw Materials	183
4.3.1. Nickel	183
4.3.2. Cobalt	187
4.3.3. Chromium	189
4.3.4. Aluminium	191
4.3.5. Copper	195
4.3.6. Tantalum and Niobium	202
4.3.7. Beryllium	205
4.3.8. Gold	206

4.4. Types of Raw Materials with Unclear Prospects	222
4.4.1. Vanadium	223
4.4.2. Lead and Zinc	223
4.4.3. Tungsten	227
4.4.4. Molybdenum	229
4.4.5. Platinum Group Metals	233
4.4.6. Strontium	235
4.4.7. Magnesium	235
4.4.8. Arsenic	238
4.4.9. Rubidium and Cesium	238

Chapter 5. Non-Metallic Minerals	240
5.1. Traditional Raw Materials	240
5.1.1. Kaolin	240
5.1.2. Foundry Sands	245
5.1.3. Building Stones	247
5.1.4. Facing (Decorative) Stones	248
5.1.5. Refractory Clays	254
5.2. Highly Promising Types of Raw Materials	257
5.2.1. Graphite	257
5.2.2. Potassium Salts	262
5.2.3. Abrasive Raw Materials (Garnet)	264
5.2.4. Quartz Raw Materials	267
5.2.5. Piezooptical Raw Materials (Piezoquartz)	271
5.3. Promising Types of Raw Materials	273
5.3.1. Phosphorites	273
5.3.2. Apatite	276
5.3.3. Fluorspar (Fluorite)	278
5.3.4. Glauconite	289
5.3.5. Flux Limestones and Dolomites	290
5.3.6. Limestones for the Sugar Industry	294
5.3.7. Bentonite Clays	297
5.3.8. Feldspar Raw Materials	299
5.3.9. Gemstone and Facing-Stone Raw Materials	302
5.3.9.1. Amber	303
5.3.9.2. Marble Onyx	307
5.3.9.3. Rhodonite	307
5.3.9.4. Jet	307
5.3.9.5. Diamond	308
5.4. Raw Materials with Unclear Prospects	312
5.4.1. Barite	312
5.4.2. Boron	314
5.4.3. Dawsonite	315
5.4.4. Bromine and Iodine	316

5.4.5. Mineral Absorbents (Zeolite, Vermiculite)	317
5.4.5.1. Zeolite	317
5.4.5.2. Vermiculite	318
5.4.6. High-Alumina Raw Materials (Sillimanite, Disthene, Andalusite)	320
5.4.7. Raw Materials for the Production of Mineral Paints	323
5.4.7.1. Ores of Ferrous and Non-Ferrous Metals	324
5.4.7.2. Coloured Clays	324
5.4.7.3. Glauconite	324
5.4.8. Fluorine	325
5.4.9. Sulphur	325

Chapter 6. Expert Assessment of Investment Attractiveness of Mineral Resources of Ukraine	329
6.1. Metallic Minerals	332
6.2. Non-Metallic Minerals	335

Chapter 7. Critical Raw Materials – The Global Context	337
7.1. Overview	337
7.1.1. Lithium-Ion Batteries	339
7.1.2. Electric Vehicles (EVs)	340
7.1.3. Clean Energy: Solar Photovoltaic Panels, Wind Turbines and Hydrogen	340
7.1.4. Consumer Electronics	341
7.1.5. Some Other CRM and Their Applications	342
7.2. Critical Raw Materials Policies of Selected Economies	343
7.2.1. European Union	343
7.2.2. United States of America	348
7.2.3. Canada	355
7.2.4. Australia	356
7.2.5. Ukraine: a CRM Review	357

Conclusions	360

References	363

List of Figures

Introduction

Number and Title	Page
I.1. Principal administrative units of Ukraine	
I.2. Historical, ethnographic and geographic areas of Ukraine	
I.3. Comparison of JORC and FSU resource classifications	
I.4. Comparison of CRIRSCO and FSU resource classifications	
I.5. Comparison of CRIRSCO and Russian resource classifications	

Chapter 2

Number and Title	Page
2.1. Geological structure of Ukraine	
2.2. Geological units of the Ukrainian Shield	
2.3. The most important mining areas and ore deposits of Ukraine	
2.4. The main oil and gas regions of Ukraine	

Chapter 3

Number and Title	Page
3.1. Procedure for obtaining the special permits for subsurface use	
3.2. Geological map sheets (may be combined where appropriate)	
3.3. Snapshot of one of the map sheets of the State Geological Map of Ukraine in the scale 1:200 000, map sheet M-34-XXXV (Uzhgorod), geological map of pre-Quaternary sediments, (State Geological Map..., 2008)	
3.4. Flowsheet of an economic evaluation of a mineral property	
3.5. Base metals: real prices, lower and upper real price benchmarks, and real total cash costs solid line for real price, solid horizontal line for lower real price benchmark, dashed line for upper real price benchmark, grey line for real total cash costs, real prices and cash costs deflated by using US Producer Price Index PPI, basis 2017, vertical dashed line indicates break in price specifications	
3.6. Operating cost as a function of daily production capacity cp : A – for underground lead-zinc-mines, B – for copper open pit mines, excluding heap leach operations	
3.7. Cash Flow box	
3.8. Annuity present value factors b_n . The x-axis is the life time of the project in years	
3.9. Schematic of the mineral exploration value chain	

Chapter 4

Number and Title	Page
4.1. Iron ore areas of the Ukrainian Shield	
4.2. Cross-section of the Kryvyj Rig iron ore district	
4.3. Mining infrastructure of the Kryvyj Rig iron ore area	
4.4. Cross-sections of the Pivdenno-Bilozerske and Pereverzivske deposits	
4.5. Cross-sections showing the structure of the ore formation in the Oleksandrivskiy and Bogdanivskiy quarries	
4.6. Titanium and zirconium deposits of Ukraine	
4.7. Uranium deposits in Ukraine	
4.8. Cross-section of the Vatutynske deposit	
4.9. Distribution of rare metal and rare earth deposits of Ukraine	
4.10. Geological map of the Oktyabrskiy Massif	
4.11. Geological map (A) and cross-section (B) of the Azovske deposit	
4.12. Geological map (A) and cross-section (B) of the Yastrubetske deposit	
4.13. Geological map of the Sorokyno-Shevchenkivskiy pegmatite belt	
4.14. Geological map of the Shevchenkivske pegmatite field	
4.15. Geological map (A) and cross-section (B) of the Polokhivske deposit	
4.16. Geological map (A) and cross-section (B) of the Stankuvatske deposit	
4.17. The scandium mineralization zone within the western limb of the Zhovtorichenska syncline (A) and associated cross-section (B)	
4.18. Geological map (A) and cross-sections (B and C) of the Tarnuvatske deposit	
4.19. Geological map (A) and cross-section (B) of the Kapitanivske chromite deposit	
4.20. Cross-section of the Vysokopilske bauxite deposit	
4.21. Dynamics of copper prices in 1990-2022	
4.22. Distribution of some non-ferrous metals deposits and occurrences	
4.23. A cross-section segment along the line of wells at the Zhyrychi native copper ore occurrence	
4.24. Geological cross-section of the Perzhanske deposit	
4.25. Distribution of precious metals deposits of Ukraine	
4.26. Geological map of the Sergiivske deposit	
4.27. Geological map of the Balka Shyroka deposit	
4.28. Geological map of the Surozke deposit	
4.29. Geological map of the Maiske deposit	
4.30. Geological map of the Klyntsiivske deposit	
4.31. Geological map of the Yuriivske deposit	
4.32. Cross-section of the Muzhyivske deposit	
4.33. Geological map of the Saulyak deposit	
4.34. Cross-section of the Beregivske deposit	
4.35. Geological map (A) and cross-section (B) of the Bilyaivskiy salt dome	
4.36. Geological map (A) and cross-section (B) of the Dmytrivskiy occurrence	

Chapter 5

Number and Title	Page
5.1. The distribution of kaolin deposits in Ukraine	
5.2. Cross-sections of the weathered crustal zones in the Glukhovetske and Velykogadomynetske deposits	
5.3. Distribution of foundry sand and bentonite clay deposits	
5.4. Potential sources of building stones in Ukraine	
5.5. Potential sources of decorative stones of Ukraine	
5.6. Geological map (A), cross-section(B) and images of the Zavallivske graphite deposit	
5.7. Cross-section of the Stebnytske potassium salt deposit	
5.8. Cross-section of the Kalush-Golynske deposit	
5.9. Distribution of deposits and occurrences of associated abrasive raw materials	
5.10. Distribution of quartz deposits	
5.11. Cross-section of the Ardivske deposit	
5.12. Plan view (A) and internal structure (B) of the pegmatite chamber of the Volynske deposit	
5.13. Geological cross-section of the Zhvanske deposit	
5.14. Geological map (A) and cross-sections (B-K) of the Novopoltavske deposit	
5.15. Distribution of fluorite and staurolite zones, deposits and occurrences	
5.16. Geological map (A) and cross-section (B) of the Bakhtynske deposit	
5.17. Cross-section of the Petrovo-Gnutivske occurrence	
5.18. Geological map (A) and cross-section (B) of the Pokrovo-Kyreivske fluorite deposit	
5.19. The relative value of fluorite deposits and occurrences	
5.20. Distribution of limestone deposits and their end-use purpose in the Podilski Tovtry (VPP)	
5.21. Distribution of feldspar-yielding deposits	
5.22. Distribution of gemstone and facing stone deposits of Ukraine	
5.23. Distribution of amber fields, deposits, amber mineralization sites and active and non active production sites of Ukraine	
5.24. The lithostratigraphy of amber-bearing sediments of the Klesivske deposit exposed in the quarry No. 43 (Velykiy Pugach)	
5.25. Cross-section of the Prelutske rhodonite deposit	
5.26. Distribution of diamond findings and prospective sites in Ukraine	
5.27. Cross-section of the Biganske deposit	
5.28. Distribution of sillimanite, disthene, and andalusite deposits and occurrences	
5.29. Cross-section of the Rozdolske deposit	
5.30. Cross-section of the Yazivske deposit	

List of Tables

Chapter 1

Number and Title	Page
1.1. Recent communications and their objectives to boost Europe's raw materials integrity	
1.2. Some key actions of EUs solidarity with Ukraine (excerpt)	

Chapter 2

Number and Title	Page
2.1. Mineral reserves of Ukraine as of 01.01.2021	
2.2. Strategic minerals of Ukraine	
2.3. List of the world's largest mineral producing countries, 2019	
2.4. Dynamics of mining in the world in 2015-2019	
2.5. Dynamics of extraction of the most important minerals of Ukraine	

Chapter 3

Number and Title	Page
3.1. Classes of mineral reserves and resources of Ukraine	
3.2. NF-factors	
3.3. Suggested mine capacities and ranges after Long (2009) and Wellmer and Drobe (2019).	
3.4. Investment attractiveness of the main strategic mineral occurrences of Ukraine	

Chapter 4

Number and Title	Page
4.1. World mining iron production and reserves	
4.2. Extraction of iron ore in 2020	
4.3. World manganese mining production and reserves	
4.4. Manganese ore reserves and resources of Ukraine	
4.5. Manganese ore types of Ukraine	
4.6. Composition of manganese ores of Nikopolske deposit	
4.7. Composition of manganese ores of Burshtynske deposit	
4.8. Mineral resources of Kerchenskiy Iron Ore Basin	
4.9. Average composition of manganese ores of Kerchenskiy Iron Ore Basin	
4.10. World titanium mining and reserves	
4.11. Mineral reserves of apatite-ilmenite ores of Stremygorodske deposit	
4.12. Mineral resources of P ₂ O ₅ of Fedorivske deposit	
4.13. Mineral reserves and resources of Tarasivske deposit	
4.14. Composition of sandy clays at Yuriivsko-Koziivska site	
4.15. Mineral composition of sands at Gaidarivska site	
4.16. World uranium mining production and reserves	
4.17. World REE mining production and reserves	
4.18. Minor REE content in apatite of Novopoltavske deposit	

Number and Title	Page
4.19. REE content of technological sample, Azovske deposit	
4.20. Composition of bastnaesite, Azovske deposit	
4.21. Composition of the ore and xenotime in Balka Korabelna occurrence	
4.22. World zirconium mining production and reserves	
4.23. Average grades of zirconium concentrates at some deposits	
4.24. Composition of some minerals of Yastrubetske deposit	
4.25. World lithium mining production and reserves	
4.26. Chemical composition of petalite in the Polokhivske deposit	
4.27. Chemical composition of spodumene in the Polokhivske and Stankuvatske deposits	
4.28. Chemical composition of ores in the Polokhivske and Stankuvatske deposits	
4.29. Mineral composition of ores in the Polokhivske and Stankuvatske deposits	
4.30. The content of useful components of ore zones of the Balka Kruta deposit	
4.31. Content of scandium and related components in the ores of the Zhovtorichenske deposit	
4.32. World germanium mining production	
4.33. Distribution of germanium grade by ferruginous quartzite ore types	
4.34. World nickel mining production and reserves	
4.35. World cobalt mining production and reserves	
4.36. World chromium mining production and reserves	
4.37. World aluminium mining production and reserves	
4.38. World bauxite mining production and reserves	
4.39. World copper mining production and reserves	
4.40. Metal grades of massive copper sulphide ore bodies in the Dilovetskiy area	
4.41. Average metal contents in ore zones of the Prutivske occurrence and Zheleznyaki site	
4.42. Metal grades and resources in waste of Konstantynivskiy plant	
4.43. World tantalum mining production and reserves	
4.44. World niobium mining production and reserves	
4.45. World beryllium mining production and reserves	
4.46. World gold mining production and reserves	
4.47. World vanadium mining production and reserves	
4.48. World lead mining production and reserves	
4.49. World zinc mining production and reserves	
4.50. Breakdown of lead and zinc reserves and resources at Berehivske and Muzhyivske deposits	
4.51. World tungsten mining production and reserves	
4.52. World molybdenum mining production and reserves	
4.53. Content of impurities in molybdenite of the Verbynskiy occurrence	
4.54. World platinum mining production and reserves	
4.55. World palladium mining production	
4.56. World rhodium Mining production	
4.57. World strontium mining production and reserves	
4.58. Major-element composition of altered ultramafic rocks at the Pravdynske deposit	
4.59. World arsenic mining production	

Chapter 5

Number and Title	Page
5.1. World Mining and Kaolin Reserves	
5.2. Chemical composition of kaolin	
5.3. Composition of kaolins in Zhezhelivske deposit	
5.4. Chemical composition of kaolins in Novoselytske and Pologivske deposits	
5.5. Main enterprises producing facing (decorative) stones	
5.6. Composition and properties of labradorites in Golovynske deposit	
5.7. Composition and properties of granites in Omelyanivske deposit	
5.8. Composition and properties of granites in Lyznytske (Leznikivske) deposit	
5.9. Physico-mechanical properties of limestones in Velykokamyanske deposit	
5.10. Physico-mechanical properties of travertine in Velykokuzhelivske deposit and tuffs in Beretyanske deposit	
5.11. Chemical and mineral composition of clays in Chasiv-Yarske and Novorayske deposits	
5.12. Chemical composition of refractory clays and kaolin in Pologivske and Volodymyrivske deposits	
5.13. World graphite mining production and reserves	
5.14. Reserves of graphite deposits	
5.15. Dynamics of graphite production in Ukraine in 2010-2020	
5.16. Requirements of Ukrainian Standards for graphite concentrate and graphite	
5.17. World mineral production and reserves of potassium salts	
5.18. World garnet mining production and reserves	
5.19. Mineral composition of biotite-garnet granites of the Berdychivskiy Complex in Slobidske deposit	
5.20. Composition of garnet in Slobidske deposit	
5.21. Mineral composition of biotite-garnet granites in Loznenske deposit	
5.22. Composition of garnet in Loznenske deposit	
5.23. Particle size distribution and chemical composition of quartz in Avdiivske deposit	
5.24. Mineral and chemical composition of quartz sands and particle size distribution of quartz in Velykoglibovytske deposit	
5.25. World phosphate mining production and reserves	
5.26. World fluorspar mining production and reserves	
5.27. Summary of fluorite reserves and resources of the Bakhtynske and Pokrovo-Kyreivske deposits	
5.28. Mineral composition of ores in Bakhtynske deposit	
5.29. Breakdown of reserves and resources of the Bakhtynske deposit	
5.30. Chemical composition of Bakhtynskiy fluorite concentrate	
5.31. Fluorite deposits and occurrences of Bakhtynske ore field	
5.32. Breakdown of reserves of the Pokrovo-Kyreivske deposit	
5.33. World limestone production	
5.34. Characteristics of flux limestone deposits	
5.35. Chemical composition of limestones in Zakhidno-Psilerakhska site	
5.36. Physical and mechanical properties of limestones and dolomites	
5.37. Content of chemical components in limestones	
5.38. World bentonite clay mining production	
5.39. Main companies for bentonite mining	

Number and Title	Page
5.40. World feldspar mining production and reserves	
5.41. Main companies for extraction of feldspar raw materials	
5.42. World jewelry diamonds mining production	
5.43. World industrial diamonds mining production and reserves	
5.44. World barite mining production and reserves	
5.45. World boron mining production and reserves	
5.46. World bromine production and reserves	
5.47. World iodine mining production and reserves	
5.48. Content of useful components in industrial waters, North Syvaske deposit	
5.49. World zeolite mining production	
5.50. World vermiculite mining production and reserves	
5.51. Average chemical composition of the disthene quartzites of the Perzhanske deposit	
5.52. Bulk chemical composition of concentrate of the Malyshevske deposit	
5.53. The main types of mineral pigments in Ukraine	
5.54. World sulphur mining production	

Chapter 6

Number and Title	Page
6.1. Expert assessment of investment attractiveness of metallic minerals of Ukraine	
6.2. Expert assessment of investment attractiveness of non-metallic minerals of Ukraine	

Chapter 7

Number and Title	Page
7.1. Degree of criticality of raw materials	
7.2. Breakdown of the cells in the average battery	
7.3. The EU Critical Raw Materials	
7.4. The EU dependence on mineral imports	
7.5. US Critical Minerals	
7.6. World resources and reserves of critical minerals	
7.7. US Dependence on Mineral Imports	
7.8. Critical Minerals of Canada	
7.9. Comparative characteristics of critical minerals in different countries	

Gallery

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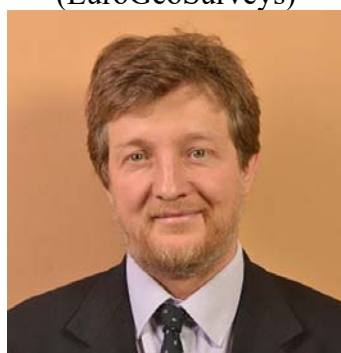
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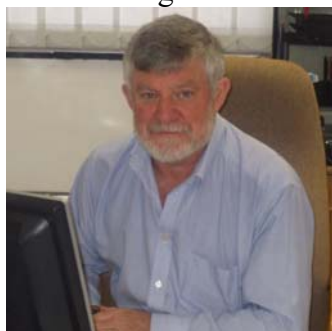
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FOREWORD

This book is about the European values. It stresses on the minerals of Ukraine, but actually this book is about the European values.

This year Ukraine was permanently in the top breaking news. But these headlines were mostly terrifying and not concerned the times of peace while we have to think and talk about times of peace and times of progressive development instead of the times of destruction. The European values are those that concern sustainable development of the European nations and that's why this book was written for the times of peace when European values would predominate, thus this book is definitely intended to give the opportunities for development and recovery of Ukraine.

This book is a joint collaborative activity of BRGM, the French Geological Survey, and EuroGeoSurveys (EGS), the Geological Surveys of Europe. Together, we were striving to strengthen the European knowledge on the mineral resources of Ukraine under the circumstances that happened in Europe after 24 February 2022, the military Russian aggression and start of the full-scale war against Ukraine. The core team of the book – Ukrainian geoscientists – were then scattered over Ukraine and the EU, and in the first weeks after mentioned date it was felt that geological and mineral data of Ukraine may be completely lost because of extensive shelling, bombing and blasting that covered Ukraine. That's why BRGM who accommodated the refugee Ukrainian mineral expert (Boris Malyuk) had supported the idea to prepare the book on the minerals of Ukraine, and then the EGS MREG, the Mineral Resources Expert Group, had also concluded on the needs to make a summary of the mineral resources of Ukraine.

Ukraine joined EGS in 2007, as a result of the changed European approach devoted to the EU enlargement, and further spreading out the European values over the countries that were not yet member states. The EGS has served as the platform to share these European values through mutually benefited collaboration and especially through the joint participation in research projects, either bilateral or those implemented in the frame of the EU framework programmes FP7 and then Horizon 2020 and Horizon Europe.

The role of mineral resources and their contribution to the European values are described over last decades in various conceptual and regulatory documents of the EU. The green-energy transition and circular economy, as the core part of the European values, comprise therefore the major targets for Ukraine that coupled with the UN Strategic Development Goals provide the long-term ground for the sustainable development of Ukraine, and under current circumstances even more than ever since Ukraine not only need to be recovered after the Russian war but requires the strong, persistent and irreversible impulse for the future achievements and complete integration into the EU, actually to become the EU member state.

We, undersigned this foreword, represent the EGS across the time, from the period prior to the EU enlargement, through the phase of the new geological surveys involvement, and up to the present time when Ukraine is the EGS associate member. Nevertheless, we all permanently supported Ukraine in its European trend and were thinking that Ukrainian engagement to the EU activities in the frame of EGS would facilitate the European integration of Ukraine as a whole. And this is especially important in the field of geosciences, one of a few human spheres where administrative and political borders are often crossed or even unified in order to get the holistic knowledge of the natural phenomena and their value for society, specifically, mineral resources, and of the latter – the critical raw materials.

Thus, we always supported Ukraine on its European way, and we always considered Ukraine as the “part of pie” which is critical for the understanding of the “whole pie”, that is geology of Europe as a whole. This concerns not only mineral resources, but also geodynamics, igneous and metamorphic petrology, stratigraphy, groundwater, and certainly the environment. The EU goals of the carbon-neutral continent require contributions from and efforts from all European countries including Ukraine. And certainly attention to the European sources of critical raw materials would include Ukraine as an important part of the European mineral value chain.

The European geological knowledge base comprises the major objective of the consecutive EU projects GeoERA and GSEU where Ukraine took part as a full partner. This knowledge base requires standardization, unification and harmonization of geological data, the mineral data in particular, and these tasks are being developed nowadays through the application of modern information technologies. This direction is therefore equally important for Ukraine, and mineral data contained in the given book, should be considered as the basis for subsequent European alignment.

The book is evident that the EU knowledge of Ukraine is still incomplete. A wide range of issues still look controversial while being considered either from the EU or Ukrainian points of view. Unfortunately, Ukraine was not connected with the Western Europe for a long time that caused insufficient or limited exchange in people, in skills, and in knowledge. The European integration of Ukraine would require therefore restoring of the great number of quite common links and connected things, and these tasks also are in priority of the EGS while making the long-term pan-European concepts, specifically, explained in the SRIA, Strategic Research and Innovation Agenda that had been recently developed by the EGS. Ukraine is very welcome on this way, and permanent participation of Ukrainian experts and geoscientific activities of the EU is foreseen and fairly supported by the EGS and its members.

We recognize the European values in this book in the broad engagement of various contributors. Besides the core team of Ukrainian experts, the EGS/MREG input had been provided by the experts from EGS Secretariat as well as Geological Surveys of France, Germany, Portugal, and Hungary. Quite impressive team had been gathered for the English-language proofreading and included the geoscientific experts retired from the BGS, the British Geological Survey.

Extent to which Ukraine is recognized at the European geoscientific community is seemed to be rather junior – we are aware of the huge amount of geological studies and works performed in Ukraine both in Soviet times and afterward, but this awareness is much less prominent and we would rather conclude that Ukrainian geology and mineral resources are still essentially underexplored by the European geologists. For various reasons this is considerably caused by the lacking of English- or European-speaking publications about Ukraine, as well as a limited number of available internet resources, which in turn are not often provided in the European languages. This definitely comprises the real knowledge gap of the geology and minerals of Europe while we consider Europe as a whole, including Ukraine. The scarcity of these publications and resources negatively affects not only the European geological knowledge base, but also significantly hamper the interest of investors, both European and worldwide. Thus, this book is trying to fill this gap at the initial extent at least, providing the background to the further more extended, advanced and comprehensive publications.

Christophe Poinssot (BRGM Manager General, EGS President 2023-2025)

Ralph Watzel (BGR President, EGS President 2020-2022)

Friedrich Wellmer (former BGR President, EGS President 2004-2005)

Jacques Varet (former BRGM Director, EGS President 1999-2003)

Julie Hollis (EGS Secretary General 2021-2025)

Patrice Christmann (former BRGM Director, EGS Secretary General 2005-2009)

Jean-Claude Guillaneau (BRGM Director for International Cooperation)

INTRODUCTION

This Book: Its Purpose, Contents and Intended Audience

The title of this book suggests that it was written for the sake of mineral investments in Ukraine. This purpose however requires not only insights of mineral economy but also a wide range of geological information. Thus, this book had been written by geoscientists aiming to update the European mineral resources knowledge base with data from Ukraine (that has recently become a candidate country for EU accession).

The core team of the draft book included Ukrainian geologists from the Institute of Geology, Kyiv National University, and State Research and Development Enterprise “Geoinform of Ukraine”. Then, once the book preparation moved to France, the book team was enlarged with experts from the French Geological Survey (BRGM), and later from the Mineral Resources Expert Group (MREG) of the European Geological Surveys (EuroGeoSurveys or EGS). The book is divided into two major parts. The first part (Chapter 1), provides the European setting of Ukraine’s mineral resources. The second part (chapters 2-6) is devoted to the geology and minerals of Ukraine.

The book is also intended to fill the gap of available English publications on Ukrainian geology and mineral resources. Thus, the principal idea was to write a book that will be readable, up-to-date, and understandable for English-speaking readers. Initially, the draft book written in Ukrainian was automatically translated into English using the Google Document Translation service, and then preliminary spelling check was undertaken by the Ukrainian authors. Subsequently, the rough English draft was submitted to the native English-speaking authors for their proofreading and text updating and improving.

So, the book drafting team was rather complex and evolved. At the European stage of the book preparation (commenced in March 2022) in France, experts from BRGM joined the author’s team, and then (in June 2022) several experts from other European Geological Surveys (Portugal – LNEG, Germany – BGR, and Hungary – HSFSZ) were involved after the EGS MREG meeting in April 2022. Furthermore, thanks to one of the invited authors, David Ovadia, more geoscientific and mineral exploration experts were engaged and they were conventionally named ‘BGS Retirees Team’ being consisted of the British Geological Survey retired staff members.

The MREG Team focused on the European context of the book, that is Chapter 1, and the ‘BGS Retirees Team’ was involved in the proofreading and updating of the chapters on the geology and mineral resources of Ukraine. Both teams were focussed on maintaining the book’s relevance to the intended wide readership, particularly

Western readers. The term ‘Western’ in this context essentially covers the EU, North America and other countries with significant interest in the mineral industry.

This book contains detailed information about Ukraine’s known mineral resources and will form an important reference for those seeking future public and private inward investment into Ukraine's mining sector, including,:

- Geoscientists
- Investors
- Politicians
- Academic researchers
- Exploration companies
- Environmental researchers
- Students and post-docs

Having the goal to make the book useful, we were trying to make it compliant with the listed various demands and potential readers. While the EGS Team had provided the comprehensive overview of the EU strategy and policy with regard to critical raw materials, boosting mineral exploration and geosciences in Ukraine in line with the EU trends and needs (green energy transition, circular economy, etc.), the ‘BGS Retirees Team’, besides proofreading, was involved in the huge exercise on the unification and interpretation of the terminology, jargon, slang, etc., in the original text written by the Ukrainian Team. This was a real challenge, and the tasks that the ‘BGS Retirees Team’ were faced with, were quite different and varied, from the different meanings of ‘mineral reserves’ in the West and in Ukraine, up to the use of single units like ‘thousand tons’ used in quantifying reserves. The results of these ‘consenting’ efforts are summarised in this ‘Introduction’ which includes several sections intended to simplify the reading and understanding of this book. Specifically, the section ‘What Conventions Are Used in This Book?’ describes the terms that are retained from their usage in Ukraine with the necessary comments of their meaning in subsections ‘Units’ and ‘Glossary’. A subsection provides a list of abbreviations used in the book. There might be apparent overlapping between the terms mentioned in the subsections noted above, but these entries do not contradict each other and simply provide additional clarification to the terms and expressions under consideration.

The authors hope for the readers’ understanding on the issues involved in the translation process and believe that this book will give rise to extended studies and research in Ukraine, and that Ukraine’s mineral potential will become an attractive investment prospective for the readers.

The Research Scope of This Book

As stated in the draft law of Ukraine "On Amendments to the National Program of Development of Mineral Resources of Ukraine until 2030", A powerful domestic mineral complex based on its own mineral resources comprises the basis for sustainable and efficient development of the national economy, especially its mining and processing industries” (Draft Code 2021).

Ukraine has a strong mineral resource base (MRB) and in this respect it is one of the leading countries in the world. This is due primarily to the complexity and diversity of its geological structure and multi-stage development of its territory. More than 8,000 deposits and over 12,000 occurrences of 100 mineral types have been discovered in Ukraine; a significant part of which is being developed or has been developed (more than 3,300 deposits). Deposits and occurrences of combustible minerals (oil, gas, coal, peat, oil shale), metallic (iron, manganese, chromium, titanium, vanadium, aluminium, magnesium, copper, lead, zinc, nickel, cobalt, molybdenum, tungsten, tin, mercury, antimony, gold, silver, platinum, uranium, beryllium, lithium, germanium, tantalum, niobium, zirconium, hafnium, scandium, yttrium, lanthanides), and non-metallic raw materials are known. Such a number and variety of minerals allow for a significant mining development, which is now possible with capital investment, both domestic and foreign. Extraction and processing of mineral raw materials are traditionally capital-intensive industries that involve the creation and operation of costly facilities, and the purchase of mining and transportation equipment. The development of mineral deposits also usually requires a significant time period, which entails many investment risks. These factors determine the relevance of investment assessment of domestic MRB at different levels: local, for individual mineral deposits, and regional and State – with the definition of most strategically important types of minerals.

The operation of MRB is vital for Ukraine's economy; in particular, the export of mined ore products accounts for over 60% of Ukraine's foreign currency earnings. However, Ukraine imports significant amounts of chromium, vanadium, aluminium, copper, zinc, lead, tin, tungsten, molybdenum, precious metals (gold, silver, platinum), magnesite, fluorite, bauxite, magnesium chloride and some other minerals, including significant amount of oil and gas, partly coal. Therefore, the assessment of the country's mineral potential is extremely relevant and of great economic importance (Mykhailov, Hrinchenko 2018).

The first generalizing summaries of the geological structure and minerals of Ukraine are given in the relevant volumes of the fundamental work "Geology of the Soviet Union" (1944-1958), and in the monograph of V.G. Bondarchuk "Geology of Mineral Deposits of Ukraine" (1969). Questions about mineral resources and geology of mineral deposits of Ukraine were covered in the works of O.K. Babynin, A.K. Bakarzhiev, Ya.M. Belevtsev, O.B. Bobrov, V.G. Bondarchuk, A.S. Voynovskiy, L.S. Galetskiy, E.B. Glevaskiy, P.F. Gozhyk, S.V. Goshovskiy, D.S. Gurskiy, K.Yu. Esipchuk, E.Ya. Zhovynskiy, V.M. Zagnitko, P.M. Zarytskiy, V.B. Koval, S.G. Kryvdyk, E.O. Kulish, E.K. Lazarenko, M.I. Lebed, O.I. Matkovskiy, V.S. Metalidi, S.V. Nechaev, B.S. Panov, V.L. Prykhodko, M.P. Semenenko, A.O. Sivoronov, V.I. Skarzhinskiy, S.M. Strekozov, E.F. Shnyukov, V.O. Shumlyanskiy, G.M. Yatsenko and many others. The two-volume monograph (Gurskiy et al. 2006a, b) and a series of textbooks (Mykhailov et al. 2007, 2008a, 2009) provided information on the mineral resources of Ukraine accumulated by the beginning of the XXI century.

These and other works lacked a modern critical analysis of MRB of Ukraine and do not provide geological and economic assessment of raw materials in modern

market conditions. However, in recent years, further attention has been paid to the geological and economic assessment of MRB of Ukraine (Gaylin et al. 2017; Gurskiy 2008; Dovgiy et al. 2007; Mykhailov, Kurylo 2010a, b, 2015a,b; Rudko et al. 2010, 2011, 2015; Mykhailov 2016). Theoretical issues of such assessment were developed (Korzhnev et al. 2006; Mykhailov et al. 2014a), and textbooks and manuals have been published. (Korzhnev et al. 2006; Mykhailov et al. 2007, 2008a; Mykhailov, Kurylo 2015; Mykhailov et al. 2018). Notably, the monograph of D.S. Gurskiy (Gurskiy 2008), provides information on a group of strategically important minerals for the country's economy: its gross domestic product, foreign currency earnings, contribution to the State Budget, economic and defence security of the country. The minerals were divided into 4 categories:

- A. gas, oil, condensate, methane from coal deposits, coal, iron, manganese, titanium ores;
- B. aluminium, nickel and cobalt, uranium, potassium salts, sulfur, carbonate chemical raw materials, kaolin;
- C. lithium, rare-earth elements (REE), gold, silver, flux limestones and dolomites, bentonite clays, etc.;
- D. chromium, copper, lead and zinc, tantalum and niobium, tin, tungsten, molybdenum, zirconium and hafnium, platinum group metals (PGM); phosphorites, apatite, barite, glauconite, fluorite, magnesite, high alumina raw materials, stone raw materials, technogenic secondary raw materials.

The issue of the incomplete database of explored reserves of domestic MRB was also raised in the publications of L.S. Galetskiy, who noted the lack of a full cycle of production (from mining to production of end products). Most often, companies are engaged only in the extraction and primary processing of raw materials, which underestimates the significant added value of the local production of the end products. The main reason for this is insufficient investment in beneficiation and metallurgical or chemical processing of raw materials.

Most of the published works contain an assessment of MRB in general and its individual components, but lack details of their quantitative and qualitative evaluation, geological settings and patterns of distribution of mineral deposits and occurrences. Some publications contain the results of geological and economic assessment of reserves and resources of minerals, but, as a rule, these are the results of regulatory or comparative assessment, which does not contain a detailed investment analysis of subsurface mining projects.

The development of MRB in Ukraine is hampered by a number of factors including: an imperfect legal framework and the erroneous investment policy of the late 1990s – early 2000s; outdated technologies for mining and extraction of useful components; lack of economic evaluation of many types of minerals and their deposits, taking into account market economy mechanisms; lack of investment. This necessitates the development of an up-to-date pragmatic approach to the assessment of our MRB, for Ukraine's entry into the world market of mineral resources. The main task for Ukraine in the coming years is to re-evaluate its own mineral resources according to modern economic criteria, especially the investment attractiveness of its

deposits and occurrences. Assessing the investment attractiveness of MRB in Ukraine, taking into account the risks, current and forecast conditions is necessary to successfully attract investment and to obtain the greatest economic benefits at all stages of implementation of mineral-related projects. The results of such research are important before signing the Production Sharing Agreement, creating favorable conditions for the implementation of investment projects. The offered scientific research is devoted to these questions.

Our main purpose is to show the investment attractiveness of MRB in Ukraine, which is an extremely important issue given the need to attract investment for the development of our economy. The main objectives of the work are to develop consistent methods, criteria and indicators for assessing the investment attractiveness of MRB of Ukraine.

What Conventions are Used in This Book?

A range of geological terms in the book are retained from their primary use in Ukraine. Sometimes, these terms are either unfamiliar to, or used in a different context by, western readers. The ‘BGS Retirees Team’ noted this and after a number of discussions it was concluded that original Ukrainian terminology should be retained. At the same time, we concluded that this special subsection was added to make western readers aware of these linguistic mismatches. Some Ukrainian terminology doesn’t have direct analogues in the West, and it was not always possible to give a comprehensive understanding of Ukrainian terms using simple Western terms. Mostly this is due to historical reasons when Ukrainian terms were developed in a way different from the Western approaches. Thus, to avoid the deep examination of the terms that may confuse the reader, it was agreed to present a brief list of conventions that would cover most controversial terms.

Geography and Proper Names

Some readers of this book might not be too familiar with the geography and administrative divisions of Ukraine. Fig. 1.1 shows the administrative subdivisions of Ukraine. The ‘regions’ are shown in italic whereas their administrative centers have normal font face. Mostly the names of ‘regions’, and their administrative centers coincide, but in some cases they are different (e.g. Uzhgorod – Trans-Carpathian, Kropyvnytskiy – Kirovohrad, etc.). The principal administrative units are called ‘oblast’ in Ukrainian which roughly corresponds to the term ‘region’. The latter is commonly written in small letters, and in the text the reader will find the references to the ‘oblasts’ like ‘Cherkasy region’, etc.

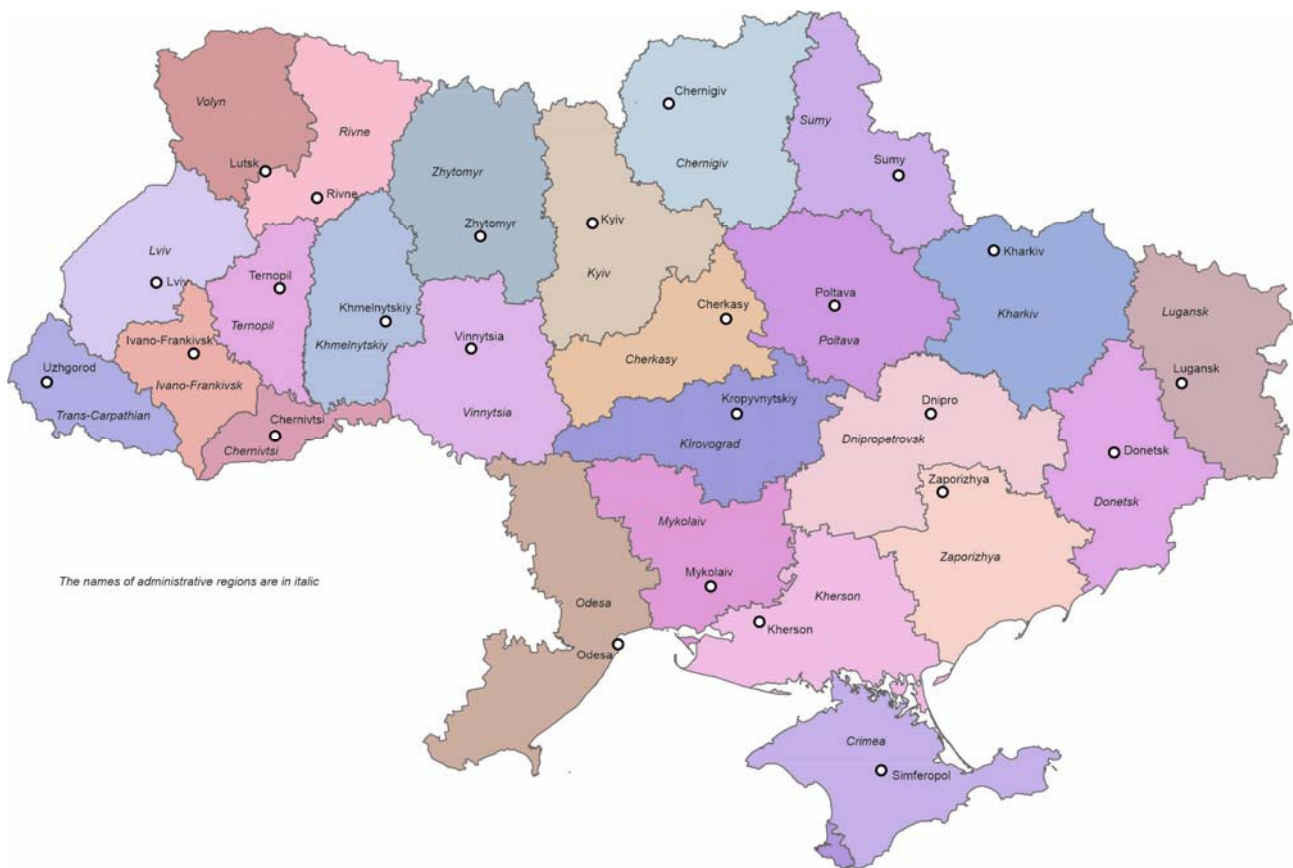


Fig. I.1. Principal administrative units of Ukraine.

Furthermore, traditionally some historical, ethnographic and landscape areas of Ukraine are given distinct proper names. Of these, Pryazovya, Prydniprovya, and Pobuzhyya (Fig. I.2), are frequently used in the text covering areas enriched in minerals. These areas take their names mostly from the rivers or seas, and their proper names are retained from Ukrainian.

The local names in Ukrainian are often used to derive the names of geological units. It is not always possible to provide the right and correct English translation since the names of geological units may come from the geographic location, river, lake or sea, but can also refer to the cardinal directions. For example, West-Pryazovian Series is derived from the western part of Pryazovia. But ‘West’ is the English term whereas ‘Pryazovia’ is not. That’s why somewhere the term ‘Zakhidnopryazovska Series’ sounds more correct being simply translated from Ukrainian. Thus, we had a lot of discussion on the issue and finally concluded that the Ukrainian terms might be better to retain, providing in this way also the preserved original spelling in Ukrainian.

discussed over the last decades (Henley 2010, 2018; Henley, Allington 2012; Dixon, Podturkin 2010; Henley, Malukhin 2010; Fahey 2018). For more information, the reader is referred to the listed sources, whereas the simplified tools used in the book are presented below.

Regarding the mapping of A-B-C and JORC/CRIRSCO/PERC codes, a simple conventional sketch (Fig. I.3) was formerly discussed (Malyuk et al. 2007) with reference to the Annual Report of the company Palladex Plc. (Palladex 2004), which worked in Tajikistan and Kyrgyzstan, and this sketch was adopted by Palladex after SRK Consulting Ltd. and Resources Computing International Ltd.

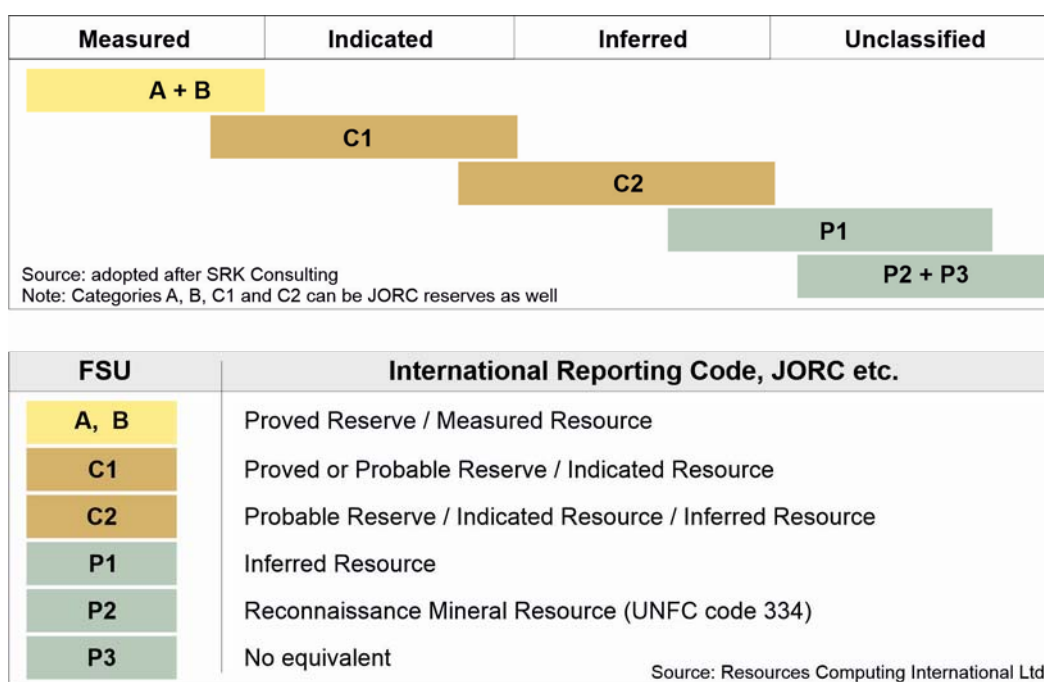


**Fig. I.3. Comparison of JORC and FSU resource classifications
(modified after Malyuk et al. 2007; Palladex 2004)**

Recently the correspondence and relationships of A-B-C and international codes were discussed in a range of publications (Henley 2018; Henley, Allington 2012; Dixon, Podturkin 2010; Henley, Malukhin 2010; Fahey 2018), and Fig. I.4 and I.5 provide the sketches that are roughly compliant with Fig. I.3.

A-B-C categories	C2	C1	B	A
Approved (Balance) Mineral Reserves				
CRIRSCO category of Mineral Reserves	Probable	Proved	Proved	Proved
Not-Approved (Off-Balance) Mineral Reserves and Resources				
CRIRSCO category of Mineral Resources	Indicated	Measured	Measured	Measured

A-B-C categories	P3, P2	P1
“Prognostic Resources”		
CRIRSCO category	Exploration Results	Inferred Resources

Fig. I.4. Comparison of CRIRSCO and FSU resource classifications (modified after Henley, Malukhin 2010)

CRIRSCO (JORC/PERC)	Resource	Measured	Indicated	Inferred	Exploration Potential or Target
	Reserve	Proven	Probable		
Russian State Classification	Reserve	A, B and C1	B, C1 and C2	C2 and P1	P2 and P3

Fig. I.5. Comparison of CRIRSCO and Russian resource classifications (modified after Fahey 2018)

Taken together, these sketches can be used by readers of the present book. Specifically, those reserves shown as A, B and C₁ come from the State Inventory of Mineral Reserves of Ukraine, and can be considered as the CRIRSCO-compatible reserves according to Fig. I.4 and I.5, since they are recorded in the Inventory after approval of the State Commission on Mineral Reserves of Ukraine. Any other categories (C₂, P₁, P₂, P₃) by default might be considered as resources of mostly Inferred category by CRIRSCO/JORC. At the same time, the reader is cautioned to be careful with the direct acceptance of reserves A-B-C categories since resources and reserves quoted through the text have been made by varied standards in the past, some are compliant with the international stock market standards while some comply with the national or government-imposed standards. Therefore, caution should be used when using the reserves/resources figures for future purposes.

Stratigraphy

The following definitions are used in Ukraine for the purposes of stratigraphy:

Series – A taxonomic unit of high-ranking local stratigraphic divisions. It is a complex multifaceted geological body that reflects the stages of events in the respective territories and is characterized by common features: conditions of formation (marine, continental, volcanogenic, metamorphic, etc.), the corresponding material composition of rocks (sedimentary, terrigenous, carbonate, volcanogenic, etc.), the structure (rhythmicity, etc.).

As a rule, it is divided into Suites, the set of stratotypes of which constitutes the stratotype of the Series. Unsegmented Series have their own stratotype. Stratigraphic boundaries are isochronous or diachronous, expressed by planes of regional angular or stratigraphic unconformities, as well as manifestations of intrusive magmatism. Name — after any geographical object in the area of distribution (e.g. Poliska, Maikopska Series) (Stratigraphic Code 2012).

In the West the term *Series* is used in chronostratigraphic descriptions. In the West the equivalent lithostratigraphic terms used is Group (Salvador 1994).

Suite – The main taxonomic unit of local stratigraphic subdivisions and the main mapping unit of regional (basin) stratigraphy in large-medium-scale mapping, geological prospecting, geological exploration works. Mostly, it is a complete rock-layered system (body) with a characteristic biolithofacies composition different from the adjacent geological bodies.

With some variability, the Suite can be divided into subsuites, layers with geographical names. Auxiliary litho- and biostratigraphic subdivisions can also be distinguished. In the rhythmical sequences the Suite comprises a thick sedimentation cycle (macrocycle) (Stratigraphic Code 2012).

In the West the term *Suite* is used in lithostratigraphic descriptions of non-layered metamorphic and igneous rock. In the West, the lithostratigraphic term *Formation* is used in the same sense as the term *Suite* is used in Ukraine. (Salvador 1994).

Units

The standard CI units are used in the book except where specified. Particularly, when ‘tons’ is written, this always means metric tons although the classic English expression of metric tons is ‘tonnes’.

Traditionally the oil and gas industry of Ukraine uses tons and cubic meters for oil and gas reserves and production instead of barrels and cubic feet, respectively. In the mining industry, some minerals are being measured in kg/ton per cubic meter. Conversion of these units is currently easy to find out on the web so we do not put these relations in the book.

While expressing the numbers, and tonnage in particular, the units were used separated by comma (thousands) and dot (decimals) – e.g. 100,000.00.

The following abbreviations were used for tonnage units in particular:

- thousand of metric tonnes – kt
- million of metric tonnes – Mt

While the grades were indicated, g/t does always mean grams per metric tonne, and other specific units may be specified locally in the text.

Glossary

Term	Meaning
% w/w	weight by weight percentage
LOI	loss on ignition
Oblast	administrative unit of Ukraine (see Fig. I.1), mostly not used in this book where the word ‘region’ is used instead
Hydromica	not used in the West, where the term ‘illite’ is used instead
Gangue	Usually means the unwanted minerals, commercially worthless material that surrounds, or is closely mixed with, a wanted mineral in an ore deposit
kgf/m ²	kilogram-force per m ² , compressive strength
kg/mm ²	kilogram per square millimetre, microhardness
thermo-emf	thermoelectromotive force, $\mu\text{V}/^\circ\text{C}$
Cone grinding devices:	
CCG	coarse
CMG	medium
CFG	fine
Beneficiation	Mineral processing term that generally means production of concentrates from ores; some readers may be more familiar with the term ‘enrichment’ – the term ‘beneficiation’ is used in the book to make difference between the human technological process (beneficiation) and natural process common in geochemistry or petrology (enrichment)
Verkhovna Rada of Ukraine	Parliament of Ukraine
Cabinet of Ministers of Ukraine	Government of Ukraine

List of Other Abbreviations

CAGR – compound annual growth rate
CMP – chemical and metallurgical plant
CMU – Cabinet of Ministers of Ukraine
CRM – critical raw materials
DDD – Dniprovsko-Donetska Depression
Derzhgeonadra – see SSGSU
FDP – flux dolomite plant
GSS – greenstone structure
IOA – iron-ore area
IOB – iron-ore basin
LLC – limited liability company
MBP – mining-beneficiation plant
MRB – mineral resource base;
NAL – neutron activation logging
PGM – platinum group metals;
PJSC – Public Join-Stock Company
PV – photovoltaic
REE – rare earth elements
SCMR – State Commission on Mineral Reserves;
SDG – Sustainable Development Goals
SIMR – State Inventory of Mineral Reserves of Ukraine
SME – small and medium enterprises
SSGSU – State Service of Geology and Subsoil of Ukraine (Derzhgeonadra)
TMZ – tectono-metallogenic zone
UOA – uranium-ore area
VPP – Volyno-Podilska Plate

Executive Summary

This book is the culmination of a massive effort by many people to bring together, in a single publication, a comprehensive description of the mineral potential of Ukraine. There has previously been a vast collection of geological information and publications available in the various state institutions and universities of Ukraine, but much of that valuable resource was of limited use to international readers either because it was held locally in analogue form only or published in the Ukrainian language, or both. Thus began a programme to update the most important of these works, translate them into English, and publish them in a single compilation that would be easily accessible internationally in digital as well as hard copy form.

The recent geopolitical events in Ukraine have brought new impetus to this programme, which was generously supported by the Bureau de Recherches Géologiques et Minières (BRGM) in Orléans, France and the European Union through EuroGeoSurveys, and its member organisations, in the knowledge that Ukraine will need a huge amount of economic and infrastructural reconstruction, and that exploiting Ukraine's mineral resources is likely to form a significant part of that process. However, opening up Ukraine's mining to global markets, and hence enabling the country to benefit from rebuilding funds provided by international donor governments and agencies, as well as inward investments from the private sector, will not be a simple matter.

It would be naïve to suggest that simply having a book about minerals available on the bookshelves, no matter how worthy and comprehensive such a book would be, could in itself generate the economic recovery of a post-conflict nation. That is not to say that this book should not be on the bookshelves; quite the contrary – this is a work of such importance that it should have a place in the library of every university and geological institution, as well as on the (digital) shelf of many of the world's exploration and mining companies. It is a comprehensive reference, in English, describing the nation's mineral rich geology, and hence it is a means to an end (of securing economic growth through extractives) but it is not an end in itself.

The science of geology does not exist in isolation. From the earliest times, an understanding of geology in general and mineralisation in particular has been part of the toolkit for finding and extracting those commodities required by the societies of the time. It has long been recognised that all raw materials that cannot be grown and all energy that cannot be generated by renewables have to be found in their geological setting. The first geological map known to us was drawn on papyrus to represent the Fawakhir gold mine in (present day) Egypt. Iron was smelted from ores in Aswan and smelting was also carried out at Naukratis and Defna in the Delta region. The map was drawn in about 1160 BC by the Scribe-of-the-Tomb Amennakhte, son of Ipuy. It was prepared for Ramesses IV's quarrying expedition to the Wadi Hammamat in the Eastern Desert, to be used for statues of the King (Harrell, Brown 1992). Many centuries later, the modern industrial revolution which,

arguably, started in the 1760s in Britain, was based on the natural resources then abundant in northern England of water from the Lancashire valleys for cotton milling, steam power from Carboniferous coal and co-located iron ore and limestone for steel making. These events led to the publication of what is generally claimed to be the first modern geological map, compiled by William Smith in 1815 (Winchester 2001) but it should be noted that the main purpose of this map was to assist engineers in the building of canals; an academic understanding of the geology depicted on the map was never its prime purpose. In the same way, what is published in this book is primarily for the purpose of promulgating information about the commercially viable mineral locations in Ukraine and their potential for exploitation, to which the necessary and comprehensive geological explanations are applied. Put another way, the focus of this book is to describe the actual and potential mineral targets and to explain the geology that has produced them, rather than describe the geology and leave it to the reader to work out the consequences.

This takes us to the question of who would be the target readership. The answer is understandably complex. Students and researchers interested in the geology of Ukraine will find it full of information on which to base new knowledge. That is necessary but not sufficient to the case for stimulating economic benefit.

It is important to understand that mineral exploration leading to mining, as carried out mainly by the private sector in most so-called free market economic systems, depends almost entirely on securing the necessary investment capital to pay for the work in what is generally a high risk, expensive and lengthy process. Most new mineral exploration is carried out by junior and mid-cap companies, who have to raise funds privately or on the stock markets, where they are in direct competition in such fund raising with alternative sectors, such as technology or pharmaceuticals, also seeking to attract the funds held by individuals, banks and pension funds, and who are frequently able to offer quicker, better and less risky returns. So the readership of this book whose aim is to use its contents to search for minerals that can be mined profitably, must use the content to assess the risk-reward possibilities of extracting the minerals from the described geology. This reader must also be assured that there is a regime for secure tenure of the exploration and mining land over what is usually a lengthy period, and that the necessary infrastructure of roads, railways, power, water and labour is, or will be, available. The book does not address these matters directly but it does attempt to set the geological descriptions in a context of indicating where various economically important minerals are likely to be found, in what quantities, depths and grades. The book describes existing and historical mining activities, although these were not always undertaken against the constraints of modern investment and feasibility criteria, given the high level of central planning and state control that existed in former times. Nevertheless, “near-ology” is an important if not very scientific factor in securing confidence and hence investment for mineral exploration.

Furthermore, when it comes to the investment returns that can be derived from the extractives sector, not all minerals are equal, and the relative attractiveness of such minerals is changing rapidly, partly as a result of the changing world order that has,

in part, stimulated this book. The current trends in globalisation, supply chains, security and climate change / net zero are all helping to redefine what are regarded as critical minerals in the eyes of governments, industries and investors. In the transition from energy produced from hydrocarbons towards renewable sources, insufficient attention is often paid, particularly by politicians, the media and the public, to the need for ever growing quantities of rare earths to be used in the magnets of wind turbines, for example. Electric vehicle batteries will require vastly greater sources of lithium and nickel than are currently discovered. Nuclear fusion depends on quantities of tungsten and beryllium that exceed current world production by orders of magnitude. National defense of one country cannot sensibly depend on raw materials supplied only from sources that are controlled by potential adversaries. Even the traditional sourcing of bulk commodities such as iron ore, bauxite or copper from global markets is being re-evaluated in the light of supply chain constraints in the post-Covid pandemic world of today. By the time this book is published, those minerals which currently appear to be strategic and of the highest priority, may be rendered less important as a result of changing demand and new technologies. Conversely, minerals that might only be mentioned in passing could become the commodity hot-spots of the future. For these reasons, this book attempts to set out the facts and provide the information that current and future practitioners in the mining sector will need for their informed decision making.

At a more prosaic level, the book attempts to act as a bridge between concepts and terminology that have been used in Ukrainian mineral thinking over past decades and to relate these to those commonly used in today's market economies. This is not always an easy task, and how it has been addressed is described in more detail elsewhere. There are not always straightforward one-to-one conversions to, for example, JORC resource assessments (Stephenson 2001), but it is hoped that sufficient detail is made available for informed understanding.

In summary, this book puts into one place a vast source of reference material that will assist those considering how best to use Ukraine's rich mineral resources for the benefit of her people and humankind more widely. It is a compendium of geological and related information for those with a purely academic interest, and a toolkit for those who wish to apply geology to economic development and quality of life improvements, in a rapidly changing world.

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Each book has its own history, and the history of this book was complex. It mostly reflects the feelings of Ukrainian co-authors while our European colleagues are either co-authors to this book or are mentioned below accordingly.

The idea of this book had been inspired in 2021 once the authors (Volodymyr Mykhailov (VM) and Boris Malyuk (BM)) were invited by Morten Smelror (NGU) to take part in the Geological Society of London Special Publications "The Green Stone Age: Exploration and Exploitation of Minerals for Green Technologies"

(Mykhailov et al, 2022a). Unfortunately, our third co-author – Oleksandr Hrinchenko – had passed away due to cancer exactly on the day of the paper submission, on August 5, 2021. VM continued the book drafting while the paper reviewing and processing was completed with the article acceptance for publication on February 15, 2022. The article proof-reading and final publication then coincided with the beginning of the Russian war against Ukraine, and in March 2022 when BM moved to France and was employed by BRGM, Geological Survey of France, the idea of this book publication in BRGM came up and started to develop.

Initial stage of the book preparation in France, and further organizational, technical and especially financial arrangements of the book publication were only possible thanks to the incredible courtesy of BRGM heads, and in particular Christophe Poinssot, Director General, as well as Jean-Claude Guillaneau, Director for International Cooperation, Christophe Didier, Director of Georesources, Patrick D'Huges, Director of Research Programs of Georesources, and Pierre Nehlig, Director of Geological System Programs. BM is extremely grateful to the staff of the Department of Mineral Resources (GEM) who contributed to the book in various extents and first of all for the variable friendly support and heartwarming patience of Fenintsoa Andriamasinoro, Laurent Bailly, Antoine Boubault, Léo Chabot, Nicolas Charles, Matthieu Chevillard, Sebastien Colin, Lucile Esnee, Eric Fournier, Eric Gloaguen, Blandine Gourcerol, Laurent Guillou-Frottier, Thomas Gutierrez, Matthieu Harlaux, Alix Hauteville, Maïté Le Gleuher, Gaetan Lefebvre, Mathieu Leguerinel, Paul Notom, Maxime Picault, Anthony Pochon, Anne-Sophie Serrand, Alex Vella, Léane Verhulst, Guillaume Vic, Nana Abdou Toure, Issiaka Sangare, Emma Saulnier, Emmy Penhoet, and Valentine Charvet. Obviously, the key role of GEM Head, Guillaume Bertrand, has to be emphasized, it was him who had been faced first with all problems and who extremely helped BM to find out proper solutions.

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The book idea that was growing in BRGM, had received additional incentive in April 2022 when at the meeting of EGS MREG, Mineral Resources Expert Group, the MREG Chair, Daniel Oliveira (LNEG, Portugal) had suggested to prepare a special EGS/MREG publication on Ukraine. Two mentioned lines were then combined and further developed upon consent by Julie Hollis, EGS Secretary General. Daniel Oliveira had further strived to engage the MREG members whose contribution is reflected in the current list of the book co-authors, of these Antje

Wittenberg (BGR, Germany) became the engine of the EU overview of CRM in Chapter 1 while Zoltan Horvath (SZTFH Hungary) essentially updated this Chapter with the resume of the mineral inventory in Europe and UNECE developments. Julie Hollis under participation of Patrick Wall and Laura Quijano Gaudes of EGS Secretariat had outlined the European policy and strategy with regard to the raw materials as a whole and CRM in particular, the EGS role in the development of European mineral knowledge base, and the history of Ukraine integration to the EGS. BM would especially thank to David Ovadia who had engaged the volunteer team of retired experts from BGS, British Geological Survey (William Hatton, George Strong, Mark Parker, Stephen Henley, Roger Key, Alexander Macfarlane, Bill McCourt, Steve Booth and Stephen McCourt) who were first the proof-reading consultants, and many of them then became the reviewing contributors of the book and whose highly-professional proof-reading and valuable contributions are greatly appreciated while their outstanding work finally made possible to hope for the book acceptance by the English-speaking readers.

The book preparation coincided in time with the approval and initial phases of the EGS project No. 101075609 “A Geological Service for Europe” (CSA-GSEU) under Coordination and Support Action of the EU Horizon Europe Programme commenced in 2022 where four organizations of Ukraine are the partners – SRDE “Geoinform of Ukraine”, Institute of Geological Sciences of the National Academy of Ukraine, Institute of Geochemistry, Mineralogy and Ore Formation of the National Academy of Ukraine, and Ukrainian Association of Geologists (with hired staff of the Institute of Geology, Kyiv National University). The Work Package 2 of this project, addressed to the critical raw materials, is led by BRGM (Guillaume Bertrand), and the given book therefore provides the first contribution and a basis for subsequent deliverables under the project. With this opportunity, BM is grateful to Sergii Prymushko, Director General, “Geoinform of Ukraine”, Academician Stella Shekhunova, Director, Institute of Geological Sciences, Academician Oleksandr Ponomarenko, Director, Institute of Geochemistry, Mineralogy and Ore Formation, and Hanna Liventseva, Chairwoman, Ukrainian Association of Geologists, for their enthusiastic perceptions and willingness to take part in the project despite the circumstances in Ukraine. The mineral data used in the book were facilitated by these organizations, and in particular by the highly appreciated scrupulous efforts of “Geoinform of Ukraine” staff members Pavlo Bovsunivskyi, Viktoria Remezova, Oleksandr Shevchenko, Alisa Lapshyna, and will be updated during the project lifetime through their direct participation and contribution. With this regard, VM is grateful to Sergii Vyzhva, Director, Institute of Geology, Kyiv National University, for his support to the book on its early stages, and then to the Scientific Council of the Institute that recognized the draft book and recommended its further elaboration and publication abroad.

CHAPTER 1. A EUROPEAN PERSPECTIVE

1.1. Brief Overview of European Raw Materials History

The spread of the Roman conquests across Europe in the time before Christ was linked to the growing quest for mineral resources, much needed for the continued expansion of the Empire. Well after the romanisation of Europe, in the 19th century, the Industrial Revolution brought about the definitive change to an industrial economy, where the industrial labour force (mining, construction, public utilities, storage, manufacturing and transport) rose and clearly outweighed the declining agricultural labour force. In due time, this was consolidated to the point where the 19th and 20th centuries saw a clear shift from agrarian to industrialised societies, together with a growing world population and changing consumption patterns. These factors inevitably led to increasing global demand for raw materials (IRP 2019; World Bank 2021). The European mining industry has a long tradition, yet today it is also among the continent's most modern and most innovative industrial sectors.

Today, non-energy minerals underpin modern economies, being essential for manufacturing and renewable energy (e.g., IRP 2019, World Bank 2021), and domestic production is a key factor in improving the security of supply of raw materials to the EU (European Commission 2008, 2011, 2018, 2019, 2022a). Projections of future trends indicate that resource use could more than double between 2010 and 2030, mostly driven by demand in developing regions (IEA 2022b).

Access to and trade in raw materials is a central element for the European Community and, as a consequence of the devastating impacts of World War II, led to the European precursor organisation, the European Coal and Steel Community (ECSC / Montanunion) in 1951. This nucleus of what is now the European Union (EU) was based on a plan for a union of Western European heavy industries, drafted by Jean Monnet¹ and now commonly known as the Schumann Declaration (European Union 2021a). The Coal and Steel Community had already declared the preservation of peace and the promotion of prosperity in Europe as its primary objective. With further developments of cooperation agreements, additional joint institutions and common administration, this European Community became the EU when the Maastricht Treaty (Treaty on European Union 1992) came into force 1993. In 2022, the EU comprises 27 European country member states united by common

¹ Jean Monnet (1888-1979, President of the High Authority of the European Coal and Steel Community (1952-1954). Monnet had largely drafted the plan for a merger of Western European heavy industry in 1950. In 1976, Monnet became the first “Honorary Citizen of Europe” (LeMO, 2021).

principles and values and committed to a single European legal framework. Currently, seven countries, including Ukraine, are candidate countries, three more listed as potential candidates to join the EU (European Union 2021b) and others, such as Norway, are associated.

While raw materials have always been scarce in human history, obtaining access to and making use of them has always been a driver for development and prosperity (Addison and Roe 2018; Sachs and Warner 1995; Schmidt 2019). Europe is no exception, but shifted its main activities in the value chain of raw materials significantly further up-stream with time, resulting in booms and busts. The four Industrial Revolutions triggered higher demand for raw materials, and more and newly developed materials added to the portfolio. Industry 1.0 to Industry 4.0 brought Europe from an agriculture and manufacturing dominated society to a highly industrialised economy. However, what seemed to be a highly diversified economy became vulnerable when vast parts of the public became decoupled from physical production, the economy became dominated by service-oriented and highly technical driven industries, transport costs reduced, and an almost blind trust in free-market economy supported further outsourcing of the upstream parts of the value chain. Recently, there has been a growing realisation that this outsourcing does not solve, but only shifts the environmental problems abroad. There is in turn a growing realisation that Europe must instead assume its share of responsibility. Moreover, the war Russia initiated against Ukraine on February 24th 2022 has brought to the forefront, further issues of sovereignty, self-assurance and solidarity to achieve raw material resilience for Europe (European Commission 2022l).

1.2. Challenges as Drivers for EU Policies and Actions

In 2019, the European Commission published the **European Green Deal**, which aims at achieving a sustainable EU economy (European Commission 2019). This is the core of the EU's environmental, climate and also industrial policy, setting out the target of climate-neutrality in 2050, zero pollution, and increasing the CO₂ reduction targets to 55% by 2030. Goals and targets, as set out by the European Commission's communication "Fit for 55", increase the demand on critical and strategic raw material (European Commission 2021d), which will be supported by trade measures and the setting of global standards.

Achieving the Green Deal objectives requires access to sustainable raw materials, in particular critical raw materials necessary for clean technologies, digital, space and defence applications, by diversifying supply from both primary and secondary sources. The Raw Materials Supply Group (RMSG, including Member States, regional authorities, industry associations, civil society, social partners and research organisations) and the European Commission have developed and agreed upon a set of voluntary, non-mandatory EU principles for sustainable raw materials. These principles will feed into an integrated approach to sustainable raw materials extraction and processing in

Europe in terms of social-, environmental- and economic performance. The European Commission adopted several initiatives in 2020, 2021 and 2022 anchored in the European Green Deal relevant to raw materials 2020 Industrial Policy for the EU and the 2021 Industrial Strategy Update. The aim is to advance the twin transitions to climate neutrality and digital leadership, and to secure the competitiveness and strategic autonomy of Europe's industry at a time of increasing global competition (Table 1).

Table 1.1. Recent communications and their objectives to boost Europe's raw materials integrity

Title	Objective	Reference
A new Circular Economy Action Plan	Increasing the circularity and retention of raw materials in the EU economy, including a new regulatory framework for batteries	COM(2020) 98 final, European Commission 2020a
2020 Circular Economy Action Plan: international aspects	Proposes as one of the international activities the "Global Alliance on Circular Economy and Resource Efficiency".	European Commission 2020b
Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability.	Updated list of raw materials critical for the EU, including and a Critical Raw Materials Action Plan for increased resilience in EU's supply chains through secure and sustainable supply of critical raw materials	COM(2020) 474 final, European Commission 2020c
Proposal for a Regulation on batteries and waste batteries ensuring a competitive, sustainable and circular batteries value chain in Europe.	Provisions for more efficient recycling processes and material recovery, thereby mainstreaming circularity and reinforcing secondary raw materials markets.	COM (2020) 798, European Commission 2020f
EU principles for sustainable raw materials	Align the understanding of sustainable raw materials extraction (from exploration to post-closure) and processing operations in the EU amongst Member States and define the general direction towards the SDGs.	European Commission 2021f

Title	Objective	Reference
The Critical Raw Materials Action Plan	The main building block to strengthen the sustainable and responsible domestic sourcing; processing of raw materials in the European Union. It stresses the need for public acceptance and the EU principles for sustainable raw materials. In the “State of the Union” of 14 September 2022 the European Commission President Ursula von der Leyen stated the “EU would identify potential strategic projects along the supply chain from extraction to refining, from processing to recycling. And we will build up strategic reserves where supply is at risk.”	European Commission 2021a, b
2022 Strategic Foresight Report – Twinning the green and digital transitions in the new geopolitical context.	Identifies 10 areas of action, among those as action 1 Strengthening resilience and open strategic autonomy in sectors critical for the twin transitions via for instance, the work of the EU Observatory of Critical Technologies; 3) Strategically managing supply of critical materials and commodities, by adopting a long-term systemic approach to avoid a new dependency trap.	COM(2022) 289 final, European Commission 2022a

Securing reliable and undistorted access to raw materials is an increasingly important factor for the EU’s economic competitiveness. Recognising this, the European Commission adopted, in November 2008, a Raw Materials Initiative, which sets out targeted measures to secure and improve access to raw materials for the EU and which is still Europe's raw materials master strategy. The Raw Materials Initiative is based on three pillars: ensuring access to raw materials from international markets under the same conditions as other industrial competitors, setting the right framework conditions within the EU to foster a sustainable supply from European sources, and boosting overall resource efficiency and promoting recycling in order to reduce the EU’s consumption (European Commission 2008, 2020b).

Building on the EU’s Raw Materials Initiative (European Commission 2008), the resulting EU list of critical raw materials (CRM) provides a factual tool to support EU policy development (European Commission 2011, 2014, 2017, 2020c). The methodology for assessing the risk of raw materials criticality in Europe addresses the risks of supplier dependency at country and company level, market distortions, recycling rates and recyclability, as well as the substitutability of materials (Blengini et al. 2017). The European Commission takes the list into consideration when negotiating trade agreements or seeking to

eliminate trade distortions. The list helps to identify investment needs, and to guide research and innovation under the EU's Horizon 2020, Horizon Europe and national research and innovation programmes, especially on new mining technologies, substitution and recycling. It is also relevant for the circular economy, to promote sustainable and responsible sourcing, and for industrial policy. Member States and companies may also use it as an EU reference framework for developing their own specific criticality assessments (European Commission 2020c). The European Commission provides further details and up-dates on CRM related policies and actions summarised by the responsible Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (Critical raw materials 2020). Further stimulations to gain higher degrees of an autonomous CRM value chain in Europe will be set through a future European Critical Raw Materials Act announced by European Commission President von der Leyen in 2022 (von der Leyen 2022). The blog of Commissioner Thierry Breton highlights the most recent actions (Breton 2021).

The Russian invasion of Ukraine has refocused actions of the western world viewed through an energy and CRM security lens (IEA 2022a). Investments in infrastructure and pilot projects are reshaped, and reliable long-lasting as well as new trading bonds are intensified to achieve greater autonomy. The urgent need to become independent from e.g. Russian fossil fuels, raw materials, and semi-final products affect the dual transition process of the EU for which sustainable produced and supplied CRM are vital.

1.2.1. The EU, A Society in a State of Constant Development (The EU A Society in Transition Towards a Green and Digital Transition)

The European continent has experienced many changes and developments in its long lasting history. Some of them are due to geological events that led to the formation of raw material deposits while others of a societal nature build on raw materials. Although some continued population growth affects other continents much more than Europe, this development in Europe still has a strong impact on the demand for raw materials. The reasons for this include demographic change and the vision of ensuring a robust European economy with a high standard of living for all (European Commission 2020c, d, 2021d, e; Karakaya et al. 2021), while at the same time there is a shift of wealth from U.S. and Europe to wealthy individuals in Asia (World Bank 2021). Economic, environmental and technical constraints, as well as the need to react responsibly to global challenges (e.g. climate mitigation and adaptation; large crises, incl. pandemics), are factors that stimulate recent EU actions and set the course for a green economy in Europe (European Commission 2019) in the light of a fair and open markets and the European vision (European Commission 2021d).

The EU ambitions are of great concern to the UN which has expressed 17 Sustainable Development Goals (SDGs) key to mankind (United Nations, 2015-

2030). The EU is committed to the 17 SDGs, most of which are related to access to raw materials, despite the fact that none refer specifically to raw materials.

Responsible sourcing: Never before has Europe taken its responsibilities related to mining as seriously as it does today. We have recognised that with wealth and power comes responsibility and due diligence. Alongside our ethical and social standards that call for fair labour, fair trade, and sharing of the wealth, we must also ensure governance, maintenance, and burden sharing. This concerns industry, trade and consumers as well as artisanal mining, where CRM concentrates are often extracted for further processing and for products manufactured and used in Europe, e.g., also through the Conflict Minerals Regulation (European Union 2017) or the European Commission's new proposed Directive on Corporate Due Diligence for Sustainability. The proposed directive includes a mechanism to ban the import of products produced using forced labour. As stated in the "Communication on decent work around the world" (European Commission 2022b), the European Commission is preparing a new legislative initiative that will effectively ban the placing of products made with forced labour on the EU market. The initiative will apply to both domestic and imported products. The new instrument builds on international standards and intends to complement the Corporate Due Diligence Directive on sustainability as well as existing horizontal and sectoral EU initiatives.

The European Green Deal aims to reach net-zero carbon emissions by 2050 (European Commission 2019). Specific Action Plans, forecast studies, and research on materials for key enabling technologies underpin the strategies (Bobbà et al. 2020; Carrara et al. 2020; European Commission 2016, 2018; Michaux 2021; Regueiro, Alonso-Jimenez 2021; Wellmer et al. 2019). Strategic and technical alliances have been forged to support industrial ecosystems for renewable energy, e-mobility and digital innovation (European Commission 2020c) that are the dynamic powerhouse for Europe's digital and net-zero economy. For many aspects, energy is the driving factor; while “green energy” can only be realised through raw materials. Faith Briol, Executive Director of the International Energy Agency (IEA) said at the launch of the CRM report as part of the IEA's World Energy Outlook: "The data show a looming disconnect between the world's strengthened climate goals and the availability of critical minerals" (IEA 2021)

Europe's green economy vision can only be realised through technical solutions (Muench et al. 2022) built by raw materials of which many are listed as critical by the EU (Bobbà et al. 2020). The twin challenge of a green and digital transformation of the EU expresses once more the closely interlinked relationship between the usage of raw materials and the evolution of a society (European Commission 2020c, d, 2021e). Europe Imperative on Innovation calls for productivity growth, green and digital transition, post-COVID recovery and for an open strategic autonomy triggered by the Russian aggression against Ukraine. Deep tech industries – those that quickly go from lab/pilot area to

business cases – are the drivers for innovation in the areas of key societal challenges. Their market uptake requires not only the right knowledge, it also requires the strong manufacturing capacities, which Europe still has in some areas, while in others these capacities need to be revitalised. However, there is a circular dependency between mineral resources, energy supply and environmentally friendly technologies. Hence, securing access to critical raw materials is recognised as a paramount objective for the EU twin transition.

Risks, crises, conflicts and other unpredictable factors: Never before has Europe been under so much pressure after 70 years of peace and increasing prosperity. Factors such as trade patterns, producer and distributor policies, population growth, lifestyle, and geopolitical considerations have triggered actions to address the increased vulnerability of Europe's economy and to gain higher autonomy.

Increasing globalisation has provided chances for growth and economic wealth and amplified competition all along the raw materials value chain. With time, society has become increasingly detached from the extractive industries, and the NIMBY ('not in my backyard') effect for infrastructure and large-scale projects has been steadily ignored for years. This has also made prospecting and exploration for future raw material deposits more difficult, despite the needs, as exploration campaigns seldom targeted minerals that are today critical before the late 20th century. As a result, Europe is largely under-explored for numerous key mineral commodities. Moreover, at the turn of the millennium, the majority of mining companies left Europe. Europe's manufacturing industry believed in fair trade and undistorted markets and increasingly managements decided to withdraw from the up-stream sector of the value chain. In consequence, Europe has few significant mining companies listed on the stock exchange and operating primarily in Europe, and few beneficiation, purification, smelters, or refinery facilities remaining, resulting in a high dependence on non-EU suppliers. In the last 20 years, this dependence has increased. A few suppliers (giant companies) or countries increasingly dominate the supply of raw materials important for the European economy. These developments have led to the CRM concept that is detailed in the following chapter.

Europe's Critical Raw Materials are those which are economically and strategically important for the European economy, but have a high-risk associated with their supply.

It is important to note that these materials are not classified as 'critical' because they are considered scarce, rather they are classified as 'critical' because:

1. They have a **significant economic importance for key sectors in the European economy**, such as consumer electronics, environmental technologies, automotive, aerospace, defence, health and steel;
2. They have a **high-supply risk** due to the very-high import dependence and high level of concentration of their production in particular countries or monopolism;

3. There is a **lack of (viable) substitutes**, due to the very unique and reliable properties of these materials for existing, as well as future, applications, and
4. **Recycling limits** caused by technical recyclability and/or low recycle rates in place.

Recent geopolitical developments have further intensified the need for action. Among those developments, Russia's military aggression against Ukraine is the strongest amplifying rationale, having "increased the importance of the geopolitical aspects of the clean energy transition and highlighted the need to accelerate it and join forces to achieve a more resilient energy system and a true Energy Union", see REPowerEU Plan (European Commission 2022b, c).

What was assessed as a nervous reaction to changing markets and distortions in world trade at the turn of the century has become an existential competition in the face of challenging global competition and the multitude of acute crises such as pandemics, financial crises, conflicts and even wars in Europe. The room for manoeuvre is becoming ever narrower while the demand for raw materials continues to rise worldwide, including in Europe. At the same time, supply chains are increasingly interrupted or even completely disrupted.

Any market distortion or failure has its consequences, some of which have hit Europe's economy unexpectedly hard (Rabe et al. 2017). There is an increasing protectionism and nationalism in some countries that dominate certain parts of the supply chain. A very notable example is the Chinese trade restrictions on rare earth elements (REE), tungsten (W) and molybdenum (Mo) that lead to a WTO dispute settlement WT/DS431/17.

In the course of the pandemic, there were supply shortages of electronic components, such as semiconductors and chips. These bottlenecks are felt by consumers through supply shortages of goods such as washing machines and refrigerators, but also through delays in the worldwide delivery of new (e-)vehicles. Due to the disrupted processes, manufacturers increasingly resorted to short-time hire of workers, a further burden for many in addition to the pandemic-related restrictions on social life (The Global Risks Report 2022).

Hence, Europe has realised the need to become more resilient while the conditions in competition are becoming harsher. Europe's raw materials strategy strikes all the strings to sustain its raw materials renaissance, with research and Innovation being key at all stages of the value chain.

Resilient economies: Never has the pressure for sustainable production and resilient supply chains been stronger in the EU before. The pandemic has highlighted the need to build integrated, sustainable, and transparent value chains, from mine to consumers. The World Economic Forum (WEE) notes again in its Global Risk Report of 2022 that there are sudden shocks in the supply and demand of systemically important goods at the global level that put a strain on corporate, public and/or household budgets, including metals and minerals, and sees a worsening of the situation during the pandemic. Consequently, in its recent communication COM(2022) 289 final, the European

Commission identifies 10 key areas of action with the objective of maximising synergies and consistency between EU's climate and digital ambitions (European Commission 2022a). The third key action lists the “need to strategically manage the EU supplies of critical commodities” by developing domestic capacities and diversifying sources of supply. It goes hand-in-hand with the Circular Economy Action Plan that promotes measures linked to environmental and social aspects along the supply chain of products, services (European Commission 2020a), and actions that enable consumers to get access to reliable information on the sustainability of goods and services to make informed choices¹.

Domestic sourcing: Never has it been more important to understand, define and document the mineral potential of Europe. Geological challenges add to the complexity of a sustainable and affordable supply of raw materials. Previously, the focus was on economic and technical feasibility, but today safety requirements, ecological framework conditions and social aspects are equally important for the assessment of a raw material project, particularly under the UN Framework Classification for raw materials. The easily accessible rich ores in Europe, and thus the deposits that could be cheaply developed using conventional methods, have largely been exhausted. Moreover, most CRM were still being mined or were not even known to exist at the time the mines were operating in Europe and most CRM occur in nature only in very low concentrations of a few milligrams or nanograms per kilogram of material. They are therefore usually only obtained as by-products in the extraction of other ores, more abundant or very valuable elements. Many of these by-products have become of economic interest lately, some of them such as the REE only over the last 20 years. Before that, those elements were only used in niche applications and hence, dumped as waste material. It is an example of what was not of economic interest might become economic in the years to come. While reassessment of mining waste of historical mining sites might be an opportunity for some CRM, the vast majority of those sites will be too small to be economic.

Recognition that waste dumps may still hold many of the CRM has led the EU Commission to fund projects such as START (Sustainable Energy Harvesting Systems Based on Innovative Mine Waste Recycling). This project, specifically focuses on the issue of using tetrahedrite from waste dumps to replace the more often used Te-based thermoelectric device manufacture.

In some places, near-surface deposits are still productive and valid, despite the fact the ore is of low concentration. Also, the continued mining of deposits invariably results in grade drop-off as the richer areas were mined first. The Aitik mine in Sweden is one example that is economical feasible despite that the concentration of the main target Cu being ca 0.22% (Boliden 2020). Economic extraction, in this case, is due to the high performance of the technical standards used.

¹ Such as the initiative empowering the consumer for the green transition (European Commission 2022f).

Many European mines, specifically those that are, in some cases, more than a century old, and inevitably suffering from decreasing grades, have to improve their mining methods to optimise extraction. Examples of these are the century old Panasqueira W mine in northern Portugal, the younger Aljustrel Cu mine in the south of Portugal, and the exploration of lithium in the German Erzgebirge (Ore Mountains).

Due to the geological settings, other places in Europe could host deposits of higher concentrations but at greater depth, of smaller size and/or with more complex geometries that make their economic viability more challenging. In this regard, improvement of mining technologies is crucial to develop deposits that were not economically viable to date. Recently, the EU-funded IMPaCT project (2016-2020) (Cordis 2020) introduced the concept of “switch on-switch off” mining, with modular containerised processing units that could be easily transported on truck beds and rapidly deployed for short time periods to process ore from small scale complex deposits. The evolution in mineral extraction technologies also means that lower grade deposits become increasingly attractive propositions, although these are inevitably connected to global market trends. Some of these potential sites indicated by Geological Survey Organisations might attract new exploration investment. Such investment is more likely to be achieved in areas with a) existing good infrastructure compared to other regions, b) short transport distances from the mine to the end user (if processing takes place in Europe), c) a large group of solvent consumers, d) high political stability throughout the EU, e) a well-educated workforce, f) a mild climate setting, g) high labour and social ethics. Altogether, this should be an asset for investment in Europe's future deposits and eventually allow for greater independence from global influences.

1.3. Research and Innovation to Support Europe's Ambitions

History, culture, shared values, and cooperation are ingredients of the European spirit that has ensured peace in the region for more than 70 years. To underpin the political vision and support joint efforts, the EU has put together specific packages. Research and innovation and strategic partnerships with like-minded partners are important components of this as regional and structural reconstruction funds that have contributed to prosperity for many. This European spirit of peace and unified action forms the strength of the EU, a small area by world standards, and has been revitalized in the wake of the recent military aggression of Russia against Ukraine.

As part of Europe's Eastern Partnership, a high-level industrial and regulatory dialogue (HLID) between the EU and Ukraine started in 2017, underpinned by subcommittees that discussed and exchanged information on priority areas such as raw materials. This resulted in the **Strategic Partnership between the European Union and Ukraine on Critical Raw Materials and Batteries**. This Partnership is embedded as one of the 10 Actions to strengthen Europe's CRM

resilience and backed-up by the Green Deal objectives, the proposed EU Critical Raw Materials Act, and the new Industrial Strategy and the EU Recovery plan (European Commission 2019, 2020c, e, 2021e). The latter, also called “NextGenerationEU”, is a temporary instrument to boost recovery and build a robust “post-COVID-19 Europe”, increasing the EU's Multiannual Financial Framework (MFF) to about 1.211 trillion EURO (10^{18}) for the period 2021 to 2027. This will invest in EU regions, farmers, businesses, researchers, students, citizens in general and EU's neighbouring countries (European Commission 2021c). Research and Innovation is supported and funded through Horizon Europe, the European Research programme 2021-2027. Challenges are tackled also by research and innovation co-funded by the European Union. It addresses for example (the links below are accessed 07.01.2023):

- a) technical developments and new facilities allowing safer exploration in extreme environments (e.g. UNEXUP (<https://unexup.eu>); ROBOMINERS (<https://robominers.eu>), iTARG3T (<https://eitrawmaterials.eu/project/itarg3t>);
- b) improving recovery and recyclability of CRM (e.g. ReSiELP (<https://www.resielp.eu>),
- c) finding alternative target areas and new solutions (e.g. FRAME (<https://www.frame.lneg.pt>); EURare (<http://www.eurare.org>); EIS (<https://eis-he.eu>); Flintstone2020 (<https://flintstone2020.eu>); and
- d) also general understanding of demands, material flows and circular economy (e.g. SCRREEN2 (<https://screen.eu>); FutuRaM (<https://www.brgm.fr/en/current-project/futuram-eu-project-plan-map-supply-critical-metals-obtained-recycling>); MinFuture (<https://minfuture.eu>).

1.3.1. Bonds and Relationships

The bonds between the EU and Ukraine are strong also in its trade relationships underlined by the pre-war trade statistics: EU is the biggest trading partner for Ukraine, accounting for 39.5% in 2021 of the Ukraine export. Also, Ukraine is the 15th largest partner for the EU. According to the European Commission, Ukraine's main exports to the EU are iron and steel (20.8% of total exports) followed by ores, slag and ash (12.5%). The EU's main exports to Ukraine (European Commission 2022g; Unguru et al. 2022) are machinery (14.8% of all exports), transport equipment and vehicles (10.2%), mineral fuels (9.4%), electrical machinery (9.3%), and pharmaceutical products (5.9%). But also for Europe's ceramic industry mostly in Italy, Spain and Poland, Ukraine was an important supplier for a variety of high quality clays, including kaolin and white-firing clays (Dondi et al. 2021). Ukraine supplied 60% of the demand for white-firing clays and supplemented the demand that can be met with 40% from domestic sources within the EU. EU extraction companies, mainly extracting industrial minerals (e.g. clays), aggregates, and

dimension stones hold licences in the Ukraine and were also active in processing prior to the war.

Despite the multiple global crises that caused significant disruptions in the supply chains with impacts on the price market (e.g. IEA 2022a; BGR 2022b), measures were taken, e.g., to integrate the Ukrainian electricity grid into that of the EU ahead of schedule (European Commission 2022h; Breton 2021). Mapping the investment opportunities in the Ukraine that will strengthen the country after the war was proposed by Germany's Federal Minister of Economy and Climate to the Ministers of trade and economy at the September 2022 G7-meeting. The chambers of commerce shall join information to support foreign investors when engaging in Ukraine (European Commission 2022i).

EU President Ursula von der Leyen announced the European Critical Raw Materials Act in her 2022 State of the Union Address (von der Leyen 2022) also in view of the geopolitics of supply chains (European Commission 2022i) expecting similar success as seen through the European Battery Alliance (European Commission 2022j) and the European Chips Act (European Commission 2022k). This Act aims to respond to the EU's need to become more agile and self-reliant by building a certain level of strategic capacity along an entire value chain from mining and processing to recycling (Vice-President Šefčovič 12.09.22, European Commission 2022l, 2022m). These ambitions are underpinned by financial assistance, with 19 billion euros already provided. The European Commission sees Ukraine as a rising hub and home to many young companies that can help to provide the innovations needed, strengthened by partnerships and by the new European Sovereignty Fund (EU-President Ursula von der Leyen 2022).

Table 1.2. Some key actions of the EU solidarity with Ukraine (excerpt)

Title of the EU Action	Type of action	URL access*
EU macro-financial assistance (MFA) packages related to Ukraine - Exceptional MFA - Emergency MFA - MFA in the context of the COVID-19 pandemic	Economy and Finance Support	https://economy-finance.ec.europa.eu/international-economic-relations/candidate-and-neighbouring-countries/neighbouring-countries-eu/neighbourhood-countries/ukraine_en
EU restrictive measures in view of Russia's actions against Ukraine	EU Legislation	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:25_2 Timeline: https://www.consilium.europa.eu/en/policies/sanctions/restrictive-measures-against-russia-over-ukraine/history-restrictive-measures-against-russia-over-ukraine/
European Peace Facility (2021-2027)	EU Legislation	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:4516647

Title of the EU Action	Type of action	URL access*
Macro-financial assistance to Ukraine	EU Legislation	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:4581923
Restrictive measures against Belarus	EU Legislation	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:4481974
1. Factsheets on EU solidarity with Ukraine	Factsheet	https://ec.europa.eu/info/publications/factsheets-eu-solidarity-ukraine_en
2. EU sanctions against Russia following the invasion of Ukraine	Factsheet	https://ec.europa.eu/commission/presscorner/detail/en/fs_22_1402
3. Factsheet: The European Union and Ukraine	Factsheet	https://ec.europa.eu/commission/presscorner/detail/en/fs_22_3862
4. Ukraine: Relief and reconstruction	Factsheet	https://ec.europa.eu/commission/presscorner/detail/en/fs_22_3169
10-point-plan for Ukraine	Humanitarian aid	https://home-affairs.ec.europa.eu/10-point-plan-stronger-european-coordination-welcoming-people-fleeing-war-ukraine_en
COUNCIL DECISION (CFSP) 2022/1272 List of persons and entities under EU restrictive measures over the territorial integrity of Ukraine	Restrictive measures	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022D1272&qid=1658933268679&from=EN
EU assistance to Ukraine	Strategic priorities	https://ec.europa.eu/info/strategy/priorities-2019-2024/stronger-europe-world/eu-solidarity-ukraine/eu-assistance-ukraine/
EU trade relations with Ukraine. - Negotiations and agreements - Trade policies - latest developments	Trade	https://policy.trade.ec.europa.eu/eu-trade-relationships-country-and-region/countries-and-regions/ukraine_en
EU Clusters Support Ukraine	matchmaking	https://clustercollaboration.eu/content/eu-clusters-supporting-ukraine
EEN Supply Chain Resilience platform	matchmaking	https://supply-chain-resilience-platform.b2match.io/
REGULATION(EU) 2022/870	Trade regulations	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R0870&from=EN
Alliance4Ukraine	Member State action	https://alliance4ukraine.org/start-english/

Title of the EU Action	Type of action	URL access*
Strategic Partnership between the European Union and Ukraine on CRM and Batteries - Approximation of regulatory mining frameworks and application of the sustainable mining principles. - Integration of (C)RM and battery value chains by facilitating joint venture projects and business opportunities. - Closer collaboration in Research and Innovation along CRM and batteries value chains	Strategic Partnership	https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3633; Roadmap: https://ec.europa.eu/docsroom/documents/46299/attachments/1/translations/en/renditions/native

*(the links are accessed 07.01.2023)

In the area of science, education and specifically regarding raw materials there are further supporting instruments to which Ukrainian research fellows and scientists can apply, see also (Wittenberg et al. 2022).

1.3.2. Europe's Raw Materials (Potential, Data, Efforts, Up-Coming Projects)

Strategic and critical raw materials (CRM) are crucial for key technologies required to meet societal goals and political targets as well as strategic needs (Fiott 2013; Pavel, Tzimas 2016). Currently, the most important technologies are used for green energy supply (Bobba et al. 2020; Huisman et al. 2020). The crucial importance of strategic and critical raw materials, amplified by the need for strategic autonomy, have triggered actions to reassess Europe's domestic raw materials potential. Actions have been set up to connect efforts between government, responsible authorities, industry and academia, among those the Raw Materials Supply Group (RMSG), set up by the European Commission, the Joint Research Centre of the European Union, the EIT Raw Materials that also manages ERMA, and the European Geological Survey Organisations and their umbrella association, EuroGeoSurveys (more details by Wittenberg et al. 2022, Jørgensen et al. 2023).

National and Regional Geological Survey Organisations (GSO) play an important role to identify and to assess the geological potential in their area. Pulling capacities and competencies together in EuroGeoSurveys lift this valuable knowledge, making it available to a broader community. Voluntarily,

each member organisation can nominate experts to join the various geoscientific thematic expert groups within EuroGeoSurveys. Recent joint efforts of the European GSOs, within the framework of the EU-cofunded project GeoERA, reassessed domestic strategic and critical raw materials through the scientific project FRAME. Several thematic maps were generated (Sadeghi et al. 2020; Bertrand et al. 2021; Oliveira 2021; Wittenberg et al. 2022). Statistical data, inventories, and other relevant data on Europe's raw materials were compiled through the GeoERA project, MINTELL4EU. Through EuroGeoSurveys' European Geological Data Infrastructure (EGDI, europe-geology.eu), availability of these compilations is ensured after the close of such projects (e.g. Jørgensen et al. 2023). EGDI is not only a tool to serve geoscientific data through a web portal, it is also a digital infrastructure that collect, organise, store and diffuse the information. For mineral resources the MIN4EU database compiles mineral resources data that is collected ("harvested") via web services from national databases developed and maintained by European geological surveys (Jørgensen et al. 2023).

Reliable information and comparable data are key to such an instrument. While listed companies are obliged to use internationally recognized codes and standards for reporting on resources and reserves, this does not apply to small and medium-sized companies or activities in Europe. Furthermore, due to historical and fragmented developments in Europe, a wide range of methods and procedures for reporting resource estimation were developed. However, a European resource management concept as well as global consideration require comparability.

The United Nations Economic Commission for Europe (UNECE) Working Party on Coal initiated the first version of the United Nations Framework Classification (UNFC) for Solid Fuels and Mineral Commodities in 1992 using the three dimensional principles developed at the Federal Institute for Geoscience and Resources (BGR), by Dietmar Kelter for reserve and resource estimations (Kelter 1991; Kelter, Wellmer 1994; Müller, Kelter 1997). Started as a UN Task Force on Coal the UNECE Expert Group on Resource Management (EGRM) has been working, facilitating the application of different versions of the UNFC at global level and providing support for all stakeholders since, including early examples of practical application (UNECE 1999). In 2004, the Economic and Social Council of the United Nations (ECOSOC) endorsed for the first time the proposal of the United Nations Framework Classification for Fossil Energy and Mineral Resources (UNFC) submitted by the UNECE. The UNFC is an evolution of the fossil fuel system that has been in place since 1977 and with the latest update in 2019 (UNECE 2019). This update covers all types of energy and non-energy resources including geothermal energy, renewables, anthropogenic resources and injection projects (UNECE 2019).

Ukraine and Romania are among the first countries that endorsed the UNFC scheme. Ukraine has mandated the use of the UNFC as the foundation of its

national resource management based on UNFC-1997 approved by the regulation (Resolution 1997). On 19 September 2018, Ukraine amended its national classification (Resolution 1997) to be aligned with the latest version of UNFC. This amendment makes Ukraine's classification up-to-date with international standards and comparable globally (UNECE 2008). However, the UNFC is not yet applied in full to the materials inventory of the country.

The European Geological Survey Organisations (GSO) have delivered many national and joint international projects, mainly EU-funded, in relation with UNFC, including mapping to national resource classification systems, harmonization-opportunities and developments of regional / EU-level guidance documents, and numerous case studies for all types of resources.

Within the framework of the successful GeoERA program, the MINTELL4EU project has conducted 19 case studies and delivered a universally acceptable and internationally applicable scheme for the sustainable management of all energy and mineral resources. MINTELL4EU has also benefited from the extensive testing undertaken by GeoERA partners. In the MINTELL4U project, geologist experts from Austria, Belgium, Croatia, Denmark, Finland, Hungary, Norway, Slovenia and Sweden have provided case studies including Au, Cu, Co, Mn, Mo, REE, phosphate, carbonates, graphite, aggregates, natural stones, peat, gypsum and perlite (Aasly et al. 2021). The case studies benefit from the basic principles developed through ORAMA, a previous EU-funded project. Within the ORAMA project, the British Geological Survey (BGS), in cooperation with the project partners, developed an important flowchart for decision making on UNFC E, F and G categories, with many different examples (Bide et al. 2022).

In 1998, by the enforcement of Romanian Mining Law and the publication of the technical instructions, a new mineral resource classification system was developed that presents the terms and codifications used in UNFC (www.unece.org).

In 2016, Hungarian data harmonization project results were published in the Bulletin of Hungarian Geological Society (Horváth et al. 2016, Horváth, Sári 2016, Kovács 2016, Nádor 2016), including an overview on international reporting codes and UNFC, and a comparison between these tools and national classification system for most types of mineral resources. In Hungary, since 2020, the legislation addresses the internationally recognized reporting standards, the UNFC and the harmonization between the related terms and the national resource classification categories.

Recent studies from different Geological Survey Organizations provided new results on mapping, data harmonization and application of the UNFC in several European countries (Hungary: Horváth et al. 2016; Horváth, Sári 2016; Kovács 2016; Nádor 2016; Czech Republic: Starý et al. 2021; Poland: Malon, Tymiński 2017; Finland: Lax et al. 2017; Hokka et al. 2020; Portugal: Ponce de Leão 2019; Spain: Bide et al. 2017).

Meanwhile, in quite some European countries first, sometimes even relevant, experience with UNFC exist in the academic field as well as with important data providers from the industry, with responsible geological survey organizations, with supervisor authorities up to ministries (Aasly et al. 2021; Aggestam et al. 2021; Bide et al. 2022; Eilu et al. 2022; Haschke et al. 2020; Hokka et al. 2020; Horváth et al. 2020; Kelter et al. 1999; Kelter, Wellmer 1994; Nieć et al. 2022; Suppes, Heuss-Aßbichler 2021a, b). Today, the UNFC is promoted by the European Commission towards Member States. However, UNFC does not replace reserve and resource estimations but supports communication (further explanations are given in Chapter 3). The very recent UNFC Guidance Europe (UNECE 2022) provides further assistance on how to apply the framework classification.

The EU-funded coordination and support action “A Geological Service for Europe (GSEU)” will build on those experiences and competences. GSEU will collect and deliver a raw material data service over five years starting September 2022. Within GSEU, the European GSO, including partners from Ukraine, will work on sharing and harmonizing their expertise to produce added-value knowledge on onshore and offshore critical mineral resources, implementing the International Centre of Excellence (ICE) and on national applications of UNFC. In this regard, a major objective of GSEU will be to harmonise mineral resources information, onshore and offshore, for primary and secondary resources, at the scale of Europe, including Ukraine.

The ICE takes advantage of GSO competencies developed through active memberships in the UNECE bureau and gained in EU-funded projects. The experience of Ukrainian geological and mining organizations and experts is essential to develop a European level resource management system based on UNFC. Hence, Ukrainian professional organizations and experts will also have crucial roles in order to develop a real European-level resource management system within the framework of GSEU.

1.3.3. Ukraine is a Partner in the European Community of Geological Survey Organisations (Effects, Assistance, Expectations)

The evolution of EuroGeoSurveys (EGS) over the last decades includes the evolution of its relationship with the GSOs of Ukraine. Since Ukraine became a member of EGS, fifteen years ago, these two evolutions have been converging.

The principal objective of the GSO of Ukraine reflected the general trend of the country towards European integration leading to its application to become EU member state. In fact, when Ukraine joined EGS in 2007, its membership has been considered as practical evidence for the implementation of EU membership. Further development of relationships between EGS and the GSO of Ukraine was mostly a sequence of steps towards European integration of the knowledge, research and expertise of the geological community of Ukraine.

Despite its status of associate member, Ukraine was always very active in EGS. Only two years after accession to EGS, in 2009, Ukraine – together with Poland – proposed to hold the 31st EGS General Meeting and field trip in 2011, the year of the EGS 40th anniversary, jointly in Poland and Ukraine. Thanks to the tight cooperation between the Polish Geological Institute (PGI) and the State Service of Geology and Subsoil of Ukraine (SSGSU), this event was organized in the two countries, for the first time in EGS history, and one of these two countries – Ukraine – was not an EU member state. This event was also quite original on logistic aspects as the plenary meetings were held in Warsaw, Poland, whereas the field trip was organized in Western Ukraine.

In the same year, 2011, two other GSOs – the Geological Survey of Finland (GTK) and SSGSU – implemented the first joint research project ICI-GIMI. This project resulted from interaction between these GSOs, after the EGS General Meeting in 2007, when their representatives met for the first time and outlined possible areas of cooperation. This project aimed at creating the modern geoinformation system for the geological sector of Ukraine.

In the following year, 2012, another joint research project, NUMIRE (Norway-Ukraine Mineral Resources), was established between the Geological Survey of Norway (NGU) and SSGSU. This was also inspired by the meeting of their representatives at the EGS General Meeting in 2007. NUMIRE was devoted to a comparative study of raw materials of the two countries and implementation of the European standards for their inventory. Being implemented in 2012-2014, this project was followed in 2015-2017 by another project, EIMIDA (European Integration of Mineral Data). Both projects were essentially oriented towards support in data selection, preparation and pre-processing for the coeval EU FP7 project Minerals4EU, where both NGU and SSGSU (represented by Geoinform of Ukraine) were the partners.

In 2015-2018 Geoinform was a third party partner, through EGS, for Horizon 2020 projects ProSUM, FORAM, ESTMAP, EUOGA, MinLand, and INTERMIN, that were focusing their research activities on European mineral raw materials. In this way, Ukraine provided relevant information to the European consortiums and networks.

In fact, the most extensive cooperation between EGS and the GSO of Ukraine was through Minerals4EU. The data harvesting and dissemination systems of this project allowed Ukraine to present the mineral data of the country to the pan-European network and through an online system which is now fully integrated in the European Geological Data Infrastructure (EGDI). At that time, Geoinform was able to present the harmonized and INSPIRE-compliant data for more than 6000 mineral deposits and occurrences in Ukraine.

In 2015, EGS was involved in an assessment of SSGSU through three missions, resulting in a report on how SSGSU should be improved to comply with EU standards of geological surveys. This report is probably more relevant now than ever and can be used as the basic guideline for the organisational

evolutions of the Ukrainian GSOs from the Soviet-inherited systems towards modern European models and structures.

In 2016, the EGS Mineral Resources Expert Group (MREG) biannual meeting was organized in Ukraine and Geoinform hosted the two days event, involving plenary meetings in Kyiv and a field trip to the Mezhyrichenske titanium placer deposit in the Zhytomyr region. In 2018, in conjunction with the 100-year anniversary of SSGSU, Kyiv hosted the Directors' Workshop on EGS Strategy, following a related workshop held in 2017 at the Geological Survey of Germany (BGR).

Geoscientific cooperation between EGS and GSO of Ukraine continued through 2016-2020 in the frame of the EU GeoERA project, an ERA-NET family project, which was devoted to the extended integration of mineral raw materials data across Europe through the development of the research area for the Geological Service for Europe. GeoERA aimed at the preparation of the research and technological environment that can be used for the long-term and deeper integration of geological surveys of Europe by means of application of the Article 185 of the Treaty of the Functioning of the European Union. It was aimed at developing the research area through thematic projects encompassing raw materials, geoenergy, groundwater, and a cross-cutting information platform. GeoERA rather became an EU dedicated program that included 15 individual thematic projects on geoenergy (6 projects), groundwater (4 projects), and raw materials (4 projects), as well as the cross-cutting information platform (single project). Assuming that all themes and projects should be not only interesting for Ukraine, but that they should also be properly developed in Ukraine to facilitate or even make possible the European integration of Ukrainian geosciences, Geoinform took part in all 15 projects of the GeoERA program.

The next phase of the EGS pan-European integrating activities started with the idea of the creation of a Geological Service for Europe. After two years of preparation efforts, EGS converged on the concept of a European Partnership on a Geological Service for Europe. The application was submitted in 2019, and in 2020 the European Commission proposed the option of a CSA – Cooperation and Support Action – which was approved by the EGS Directors at the 2020 General Meeting. This option assumes a single large project, including gathering, inventory and networking of the mineral raw materials data across Europe, with a special emphasis on critical raw materials, in line with the general strategy of the EU towards the “green, efficient and circular economy”. The project entitled CSA-GSEU – Geological Service for Europe – was approved by the Commission for implementation in 2022-2027 with a total budget in excess of EUR 24 million and a start in September 2022. In view of the importance and complexity of these issues and resulting project, Ukraine participates in this project with four partners – Geoinform of Ukraine (GIU), the Institute of Geological Sciences of the National Academy of Sciences of Ukraine (IGS), the Institute of Geochemistry, Mineralogy and Ore Formation of

the National Academy of Sciences of Ukraine (IGMOF), and the Ukrainian Association of Geologists (UAG), which will allow the broader involvement of Ukrainian geoscientists in various fields of geology and minerals.

Thus, cooperation between EGS and the GSO of Ukraine has a long (more than 15 years) and committed history. Today, EGS has a key role in supporting Ukraine during this time of Russian invasion. Besides the generic and overarching issues, EGS has taken responsibility for managing the EU travels of Ukrainian geoscientists in the frame of the CSA-GSEU project. EGS also decided to waive membership fees for Ukraine for 2022-2023, and possibly longer, as the Russian war of aggression continues. On the other hand, the GSO of Ukraine are intending to enhance EU integration, especially in view of the new status of Ukraine as candidate country for EU membership. Ukrainian geoscientists will be doing their best to accelerate standardisation, unification and harmonisation of raw materials data, aiming to ensure not only accession of Ukraine to the European Union, but also accession of the Ukrainian mineral resource base to the raw materials potential of the European Union, to make Ukrainian minerals an integral part of the European Union minerals sector. This book is in line with this strategy, a key reason why EGS was involved in the book preparation and publication. This is a next example of the fruitful cooperation between EGS and GSO of Ukraine.

1.4. Outlook – Recommendations for Future Cooperation, Impact on the Ukraine Reconstruction

Following this short introductory chapter on the European raw materials context and the role of the Ukrainian GSOs, especially through their integration within EGS, the following chapters address various aspects of mineral resources in Ukraine. The second chapter describes the notion of criticality for mineral resources, as it is defined in different parts of the world (EU, U.S.A., Canada, Australia), to replace critical and strategic mineral resources of Ukraine in a broader perspective. The third chapter deals with investment attractiveness of the Ukrainian raw material sector, with focuses on the national regulation for subsurface use, the main factors and criteria of investment attractiveness in Ukraine, with a ranking of most promising national mineral resources in this regard. The fourth chapter describes the Ukrainian resource in metallic minerals, from the geological description of deposits to their economic potential. The fifth chapter is relatively similar in its approach, but dedicated to non-metallic mineral resources. Based on this information, the last chapter proposes an expert assessment of investment attractiveness of mineral resources in Ukraine, with a ranking of most promising projects per commodity and deposit. Such decision-making tool has never been proposed before, and we sincerely hope it will both strengthen the integration of Ukraine in the European raw materials sector and facilitate the reconstruction of the country after the war it is presently enduring.

This systematic and step-by-step approach to look at the various facets of the Ukrainian mineral potential and industry will give the reader a logical and factual view of Ukraine's mineral intelligence capabilities, where it is most likely to fill gaps in critical raw materials value chains and what work still needs to be done to better understand the metallic, non-metallic and industrial mineral deposits of this now war torn country.

*"President Ursula **von der Leyen** said: "The EU continues standing by Ukraine and its brave people. Today, we propose a €1 billion tranche of the new macro-financial assistance package for Ukraine. This first part of the assistance announced in May will allow us to give an immediate answer to the urgent needs of Ukraine. The EU will keep on providing relief to Ukraine and in the longer-term support its reconstruction as a democratic and prosperous country".*

*Valdis **Dombrovskis**, Executive Vice-President for An Economy that Works for People said: "This latest financial assistance and first part of the €9 billion financial support package again demonstrates the EU's firm commitment to support Ukraine and its people in the face of Russia's continued illegal aggression. These loans will allow Ukraine to meet more of its immediate massive financing needs, with the EU showing further solidarity by covering the interest costs."*

*Josep **Borrell**, High Representative/Vice-President for a Stronger Europe in the World said: "Putin's unjustified war against Ukraine is putting massive economic pressure on the Ukrainian people. The European Union is acting with great speed to support Ukraine's financial stability and assist it in rebuilding its future within the European family. With this emergency package, we are sending a strong message: The European Union continues to stand with Ukraine and its people."*

*Johannes **Hahn**, Commissioner for Budget and Administration, said: "With this proposal, we continue to make best use of the EU budget to support our neighbour and ally Ukraine under the current extremely challenging circumstances. We count on rapid agreement by the European Parliament and Council which would enable us to make the first payment to Ukraine swiftly faced with urgent funding needs."*

*Paolo **Gentiloni**, Commissioner for Economy, said: "The European Commission is committed to supporting Ukraine in shoring up its finances as the country continues to defend itself against the Russian aggressor. This proposal marks another concrete step in making good on that commitment, making available €1 billion that can be rapidly disbursed to Ukraine. We will in parallel continue to work swiftly on a proposal for the second part of the exceptional macro-financial assistance, as announced in May."*

Source: Delegation of the European Union to Ukraine 2022

CHAPTER 2. OVERVIEW OF THE ECONOMIC GEOLOGY, MINERAL RESOURCE BASE AND STRATEGIC MINERAL RESOURCES OF UKRAINE

2.1. Economic Geology of Ukraine

Ukraine is one of the largest countries in Europe, with an area of 604,000 square kilometres and has a rich mineral endowment. The country has been estimated to hold approximately 5% of the world's known mineral resources, with about 20,000 mineral deposits and occurrences of 117 mineral types. Of these, 8,761 deposits and 1,288 recorded sites for 95 mineral types of commercial value are included in the Ukrainian Recorded Mineral Reserves, the official state inventory. This diversity is a function of the wide variety of geological settings within the country.

Ukraine occupies the southwestern part of the Eastern European Platform, with outcropping or buried Archean and early Proterozoic crystalline basement of the Ukrainian Shield occupying most of the country. To the west and south, the crystalline basement is buried beneath Palaeozoic and later platform cover sediments of the Volyno-Podilska Plate (VPP) and the Dnisterska or Fore-Black-Sea Depression. In the north and east, the Late Devonian to Early Permian rift graben of the Dniprovsko-Donetska Depression (DDD), up to 20-km deep, separates the Ukrainian Shield from the Voronezkiy Massif. The Donbas Foldbelt (DF) is the southeastern part of the Dniprovsko-Donetska Depression, inverted and uplifted by Late Cretaceous and Early Tertiary Alpine orogenic events in the Tethyan Belt. The west and south fringes of Ukraine are formed by the Carpathian and Crimean orogenic belts, which are part of the Alpine Fold Belt. (Fig. 2.1).

The exposed Ukrainian Shield is composed of 6 megablocks, each with different geological history and different complexes of rocks. From southeast to northwest, these are the Azovian, Middle Dniprean, Kirovograd, Ros-Tykych, Dnister-Boug, and Volyn Blocks. (Fig. 2.2). They are composed of high-grade metamorphic granite-gneiss complexes overlain by Archean Middle Dniprean granite-greenstone sequences (Chortomlytska, Surska, Verkhivtsivska, Bilozerska).

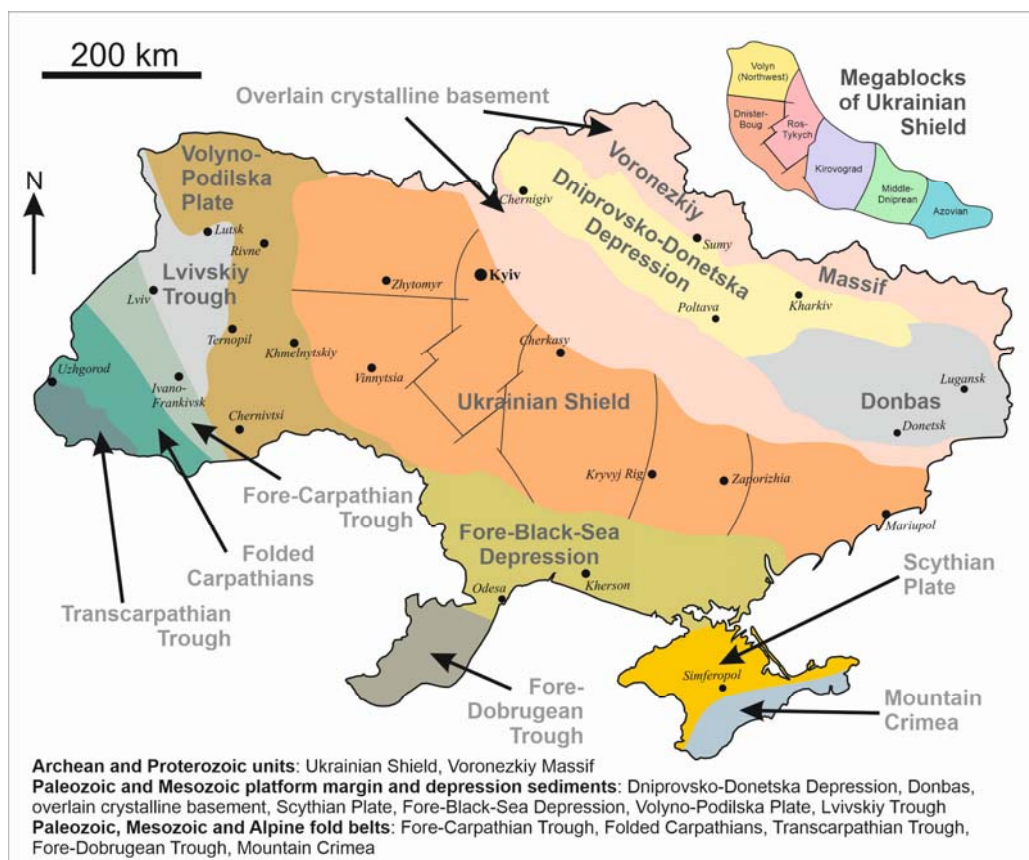


Fig. 2.1. Geological structure of Ukraine (modified after Gurskiy 2008)

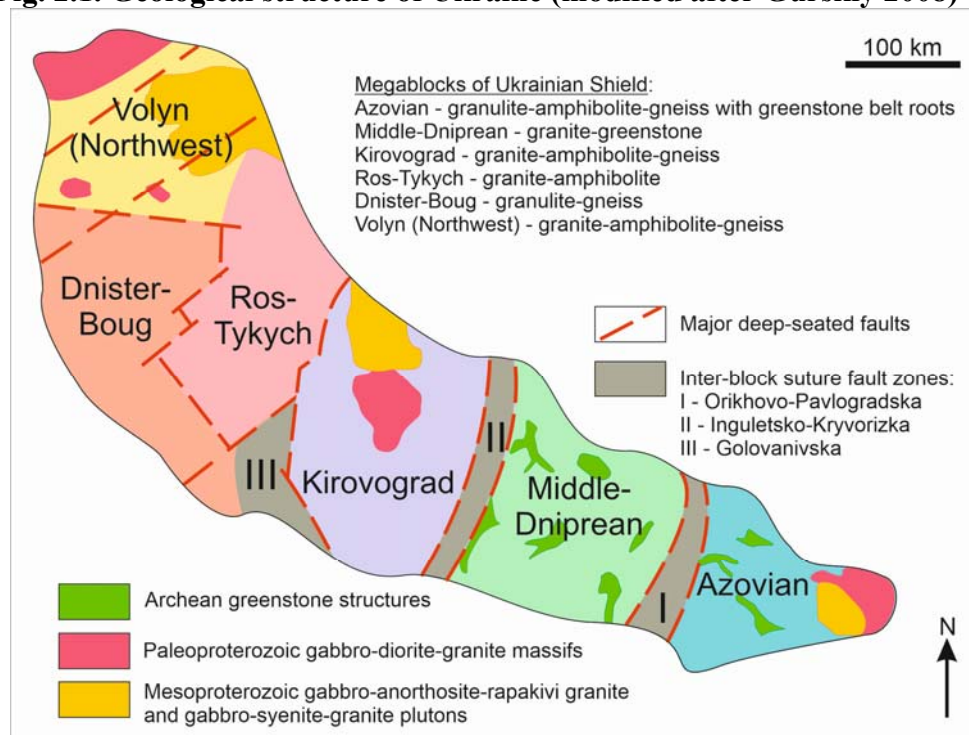


Fig. 2.2. Geological units of the Ukrainian Shield (modified after Gurskiy 2008)

The Proterozoic is represented by intrusive massifs of various compositions, and by the suture zones between some of the blocks of the central part of Ukrainian Shield (Kirovogradska, Inguletska, Kryvorizko-Kremenchutska, Pobuzka, etc.). The sutures are typically represented by submeridional tectono-metasomatic zones composed of metamorphosed Paleoproterozoic terrigenous and volcanic sequences cut by gabbro-anorthosite and granite plutons. Proterozoic ultramafic formations are described from the Zakhidno-Saksaganskiy, Kryvorizkiy, Tyshlytskiy and Volodarskiy fold belts, and in the structures of Azovian megablock.

Exploration and exploitation of minerals associated with Precambrian metamorphic, igneous and metasomatic formations are of great importance in Ukrainian economic geology, especially iron ore, uranium, titanium, gold, rare metals, rare earths, and non-metallic minerals.

In the west, the younger Ryphean to Cenozoic sedimentary and volcanic rocks of the Volyno-Podilska Plate overlaying the Ukrainian Shield host deposits of copper (Volynskiy ore area), hydrocarbons (Lokachynske deposit) and coal (Lvivsko-Volynskiy Coal Basin).

In the south, the Ukrainian Shield structures plunge beneath Fore-Black-Sea Trough, which holds deposits of manganese (Nikopolskiy Basin) and hydrocarbons (Steppe Crimea, Kerch Peninsula, Black and Azov Seas offshore).

The Ukrainian Shield is separated from the Voronezkiy Massif, located to the northeast mainly within the territory of Russia, by the giant (about 100,000km²), northwest-trending extensional trough of the Dniprovsko-Donetska Depression. The thick sedimentary sequence of the DDD, up to 20km, has Devonian volcanic and chemogenic rocks at the base, succeeded by Carboniferous to Meso-Cenozoic sediments. The DDD is the major oil and gas region of Ukraine.

In the south-east parts of the DDD, Alpine orogenic inversion has produced folded structures in the Donetsk region (Donbas). Here, terrigenous-sedimentary and organogenic complexes of Carboniferous System, which contain numerous coal layers, play an important economic role.

The southwestern part of Ukraine includes part of the Carpathian Fold System, which is the eastern extension of the Alpine Mountain Belt. From southwest to northeast, the Carpathian system in Ukraine consists of the Fore-Carpathian regional depression with gas- and oil-bearing sedimentary rocks; the folded Carpathian Mountains system of south-west verging flysch nappes; and the Trans-Carpathian inner depression, which includes volcanic-sedimentary formations hosting rock salt, zeolites, barytes, alunites, mercury and polymetallic mineralization.

The southern part of the Crimean Peninsula is composed of Alpine thrust and folded autochthonous, allochthonous and neo-autochthonous formations from Triassic to Paleocene-Miocene in age. It is part of the major Alpine-

Mediterranean-Himalayan Fold Belt, separated from the structures of Anatolian Taurus by the deep-water basin of Black Sea.

Finally, another very specific type of geological structure is known in Ukraine. Seven confirmed impact structures have been identified, ranging in size from 2.7km to 24km, which may be associated with such minerals as diamonds (Western structure), oil shale (Boltyska structure), or hydrocarbons (Obolonska structure).

2.2. Overview of the Mineral Resource Base of Ukraine

The geological resources of Ukraine fall into four categories:

- Metallic minerals, principally iron, manganese, uranium and titanium, covered in detail in Chapter 4 of this volume.
- Non-metallic minerals, including industrial minerals and building materials, covered in detail in Chapter 5 of this volume
- Oil and gas, which are largely outside the scope of this volume.
- Coal and coalbed methane, which are also largely outside the scope of this volume

2.2.1. Metallic Minerals

Historically, it has principally been deposits of iron, manganese, uranium, titanium, and zirconium ores which have been developed. Deposits of gold, beryllium, lithium, vanadium, scandium, lead, zinc, niobium, tantalum, strontium, hafnium, cadmium, silver, and REE have also been discovered and evaluated, which are known or believed to be economically viable and may be developed in future. Also, possibilities for discovery of copper, chromium, tungsten, tin, molybdenum, antimony, aluminium, nickel, PGMs, rare metals, and other deposits have been predicted (Gurskiy et al. 2000, 2006a; Zaritskiy et al. 1994; Kulish et al. 1971; Mishchenko 2007).

The most important mining regions of Ukraine, where deposits have been developed and enterprises have operated to extract metal raw materials are:

- Iron – Kryvorizkiy , Kremenchutskiy, Bilozerskiy, Kerchenskiy ore fields;
- Manganese – Nikopolskiy and Tokmatskiy ore fields;
- Titanium/zirconium – Samotkanskiy ore field;
- Titanium/apatite – Irshanskiy ore field;
- Uranium – Kirovogradskiy and Central Ukrainian ore fields;
- Mercury – Mykytivskiy ore field;
- Nickel – Pobuzkiy ore fields;
- Gold/polymetallic – Muzhyivskiy area.

Fig. 2.3 shows the locations of these ore fields and other major opportunities.

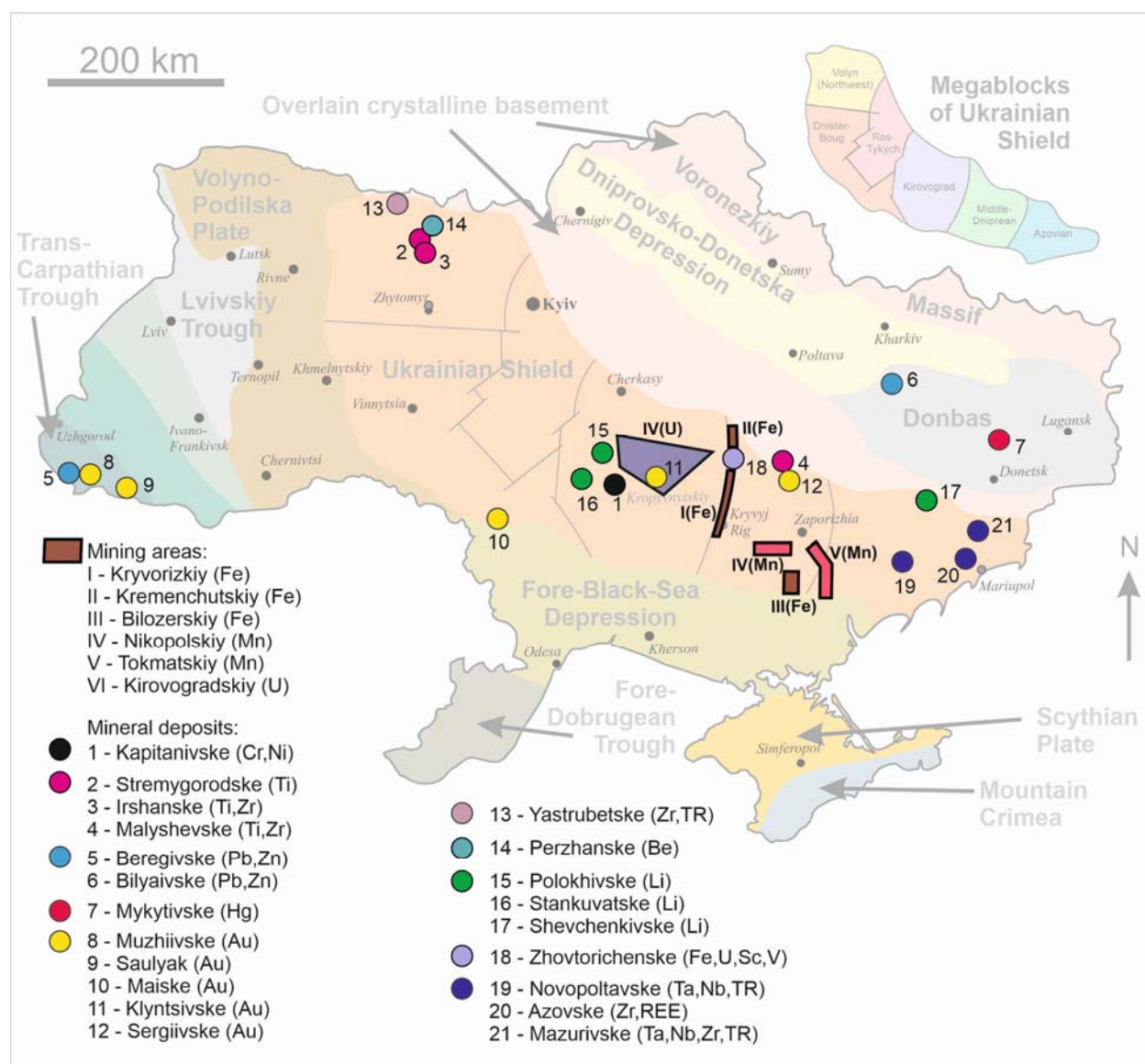


Fig. 2.3. The most important mining areas and ore deposits of Ukraine

Thus, Ukraine's traditional mining and minerals industry, focussed on iron, manganese, uranium, zirconium and titanium, represents clear prospects for further development. Potential also exists to develop known rare metal and rare earth resources, as at the Perzhanske, Mazurivske, Novopoltavske, and Azovske deposits, while there are many opportunities for exploration and evaluation of non-ferrous and precious metals deposits.

Issues which will need to be addressed in the coming years are prospecting for deposits of new geological and industrial types; solving technological problems of complex extraction of useful components; and technical and economic assessment of resources taking into account the requirements of a market economy.

2.2.2. Non-Metallic Minerals

Ukraine has a substantial base of non-metallic minerals, numbering about 4,000 deposits, of which almost 2,000 have been or are being developed. Ukraine has significant reserves and production of the following minerals (Gurskiy et al. 2006b; Mykhailov et al. 2008a):

- Potassium salt in the Fore-Carpathians (Kalush-Golynske and Stebnytske deposits);
- Rock salt in DDD, Donbas, and the Carpathians (Novokarfagenske, Romenske, Efremivske, Artemivske, Solotvynske deposits);
- Sulphur in the Fore-Carpathians (Nemyrivske, Podorozhnynske, Yazivske deposits);
- Chalk in Donbas (Raygorodske, Slavyanske, Bilogorske, Bantyshevske deposits);
- Graphite in the Ukrainian Shield (Zavallivske, Balakhivske, Petrivske, Troitske deposits);
- Kaolin in the Ukrainian Shield, Trans-Carpathians, and DDD (Glukhovetske, Bilyaivske, Polozke deposits);
- Bentonite in the Ukrainian Shield, DDD, Fore-Carpathians, VPP, and Crimea (Cherkaske, Gorbkivske, Pyzhyvske, Kudrynske, Kurtsivske deposits);
- Fire-resistant clays in the DDD, Donbas, and Ukrainian Shield (Chasiv-Yarske, Novorayske deposits);
- Dolomite in Donbas and the Carpathians (Yamske, Novotroitske, Olenivske, Stilske deposits);
- Limestones in the Ukrainian Shield, Donbass, and Crimea (Olenivske, Karakubsk, Psilerakhske deposits);
- Quartzite in the Ukrainian Shield (Ovrutske deposit)
- Foundry sands in the Donbas, DDZ, Ukrainian Shield, and VPP (Gusarivske, Chasiv-Yarske, Orekhivske, Polozke, Malyshevske deposits);
- Cement raw materials (limestone, marl, chalk, clay, tuff, gypsum and anhydrite);
- Facing and building stones (granite, gabbro, labradorite, tuff, travertine, marble, sandstone);
- Quartz sand (Papirnyanske, Novoselivske, Velykoglibovetske deposits);

There are many other deposits and occurrences of non-metallic minerals, including apatite, phosphorites, stone raw materials, ozocerite, feldspar, zeolite, fluorite, barite, bromine and iodine, vermiculite, perlite, talc, pyrophyllite, clay, gypsum and anhydrite, refractory expanded clay, raw materials for mineral paints and mineral wool, and others.

2.2.3. Hydrocarbons

A key economic issue for Ukraine, which is also of social and political importance, is the need of securing fuel and energy supplies. Before the Russian war, Ukraine produced 18-20 billion m³/year of natural gas, which is only 45-50% national consumption, and 3-4 Mt of oil (10-15% of consumption).

Ukraine holds the second largest known gas reserves in Europe, however. As of late 2019, known Ukrainian reserves amounted to 1.09 trillion m³ of natural gas, second only to Norway's 1.53 trillion m³. This would be sufficient for 40 years national consumption, but the country's annual gas reserve usage rate is only around 2 percent. Known oil reserves are smaller, around 100 million tonnes, less than 10 years' consumption. Further exploration would be likely to find additional fields, especially gas, with potential gas resources, including unconventional deposits, estimated at 5 to 6 trillion m³ (Amelin et al. 2020, Gurskiy 2008; Mykhailov et al. 2009)

Hydrocarbon production and resources in Ukraine are associated with three oil and gas regions: the DDD in the northeast, the Fore-Carpathian Trough in the west, and the largely offshore basins of northern Crimea and the Black and Azov Seas. (Fig. 2.4).

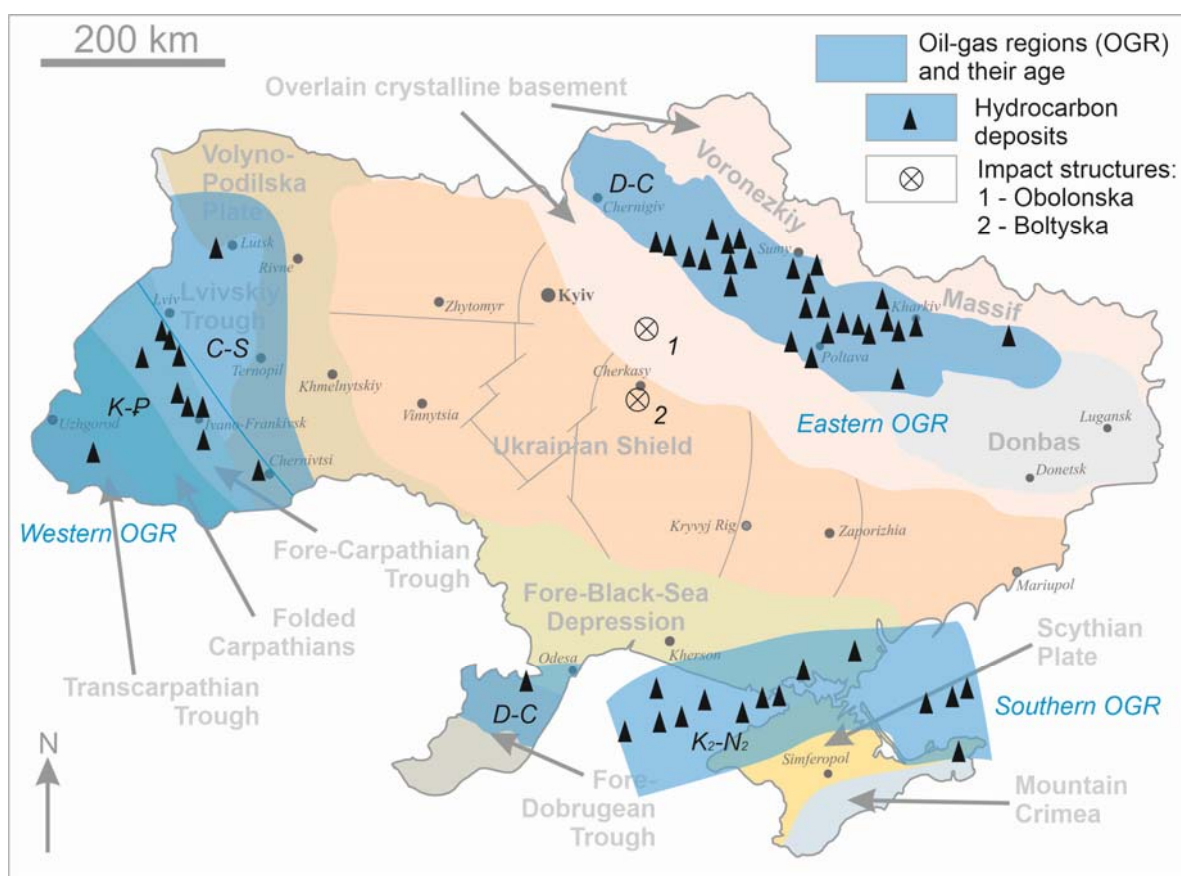


Fig. 2.4. The main oil and gas regions of Ukraine

During the 1960s and 1970s, Ukraine was a major supplier of natural gas within the former Soviet Union, following the discovery of the world-class Shebelynske gas field. At that time, gas production was about 70 billion m³/year, and oil production around 14.5 Mt.

However, one should not expect the possible discovery of large hydrocarbon deposits of the traditional type, given the relatively high level of geological study in these areas. Stable production can be maintained nevertheless through the discovery of new small oil and gas fields and exploitation of old ones. For example, the Shebelynske field is still operating, although the volume of production cannot be compared to that 40 years ago.

At the beginning of the second decade of the XXI century, consistently high demand for natural oil and gas, depletion of traditional fields and rising energy prices have aroused considerable interest in exploration of unconventional hydrocarbon deposits, including shale gas and tight-rock oil, coal-bed methane, gas-hydrates, and deposits in impact structures. All of these have potential in Ukraine (Mykhailov et al. 2014, 2021b).

2.2.4. Coal

Ukraine has large reserves of coal. Hard coal is developed in the Donetskiiy and Lvivsko-Volynskiiy basins, and brown coal in the Dniprovskiiy Basin and in the DDD, Dnistverskiiy, Carpathian and Fore-Carpathian coal-bearing areas (Mykhailov et al. 2009).

The Donetskiiy Coal Basin (Donbas) is located in the southeast of Ukraine. The basin is up to 20km thick and stretches WNW for 650 km with a width of 150 km, for a total area of 60 thousand km². It accounts for around 96% of Ukraine's hard coal resources. Donbas is one of the largest industrial regions of Ukraine. Structurally the basin is a partly inverted rift graben developed between Azovian and Voronezhskiiy crystalline massifs, with thick sequences of Palaeozoic and Mesozoic sediments overlying the Precambrian metamorphic basement. The coals are of Carboniferous age, mainly Namurian and Westfalian (suites C¹² to C³³) and include up to 300 coal seams and beds. The following structural zones can be recognised:

- Central Zone, where coal-bearing sediments are turned into large linear folds (Main Anticline);
- Northern and Southern Zones of small folds and thrusts;
- Bakhmutska and Kalmius-Toretska depressions;
- Monocline zones on the margins of the Ukrainian Shield and Voronezhskiiy massif.

The Lvivsko-Volynskiiy Basin is located in the western part of Ukraine and extends into the Lublin Basin of Poland in the west. It accounts for around 4% of Ukraine's hard coal resources. The basin is situated at the contact of the Precambrian East-European Platform and the Paleozoic central-European Platform, and is an asymmetric depression developed in a zone of pericratonic downwarp of the platform margin. Coal-bearing Carboniferous sequences 50-60 km wide occur

over a strike of 120 km, resting on Devonian and other Lower Paleozoic rocks and overlain by Permian, Mesozoic, and Cenozoic strata (Porzycki 1987). The coal-bearing formations include 88 coal seams and beds of Lower and Middle Carboniferous Visean, Serpukhovian, and Bashkirian stages. Of these, 30 beds reach minimum economic thickness. The total thickness of coal seams averages 12 m, the thickness of individual economic layers – 0.6-1.0 m, sometimes up to 1.5 m.

The Dniprovskiy brown coal basin occupies the area on the right bank of the Dnipro River, and is 650 km long from southeast to northwest, 70-175 km wide and covers an area of 100,000 km². About 200 coal deposits and occurrences are encountered, 27 of which have estimated reserves recorded by the SIMR. The rocks of platform cover are represented by Meso-Cenozoic and Quaternary sediments.

Methane deposits related to coal measures are confined to the Donetsk and Lvivsko-Volynskiy basins. It is shown that coal deposits of Donbas are complex gas-coal ones and are of interest for the extraction of associated methane from coal seams, low-permeable sandstones and shales of inter-coal beds. According to various estimates, the forecast methane gas resources of Donbas coal deposits at depths of 500 to 1800 m may be from 4 to 22 trillion m³, of which 3.3 trillion m³ are suitable for extraction, and recoverable resources may be of the order of 1 trillion m³ (Mykhailov et al. 2021b).

2.2.5. Summary of Ukraine's Mineral Resources

Table 2.1 below lists all the known mineral resources of Ukraine, with number of deposits, estimated reserves and resources (but see Introduction, section ‘What Conventions Are Used In This Book?’ for comment on the use of these terms in this volume), and production in 2020.

The SIMR lists six types of combustible minerals, 25 metallic minerals and 62 non-metallic minerals. In addition, eleven other minerals, shown in italic script in the Table, have been reported in Ukraine but are not included in the Inventory, making a total of 104 mineral types in total,

Table 2.1. Mineral reserves of Ukraine as of 01.01.2021 (Gursky 2008; Mykhailov et al. 2007, 2008a, 2018; Mineral Resources of Ukraine 2020, 2021; World Mining Data 2020, 2021)

Mineral	Deposits	Reserves	Resource	Mining, 2020
Combustible minerals				
Gas, billion m ³	391+76*	730.2	4,439.2	20.3
Oil, Mt	89+127*	107,3	705.1	1.7
Condensate, Mt	269*	40,1	323.9	0.7

Mineral	Deposits	Reserves	Resource	Mining, 2020
Methane from coal deposits, billion m ³	189*	345.2	144.6	12 thousand m ³
Coal, Mt	1039	72,618,3	43,375	17,6
Peat, kt	682	1,221,201	2,500,000	387
Metallic minerals				
Ferrous metals				
Iron ore, Mt	60	30,660.5	133,000	163.3
Manganese ore, Mt	5	2,418	410	3.8
Chromium ores, kt Chromium, Cr ₂ O ₃ , kt	2*	3,488.6 679.9	50,000	-
Titanium ores, kt **	28			564 **
Vanadium, V ₂ O ₅ , kt	13*	397.5		0.19
Light metals				
Aluminium ores, kt	1	18,885	290,000	-
Non-ferrous metals				
Copper ores, kt Copper, kt	1	34,883.1 101,3	28,242	-
Lead and zinc ores, kt Lead, kt Zinc, kt	1+3*	42,018.2 672,3 1,558.5	5,500 3,500	- -
Nickel ores, kt Nickel, kt	12	81,786.0 393.1	353	-
Cobalt ores, kt Cobalt, kt	12*	60,805.0 20,156.3	26	-
<i>Molybdenum ores, molybdenum, kt</i>	-	-	43.7	-
Mercury ores, kt Mercury, kt	11	16,828 23.2	20	-
Precious metals				
Gold ore, t **	7		3,200 **	
Silver ores, kt Silver, t	2*	19,296.3 782.11	7,000	0,65 ,0,02
<i>PGM</i>				
Radioactive metals				
Uranium ores, kt **	22	131 **	366 **	500-800 **
Rare and rare earth metals				
Beryllium ores, kt Beryllium, Be ₂ O ₃ , kt	1	3,150.9 15.8	66 (?)	-
Lithium ores, lithium, kt **	3		2,000 **	-
Coal, Mt Germanium, t	220*	16,494.6 81,662.5		14.5 77,1

Mineral	Deposits	Reserves	Resource	Mining, 2020
Tantalum and niobium ores **	2+3*			
Zirconium ores, Zr_2O_3 , kt **	2+14*		840 **	18 **
Hafnium ores, sand, thousand m^3 hafnium oxide, t	2*	211,687.9 13,834.2		4,188.4 266.8
Scandium ores **	13*			
Strontium ores, kt Strontium, strontium oxide, t	1*	955,485 952		-
Cadmium ore	1*			
Rare earth ores, kt TR_2O_3 , kt	1+2*	2,602,178 2,231.8	3,410	-
Non-metallic minerals				
Stone-colored raw materials				
Amber, t	17	2,116.7	1,700	6,4
Marble onyx, t	1	213	1,500	-
Rhodonite, t	1	419	3,200	-
Mining and chemical raw materials				
Sulfur, ore, kt S, kt	10+2*	696,666.2 170,987.2		-
Phosphorite, ore, Mt P_2O_5 , Mt	5+4*	474,7 18,9	2,500 690	-
Barite ore, kt Barite, kt	1	4,580.0 1,819.0	3,700	-
Potassium salts, kt K_2O , kt	13	3,857,401 411,030	6,758,300	-
Rock salt, kt Brine, thousand m^3	14+1*	26,856,581.8 2,444.0		1,260.8
Magnesium salts, kt MgO, kt	1+3*	1,967,177 159,541.3		-
Dawsonite, Mt	-	-	40.8	-
Bischofite, ore, kt Bischofite, kt	2	50,090.1 1,869	302,400	7.2
Boron raw materials, B_2O_5 , kt	-	-	62.4	-
Fluorite, ore, CaF_2 , kt	2+1*	303,2,8 4,076.1	4,000	-
Bromine, kt	1*	242		-
Carbonate raw materials, Mt:	44 + 16	930,683.0		1,883.3
Apatite, ore, Mt P_2O_5 , Mt	2+5*	4,102.1 102.0	112	-
Glauconite, kt	2+1*	6,367.5	5,000,000	-
Saponite, kt	1	34,653	20,000	-
Sapropel, kt	309	102,122	15,000	1.0
Raw materials for the production of mineral paints, kt	8+2*	16,027		-

Mineral	Deposits	Reserves	Resource	Mining, 2020
Fluorine, ore, kt F, kt	2*	1,016,694 3,463,1		-
Mining (industrial) raw materials				
Graphite ore, kt Graphite, kt	6	343,297.5 19,674,1	1,021,000	93.1 5.2
Abrasive raw materials, ore, kt mineral, kt	3+1*	56,990.4 3948		8.5 -
Pyrophyllite shales, kt	2	1,805	279.1	-
Bentonite clays, kt	8+1*	57,138.7	3,200,000	110.21
Kaolin, kt	41+1*	1,095,830.5	4,500,000	1,569.62
Ozocerite, kt	3	319.8		-
Piezooptical raw materials **	1			-
Feldspar raw materials, kt	9+5*	263,059.8		643.7
Petrurgy raw materials, kt	2	225,067	155 million m ³	-
Talc schists, thousand m ³	1*	77.58		-
Zeolites, kt	2+1*	280,198.4		326.7
Glass raw materials, kt	42	337,094.7		1,421.7
Staurolite, kt	5	12,31.3	25,000	30.5
Opal-cristobalite raw materials, Mt	8			0.68
Raw materials for metallurgy				
Flux raw materials, kt	20+3*	2,755,953.4		4,272.1
Refractory clays, kt	30+1*	1,079,672.2		4,547.9
Dolomite for metallurgy, kt	5+2*	843,754.0		1,364.0
Refractory raw materials: • quartzite and quartz for refractories, kt • magnesite, kt	9 1	150,519. 105,134	2,500,000 250,000	569.0 -
Foundry sand, kt	14+7*	826,128.1	12,500,000	1,292.9
Fluorspar, ore, kt CaF ₂ , kt	2+1*	30,372.8 4,076.1	18,000	-
High-alumina raw materials, disthene and sillimanite, kt	5*	2,899.0	794	33.8
Staurolite, kt	5*	1,231.3		30.5
Construction raw materials				
Gypsum and anhydrite, kt	40+7*	998,368.0		1,515.3
Refractory clay, kt	17+4*	152,487.0		210.2
Building stone, thousand m ³	760+187*	8,820,554.0		38,960.5
Facing stone, thousand m ³	255	392,761.7		587.6
Sawmill stone, thousand m ³	197+3*	1,358,462.9		10.3
Chalk, kt	64+4 *	519,443.8		205.0
Construction sand, thousand m ³	623+38*	3,548,756.7		13,240.8
Sand for locomotive sandboxes, thousand m ³	5+3*	11,204.5		-
Raw materials for land use planning and reclamation, kt	4+11*	24,096.4		273.8

Mineral	Deposits	Reserves	Resource	Mining, 2020
Raw materials for mineral wool and fibers, kt	2+2*	425,832.0		167.0
Carbonate raw materials for lime production, kt	85+23*	77 3,040.1		5,744.24
Expanded clay raw materials, thousand m ³	47+ 6*	260,553.2		33.68
Silica raw materials (cristobalite-opal), kt	8	52,116.2		0.68
Perlite raw materials, thousand m ³	3	50,392.6	100,000	3.74
Brick and tile raw materials, million m ³	1892+50*	2,632.8		1.9
Cement raw materials, kt	56+6*	4,270,812.8		13994.4
Menilite shales, kt	2	4,528.91		16.4
Sand-gravel mixture, thousand m ³	66+7*	328,102.7		761.5

Note. See note on Reserves and Resources in Introduction, section ‘What Conventions Are Used In This Book?’. Inventory reserves (A+B+C₁+C₂). *complex deposits; **mineral reserves that are confidential, assessed here using foreign sources or expert assessment based on comparisons with known deposits in the world. *Types of minerals that are not recorded by the SIMR are listed in italic script.*

2.3. The Concept of Strategic Minerals in Ukraine

The issue of minerals strategically important for the economy of Ukraine has been considered in the works of many researchers (O.K. Babynin, O.K. Bakarzhiev, V.Z. Bartoshynskiy, Y.M. Belevtsev, O.B. Bobrov, V.P. Bordyugov, L.V. Bochay, A.S. Voinovskiy, L.S. Galetskiy, P.F. Gozhyk, K.Yu. Esipchuk, V.M. Zagnitko, O.I. Zaritskiy, V.B. Koval, Ye.O. Kulish, M.I. Lebid, O.I. Matkovskiy, V.S. Metalidi, S.V. Nechaev, B.S. Panov, V.L. Prikhodko, V.V. Pokalyuk, M.P. Semenenko, A.O. Sivoronov, V.I. Skarzhinskiy, Y.I. Tretyakov, E.F. Shnyukov, V.O. Shumlyanskiy, M.P. Shcherbak, G.M. Yatsenko and many others). The most complete and conceptual work forms the monograph of D.S. Gurskiy who was a long-term Head of the State Geological Survey of Ukraine and an unsurpassed expert on MRB of Ukraine (Gurskiy 2008). In this book, the author identified minerals strategically important for the country's economy as **“raw materials, whose use provides the growth of gross domestic product, foreign exchange earnings, feeding the state budget, economic and defence security of the country.”**

Practically the same approach in defining strategically important minerals for the country's economy was used in official documents, in particular, in the draft law of Ukraine "On Amendments to the National Program for the Development of Mineral Resources of Ukraine until 2030" (Law 2011a, 2021b), which stated strategic minerals to be " ... *most important minerals of national importance that ensure economic security of the State, stability of national economy in the long run, as well as favourable and safe living conditions for citizens* ".

Criteria for the allocation of strategic minerals include their role in the formation

of gross national product, foreign exchange earnings from exports, ensuring the stability of the national currency, market conditions, and the needs of the defence and other industries, especially high-tech industries. They were divided into four categories, which correspond to those proposed by D.S. Gurskiy, further subdivided into metallic, non-metallic and energy minerals.

The Draft Code of Ukraine on Subsurface defines strategic minerals as “a specified list of minerals that are important for economic and strategic importance for the long-term development of Ukraine's economy and are part of Ukraine's national security” (Draft Code 2021).

At the legislative level, for the first time, the list of strategic minerals was approved in the Resolution (1997), subsequently revoked by the CMU (Resolution 2016). This list was recently significantly revised by the President of Ukraine (Decree 2021).

Table 2.2 below summarises these efforts to recognise the minerals of strategic importance to Ukraine, divided into four groups by opportunity and three categories by character, broadly following the categories established by Gurskiy, namely:

- 1) traditional minerals, which have been intensively developed in Ukraine for a long time, have significant explored reserves, and contribute to the State budget;
- 2) highly promising minerals, with deposits or occurrences with significant reserves or resources known in Ukraine, but are either not yet developed or are only being developed in small quantities;
- 3) promising minerals, with deposits or occurrences are known in Ukraine, but resources not reliably defined, and prospects for their development not definitively determined;
- 4) minerals with unclear prospects, with occurrences and small deposits known in Ukraine, but on scales not known to be conducive to development.

Table 2.2. Strategic minerals of Ukraine

Metallic minerals	Non-metallic minerals	Combustible minerals
Traditional		
Iron Manganese Titanium Uranium	Kaolin Foundry sands Building and facing stones Refractory clay	Gas Oil Condensate Coal
Highly promising		
Rare earths Zirconium and hafnium Lithium Scandium Germanium	Graphite Potassium salts Abrasive raw material (garnet) Quartz raw material Piezo-optical raw materials (piezo-quartz)	Methane of coal deposits

Metallic minerals	Non-metallic minerals	Combustible minerals
Promising		
Nickel Cobalt Chromium Aluminium Copper Tantalum Niobium Beryllium Gold	Phosphorites Phosphate ore (apatite) Fluorite (fluorite) <i>Glauconite</i> <i>Flux limestones and dolomites</i> <i>Limestones for sugar industry</i> <i>Bentonite clays</i> <i>Feldspar raw materials</i> <i>Semi-precious stones</i>	<i>Combustible shales</i> <i>Peat</i> <i>Shale gas</i> <i>Shale oil</i> <i>Gas of tight-rocks</i>
With unclear prospects		
Vanadium Lead Zinc Tungsten Molybdenum PGM Strontium Magnesium Arsenic Rubidium Cesium	Barytes Boron <i>Dawsonite</i> <i>Bromine and iodine</i> <i>Mineral sorbents (zeolite, vermiculite, palygorskite)</i> <i>High-alumina minerals (sillimanite, disthene, andalusite)</i> Diamond <i>Raw materials for mineral paint production</i> <i>Fluorine</i> <i>Sulphur</i>	<i>Gas hydrates</i>

The table denotes minerals not included in the SIMR in *italic script* and strategic minerals which are also critical raw materials (see Chapter 7) in **bold face** type.

2.4. Mineral Resource Base of Ukraine: Status and Challenges

Information on the geological structure and mineral deposits of Ukraine is provided in numerous scientific papers, monographs and articles (e.g. Bobrov et al. 2002, 2006; Gurskiy et al. 2006a, b; Gurskiy 2008; Mineral Resources of Ukraine 2017, 2018, 2020).

However, these works do not contain critical analysis of the MRB of Ukraine at the present stage; they do not make geological and economic assessment of raw materials in modern market conditions; and they do not consider problems of the mining industry of Ukraine related to certain shortcomings of its mineral resource base.

The fact is that Ukraine does not have resources of certain metals such as chromium, aluminium, copper, zinc, lead, tin, tungsten, molybdenum, gold, silver, and platinum, which must therefore be imported.

The development of those minerals which are present is hampered by imperfections of the legal framework; misguided investment policies in the late 1990s and early 2000s; outdated technologies for mining and extraction of minerals; and lack of geological and economic assessment of many types of minerals, taking into account market economy mechanisms. This necessitates development of a pragmatic approach to the evaluation of our MRB, taking into account the realities of today, in particular, Ukraine's involvement into the world market of mineral resources. A key task of the geological and exploration sector of Ukraine in the coming years will be to re-evaluate the MRB taking into account latest technologies and modern economic criteria, and in particular to ensure that the resources are developed profitably, taking into account the environmental, social and governance factors.

2.5. The Place and Role of Ukraine in World Mining

In recent years, global production from mines has risen steeply. In 1985, world production of all energy and metallic mineral products amounted to 9.6 billion tons; this rose to 11.3 billion tons in 2000, and 17.9 billion tons in 2019 (World Mining Data 2020, 2021). The largest volume of production is accounted for by combustible minerals (15.4 billion tons), in second position is iron and ferroalloys (1.6 billion tons), non-metallic minerals come third (0.8 billion tons), followed by other metals (0.1 billion tons). The list of the principal mineral producing countries in the world is given in Table 2.3.

**Table 2.3. List of the world's largest mineral producing countries, 2019
(World Mining Data 2021)**

By tonnage			By value (US\$)		
№	Country	Production, Mt	№	Country	Cost, \$ million
1	China	4,324	1	China	583,714
2	USA	2,335	2	USA	555,067
3	Russia	1,685	3	Russia	421,049
4	Australia	1,351	4	Saudi Arabia	276,745
5	India	1,060	5	Australia	174,640
6	Indonesia	732	6	Canada	170,820
7	Saudi Arabia	672	7	India	129,033
8	Canada	499	8	South Africa	124,963
9	Brazil	479	9	Brazil	114,529
10	Iran	413	10	Iraq	111,371
11	South Africa	320	11	Iran	106,882

By tonnage			By value (US\$)		
№	Country	Production, Mt	№	Country	Cost, \$ million
12	Kazakhstan	260	12	Indonesia	97,180
13	Iraq	244	13	UAE	95,533
14	UAE	239	14	Kazakhstan	92,631
15	Qatar	209	15	Mexico	69,236
16	Norway	175	16	Kuwait	64,117
17	Germany	170	17	Nigeria	52,678
18	Mexico	161	18	Norway	50,600
19	Kuwait	145	19	Qatar	50,318
20	Nigeria	142	20	Chile	42,445
21	Algeria	140	21	Algeria	38,699
22	Turkey	139	22	Peru	34,061
23	Colombia	135	23	Angola	32,042
24	Poland	127	24	Colombia	30,874
25	Malaysia	94	25	Oman	29,289
26	Ukraine	92	26	United Kingdom	28,852
27	Oman	90	27	Libya	27,027
28	Egypt	89	28	Turkey	25,486
29	United Kingdom	89	29	Venezuela	25,127
30	Vietnam	78	30	Malaysia	23,511

As can be seen from the table, in terms of volumes produced, the leading positions are occupied by just four countries, which together account for half of all global production: China (23%), USA (12%), Russia (9%) and Australia (7%).

China is a world leader in the production of 32 types of minerals. It ranks first in in percentage of world production of tungsten (80%), vanadium (54), aluminium (57), antimony (64), fluorspar (51), graphite (60), magnesite (66), gallium (94), germanium (89), tellurium (74), arsenic (46), bismuth (64), molybdenum (36), cadmium (35), lead (44), titanium (26), talc (25), kaolin (18), bentonite (26) and others. This dominance has led to considerable disquiet in consuming countries in recent years.

The United States produces 68% of the world's beryllium, 22% of natural gas and 15% of oil. Russia ranks first in the world in the production of diamonds (28%), palladium (41), asbestos (61), while Australia is the leader in the production of lithium (61), iron (37), bauxite (29). and zircon (40).

In terms of value, the list reflects the high value of hydrocarbons, with Saudi Arabia moving up from 7th into 4th place.

Global annual production of different minerals in 2015 and 2019 is shown in Table 2.4 below, together with the changes in production over the period, to demonstrate changing relative importance of different resources in recent years.

Table 2.4. Dynamics of mining in the world in 2015-2019 (World Mining Data 2021)

Raw materials	2015	2019	% change
Iron, Mt	1,454.5	1,539.4	+5.8
Manganese, Mt	16.0	21.4	+33.8
Chromium, Mt	13.2	15.9	+20.1
Titanium, kt	6,570.2	7,734.5	+17.7
Vanadium, kt	82.8	90.3	+9.1
Aluminium, Mt	57.9	62.9	+8.6
Bauxite, Mt	294.4	363.4	+23.5
Copper, Mt	19.4	20.7	+6.8
Lead, kt	4,984.8	4,967.0	-0.3
Zinc, kt	13,346.0	13,174.8	-1.28
Nickel, kt	2,062.1	2,709.0	+31.4
Cobalt, kt	147.0	125.2	-14.9
Molybdenum, kt	287.2	276.5	-3.7
Tungsten, kt	88.0	86.2	-2.1
Tin, kt	325.0	294.5	-9.4
Mercury, t	3 395	2 452	-27.8
Antimony, kt	149.9	125.5	-16.3
Arsenic, kt	37.3	56.6	+52.1
Bismuth, t	11,689	9,058	-22.5
Cadmium, t	23,326	23,697	+1.6
Gold, t	3,120.3	3,292.3	+5.5
Silver, kt	28,296.3	27,817.1	-1.7
Platinum, t	190.5	184.2	-3.3
Palladium, t	206.2	221.8	+7.6
Rhodium, t	23.0	23.7	+3.1
Uranium, t	72,047	64,418	-10.6
Beryllium, t	6,938	5,952	-14.2
Lithium, kt	62.6	189.6	+202.9
Germanium, t	139	95	-31.7
Gallium, t	285	374	+31.2
Tantalum, t	1,750	1,584	-9.5
Niobium, kt	87.5	135.5	+54.8
Indium, t	847	896	+5.8
Rare earths, kt	124.7	202.3	+62.3
Rhenium, t	45	44	-2.2
Tellurium, t	449	604	+34.5
Selenium, t	3,275	3,475	+6.1
Jewelry diamond, million carats	70.0	77.9	+11.2
Technical diamond, million carats	57.8	58.3	+0.9
Phosphates, Mt	82.9	71.1	-14.2
Barite, kt	9,734.9	8,814.6	-9.5
Asbestos, kt	1,309.7	1,175.3	-10.3

Raw materials	2015	2019	% change
Graphite, kt	1,126.7	1,133.1	+0.6
Boron, kt	4,754.4	4,164.8	-12.4
Fluorite (fluorspar), kt	6,301.7	7,664.0	+21.6
Bentonite, Mt	18.2	21.9	+20.4
Diatomite, kt	1,999.2	2,169.3	+8.5
Feldspar, Mt	28.1	29.8	+6.0
Gypsum, Mt	145.2	157.3	+8.3
Kaolin, Mt	38.4	38.7	+0.7
Magnesite, Mt	28.3	27.3	-3.6
Perlite, kt	2,550.0	2,701.3	+5.9
Potassium salts, K ₂ O, Mt	40.2	41.7	+3.7
Rock salt, Mt	294.4	288.9	-1.9
Sulfur, Mt	76.6	82.5	+7.7
Talc, kt	7,501.7	7,949.1	+6.0
Vermiculite, kt	429.3	415.9	-3.1
Zircon, kt	1,524.3	1,665.7	+9.3

Note. The raw materials with the production growth of $\geq 20\%$ are highlighted in **bold face**, and those with a production decline of $\leq 15\%$ in *italic script*, which should be taken into account when assessing the investment potential of raw materials.

It is interesting that in the period from 2015 to 2019, world lithium production grew particularly rapidly (by 202.9%), while production of rare earths (62.3%), niobium (54.8%), arsenic (52.1%), tellurium (34.5%), manganese (33.8%), nickel (31.4%), gallium (31.2%), bauxite (23.5%), chromium (20.1%), fluorspar (21.6%), and bentonite (20.4%) also increased significantly. At the same time, production of cobalt, molybdenum, tantalum, tungsten, antimony, beryllium, bismuth, germanium, mercury, tin, zinc, platinum, asbestos, barite, boron, magnesite, salt, and vermiculite decreased (Table 2.13).

Ukraine ranks 26th in terms of tonnage of production (92 Mt) but 40th in terms of value (\$ 11,654 million). Given its significant MRB, which, according to some researchers and various estimates, ranks 10-15th in the world, this indicates insufficient development of the mining opportunities of the country.

For certain minerals, Ukraine ranks highly in terms of world production, however. Commodities for which Ukraine is a dominant producer include: gallium (2nd in world, 6 tons, 2% of world production); germanium (5th, 1 ton, 1%); kaolin (6th, 2 Mt, 5%); titanium (6th, 519 kt, 7%); iron (7th, 39 Mt, 2.6%); manganese (9th, 683 kt, 3.4%); uranium (9th, 1.4 kt, 2%); and graphite (9th, 15 kt, 1.4%) (Krupenina 2000).

Table 2.5 lists Ukrainian production of the most important minerals, according to international data. Over the 5 years from 2015 to 2019, production of manganese, titanium, feldspar, and sulphur significantly increased in Ukraine, but output of

gallium, bentonite, zircon, coal, and uranium decreased. The sharp decline in production in 2019 compared to 2018 of such minerals as gallium, bentonite, graphite, zircon, coal, and uranium is of particular concern. These data should be taken into account when assessing the investment attractiveness of MRB in Ukraine.

Table 2.5. Dynamics of extraction of the most important minerals of Ukraine (World Mining Data 2021)

Raw materials	2015	2016	2017	2018	2019	15/19	18/19
Iron, t	42,817,200	40,240,600	38,767,600	38,751,300	40,451,100	-5.53	4.39
Manganese, t	546,600	491,500	650,500	682,700	686,100	25.52	0.50
Titanium, t	375,480	339,800	430,300	518,950	564,050	50.22	8.69
Gallium, t	9	9	9	6	5	-44.44	-16.67
Germanium, t	1	1	1	1	1	0	0
Bentonite, t	220,000	200,000	113,200	178,200	124,700	-43.32	-30.02
Feldspar, t	44,460	33,627	35,000	50,000	60,000	34.95	20.00
Graphite, t	10,000	12,000	13,000	15,000	10,000	0	-33.33
Gypsum, t	1,254,900	1,303,000	1,528,900	1,386,400	1,409,400	12.31	1.66
Kaolin, t	1,814,786	2,335,004	2,379,636	2,091,525	1,843,561	1.59	-11.86
Salt, t	2,136,500	1,783,530	1,815,684	2,191,619	2,092,795	-2.05	-4.51
Sulfur, t	171,700	171,300	175,900	222,200	220,400	28.36	-0.81
Zircon, t	30,000	29,280	27,239	21,614	18,000	-40.00	-16.72
Coal, t	23,852,700	25,121,500	18,932,900	21,648,100	19,747,200	-17.21	-8.78
Coking coal, t	6,063,900	6,508,800	5,233,900	4,606,300	5,783,200	-4.63	25.55
Gas, billion m ³	19,900	20,052	20,510	20,806	20,520	3.12	-1.37
Oil, t	2,533,300	2,272,100	2,169,900	2,293,300	2,453,600	-3.15	6.99
Uranium, t	1,156	1,185	986	1,390	944	-18.34	-32.09
Total, t	97,792,692	96,884,836	88,682,655	91,303,405	91,881,056		

CHAPTER 3. FACTORS AND CRITERIA AFFECTING INVESTMENT ATTRACTIVENESS OF MINERAL RESOURCE BASE OF UKRAINE

3.1. Basic Regulations of Ukraine in the Field of Subsurface Use

Obviously, in addition to summaries of the given deposit, extent of its study, geological and industrial type, mineral deposit conditions, the quantity and quality of raw materials, other geological and production issues, it is important for any investor, and especially a foreign investor, to be aware of the mineral policy (Gurskiy et al. 2006c; Malyuk 2016) and legal protection of his/her rights and the course of events when obtaining a special permit for subsurface use and in the process of exploration and development of the deposit. We should immediately note that the legal basis of subsurface use in Ukraine is extremely complex and ambiguous, which often causes misunderstandings between state authorities and the subsurface users.

Let's give just one example. In 2021, a new version of the Tax Code of Ukraine was published, which allows for different interpretations of the term "primary processing of mineral raw materials". In particular, the tax authorities believe that the primary processing of iron ores includes not only crushing processes, but also iron ore beneficiation and production of magnetite concentrate, which is subject to taxation (this was not the case before). Thus, some mining and processing companies faced the problem of double taxation, and resultant significant financial losses, which, in particular, for the mining and processing plants of Kryvyj Rig the taxes can reach billions of Ukrainian currency (Mykhailov et al. 2022b). This issue is currently being resolved in the court.

The issue of the legal basis of subsurface use is the subject of a separate large work, here we will consider only some of the most important aspects of the legal basis of subsurface use in Ukraine, guaranteeing the rights of investors who contribute in the development of the subsurface of Ukraine and the mechanism of obtaining the right to access the subsurface.

3.1.1. Basic Laws in the Field of Subsurface Use

There are dozens, if not hundreds, of legislative acts and resolutions of various levels regarding subsurface use, but the most important of them are, the Code of Ukraine "On Subsurface" (Law 1994b), the Mining Law of Ukraine (Law 1999b), the Law of Ukraine "On Production Sharing Agreements" (Law 1999a), the Tax Code of Ukraine (Law 2011b), as well as the Law of Ukraine on the State Geological Service of Ukraine (Law 1999c) and Statement on the State Service of Geology and Subsurface of Ukraine (Resolution 2015) with repeated amendments and additions to these basic documents.

The ***Code of Ukraine "On Subsurface"*** (Law 1994b) defines that the subsurface is the exclusive property of the people of Ukraine and is provided only for use. The concept of the State Subsurface Register is introduced, which includes both those

subsurface areas that are being used and those that are not yet in use. A part of the State Subsurface Register is the State Register of Mineral Deposits, which includes all mineral deposits (including technogenic ones). The minerals of national and local importance are distinguished. In turn, an important component of the State Register of Mineral Deposits is the State Inventory of Mineral Reserves (SIMR), which contains information on the quantity, quality and studied extent of mineral reserves in relation to deposits of economic importance, their location, the level of industrial development, as well as information on production, losses and industry backup with explored reserves of minerals. The SIMR is maintained on an annual basis by a central body of executive power for geological study and rational use of subsurface. Subsurface users can be companies, institutions, organizations, citizens of Ukraine, as well as foreign legal entities and citizens. The main types of subsurface use are geological exploration studies, including research and testing development of mineral deposits, and their mining extraction. Subsurface access can be provided for permanent or temporary (up to 50 years) use in the presence of special permits for subsurface use, which are granted, as a rule, to the winners of auctions. An investor who has received a special permit for subsurface use and mining rights, or concluded a production sharing agreement, has the exclusive right to use the subsurface within its limits in accordance with this special permit and production sharing agreement. Any activity related to the use of the subsurface within the limits of the mining concession can be carried out only with the consent of the investor to whom it is granted.

The ***Mining Law*** (Law 1999b) provides the principles of mining relations, as they arise in the course of the activity of mining companies, outlines the foundations of state policy in the mining industry, and the basic requirements for the operation of mining companies.

The ***Law of Ukraine "On Production Sharing Agreements"*** (Law 1999a) regulates the conditions for investing in mineral prospecting, exploration and extraction; regulates relations that arise during the conclusion and operation of production sharing agreements and determines the peculiarities of subsurface use during their operation.

According to the Law, Ukraine, in the person of the authorized bodies, instructs the investor to carry out prospecting, exploration and extraction of minerals in a specified subsurface area, and the investor undertakes to perform these works at their own expense with the subsequent compensation of costs and receiving a reward in the form of a part of the profitable products. According to this agreement, investors are granted special permits for subsurface use, licenses for prospecting and mining, mining allotments, and other permits. As a rule, the agreement is concluded as a result of a tender process, but in subsurface areas with insignificant mineral reserves, it can be concluded without a tender.

The production sharing agreement defines the list of types of activities, the program of mandatory works, terms of their execution, volumes and types of financing, technological equipment and other essential conditions of work. The term of the agreement cannot exceed 50 years. The manufactured products are shared

between the state and the investor according to the terms of agreement; the investor has the right to freely dispose of their part of the produced products. The right to geological, geophysical and other information obtained as a result of the works provided for in the agreement belongs to the State, the investor has the right to use this information free of charge, but is obliged to provide it to the State in the manner established by the agreement. During the execution of agreement, investor pays taxes and fees determined by the Tax Code of Ukraine (Law 2011b) and other necessary payments.

The State guarantees that, during the validity of the agreement, the rights and obligations of the investor will be governed by the laws in force at the time of signing the agreement, except for the laws that reduce or cancel the amount of taxes or fees and simplify the economic activity of the investor, or mitigate their responsibility. Guarantees regarding the stability of legislation do not apply to changes in defence, national security, public order, and environmental protection.

The **Tax Code of Ukraine** (Law 2011b) establishes general norms and rules for taxation of goods and services on the territory of Ukraine. Regarding the problems of subsurface use, the following are important.

1. National taxes and fees include taxes on the profit of companies, on the income of individuals, on added value, excise and environmental taxes, as well as rent and customs duties.

2. Among other taxes, rent taxation for the use of the subsurface for the extraction of minerals is provided for. The object of taxation in this case is *"the volume of merchandise of the mining enterprise – the extracted mineral (mineral raw material), which is the result of the economic activity of extracting minerals in the tax (reporting) period"* (Law 2011, Article 252.2). The tax rate on minerals (except iron) is 6.25%, for iron ores it varies from 2.0 to 11.0%, for coal – from 0.75 to 1.5%, for oil and condensate – from 16.0 to 31.0%, for gas – from 11.0 to 70.0%.

3. The concept of primary processing (beneficiation) of mineral raw materials includes *"a set of operations of collection, crushing or grinding, drying, classification (sorting), briquetting, beneficiation by physico-chemical methods (without qualitative change of the mineral forms of minerals, their aggregate-phase state, crystal-chemical structure), with the exception of agglomeration/lumping of ore with heat treatment, agglomeration and beneficiation by physico-chemical methods"* (Law 2011, Article 14.1.150).

The **Statement on the State Service of Geology and Subsurface of Ukraine** (Derzhgeonadra) (Resolution 2015) establishes the main tasks, rights and duties of Derzhgeonadra in the field of geological study and rational use of the subsurface of Ukraine, as the central body of executive power in this field. Accordingly, the main task of Derzhgeonadra is the implementation of state policy in the field of geological study and rational use of the subsurface. In particular, Derzhgeonadra is the authorized body for the implementation of production sharing agreements, issues special permits for subsurface use, and carries out State control over their geological study and effective use.

There are still many laws and by-laws that regulate the relationship between the State and investors in the field of subsurface use, where the issue of providing subsurface for geological study is considered; restriction, suspension and termination of this right; fees for the geological study of the subsurface; organization and legal issues of geological study of the subsurface; State examination and assessment of mineral reserves; writing off the reserves; subsurface protection; state geological control; liability for violations of geological legislation; international relations in geological activity and so on.

3.1.2. The Rights to Use Subsurface

Any activities in the subsurface, including mineral exploration and mining, are called in Ukraine “subsurface use” and are subject to the “special permit for subsurface use”. A special permit for subsurface use (or simply special permit) is a document issued by Derzhgeonadra that certifies the right of a legal entity or individual to use the subsurface for the purpose of extraction or geological study of minerals.

Obtaining special permits without holding an auction is regulated by the Procedure for granting special permits for subsurface use (hereafter – Permitting Procedure), which was approved by (Resolution 2011).

Permits are granted to the winners of auctions, as well as without auctions in the cases provided for in clause 8 of the above-mentioned (Resolution 2011) (Fig. 3.1).

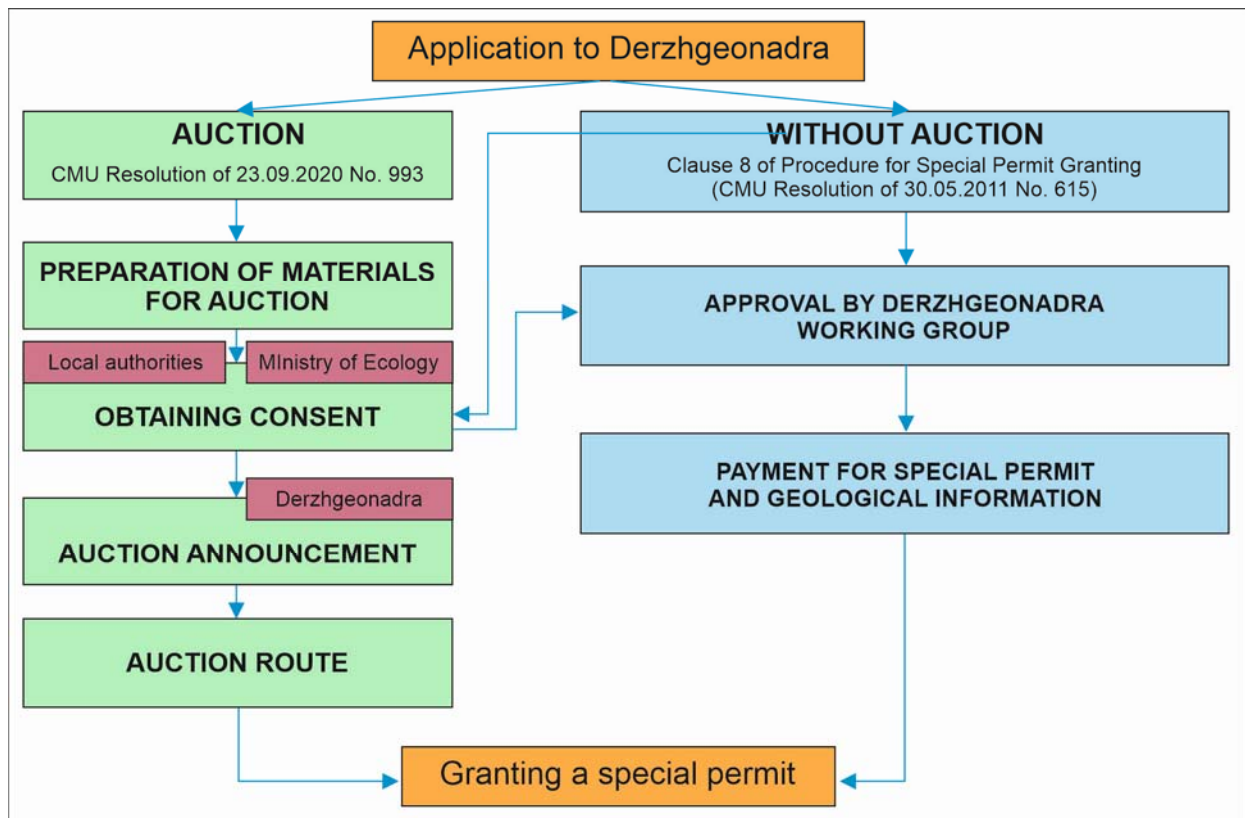


Fig. 3.1. Procedure for obtaining the special permits for subsurface use

Obtaining special permits by participating in the auction. Auction is a method of selling special permits for subsurface use through auctions. On the basis of the auction protocol, the winner and the auction organizer conclude a permit sale agreement within five working days after its completion.

The procedure for the sale at an auction through electronic bidding of a special permit for subsurface use within the territory of Ukraine, its continental shelf and the exclusive (marine) economic zone is determined by the Procedure for conducting auctions for the sale of special permits for subsurface use (hereafter – Auction Procedure), approved by the Resolution (2020).

The process starts with the application to Derzhgeonadra.

The use of the electronic bidding system for the sale of permits is carried out by:

- Derzhgeonadra – in accordance with the contract concluded between Derzhgeonadra and the administrator;
- By the Council of Ministers of the Autonomous Republic of Crimea – in accordance with the agreement concluded between the Council of Ministers of the Autonomous Republic of Crimea and the administrator, regarding the provision of subsurface for use for the development of mineral deposits of local importance;
- by the organizer (operator) – in accordance with the contract concluded between the organizer (operator) and the administrator.

Taking into account applications and additional materials (explanatory note, survey map and situational plan, catalogue of geographical coordinates of corner points, program of works) submitted by natural persons – entrepreneurs and legal entities, the Derzhgeonadra prepares proposals for determining the list of subsurface areas, permits for the use of which are issued on auction, and sends them by registered letter with a notification for approval to the relevant district, city, settlement, village councils and councils of united territorial communities – regarding the use of subsurface areas containing minerals of local importance.

If, within 45 calendar days, the authorities have not given a decision on approval or reasoned refusal of such approval, the proposals for determining the list of subsurface plots, the permits for the use of which are put up for auction, are considered approved.

Proposals for determining the list of subsurface areas, permits for the use of which are put up for auction (together with explanatory notes, survey maps and situational plans, catalogues of geographic coordinates of corner points, work programs) are submitted by Derzhgeonadra to the Ministry of Environment.

The Ministry of Environment, within a period not exceeding 15 working days from the date of receipt of proposals from Derzhgeonadra for the determination of the list of subsurface plots, the use permits of which are put up for auction, sends to Derzhgeonadra the proposals for determining the list of subsurface areas, the permits for the use of which are put up for auction, indicating the conditions, under which subsurface use is possible on the proposed subsurface areas, in terms of compliance with the requirements of environmental protection legislation, or substantiated proposals indicating ways to eliminate them regarding the impossibility of subsurface

use on the proposed subsurface areas in compliance with the requirements of environmental protection legislation. The above-mentioned proposals are published by the Ministry of Environment on the official website within three working days after the relevant decision is made.

During the re-examination of the documents received from Derzhgeonadra, it is not allowed to submit proposals regarding the impossibility of subsurface use in the proposed subsurface areas in compliance with the requirements of environmental legislation for reasons that were not previously specified in the written notice of Derzhgeonadra (with the exception of Derzhgeonadra non-removal the reasons that became the basis for the previous proposals).

In the event that the Ministry of Environment is provided with substantiated proposals regarding the establishment by legislation of restrictions on the implementation of subsurface use activities on the territory where its implementation is planned, such proposals will be considered by Derzhgeonadra when making decisions on determining the list of subsurface areas, the permits for the use of which are put up for auction.

In the event that the Ministry of Environment does not submit proposals for determining the list of subsurface areas within 15 working days from the date of receipt of the documents in full from Derzhgeonadra, it is considered that there are no proposals for determining the list of subsurface areas, the use permits of which are put up for auction.

After receiving approvals from the bodies and proposals of the Ministry of Environment, indicating the conditions under which subsurface use is possible on the proposed subsurface areas, in terms of compliance with the requirements of environmental protection legislation, Derzhgeonadra draws up and approves, by order, a list of such areas together with the relevant work programs and then makes a decision about holding an auction.

The announcement on the holding of the auction is placed by Derzhgeonadra in the system of electronic bidding for the sale of permits and on the official website of Derzhgeonadra within 10 working days from the date of approval of the list of subsurface plots and the decision to hold the auction.

Subsurface areas (mineral deposits) that are of strategic importance for the sustainable development of the economy and defence capability of the State are put up for auction only within the list of such subsurface areas (mineral deposits) approved by the Cabinet of Ministers of Ukraine.

The auction is conducted by the electronic bidding system for the sale of permits:

- after 90 calendar days from the date of posting the auction announcement (for oil, natural gas, condensate), including the day of posting the auction announcement in the electronic bidding system for the sale of permits and on the official website of Derzhgeonadra;
- after 20 calendar days from the date of posting the auction announcement (for all other minerals), including the day of posting the auction announcement in the electronic bidding system for the sale of permits and on the official website of Derzhgeonadra.

The re-auction is announced within three working days after the first auction is recognized as not having taken place, and is held 15 calendar days after the date of posting the re-auction announcement, including the day of posting the auction announcement in the electronic bidding system for the sale of permits and on the official website of Derzhgeonadra.

The second re-auction is announced within three working days after the re-auction is recognized as not having taken place, and is held 15 calendar days from the date of posting the announcement of the second re-auction, including the day of posting the auction announcement in the electronic bidding system for the sale of permits and on the official the website of Derzhgeonadra.

The auction is conducted by a 24-hour electronic bidding system for the sale of permits.

To participate in the auction, the applicant goes through the registration procedure and applies for participation in the auction by filling out an electronic form in their personal account (capacity rather than account?).

After completing the registration procedure and submitting the application, the applicant pays the guarantee fee at any bank institution on the basis of the account created by the organizer (operator) in the applicant's personal account or directly on the electronic platform using payment systems, if the functionality of the electronic platform provides such an opportunity.

The size of the guarantee fee is 20 percent of the lot bidding price, but not less than UAH 5,000,000 (five million) for minerals that are of strategic importance for the sustainable development of the economy and the State's defence capability, UAH 10,000,000 (ten million) for hydrocarbons and UAH 500,000 (five hundred thousand) – for other minerals (except for the sale lot of a special permit for geological study, including research and industrial development, extraction of underground water, including mineral water, for all needs).

If the amount of the guarantee contribution is greater than the selling price of the lot, the difference is paid in accordance with clause 32 of the Auction Procedure.

If repeated auctions are held in connection with the recognition of the auction as having not taken place, on the grounds of depriving the winner of the right to obtain a permit in the cases provided for in Clause 30 of the Auction Procedure, the amount of the guarantee fee for this lot at repeated auctions is 40 percent of the initial price of the lot, but not less than the corresponding specified amounts.

In the event that the winners, determined in accordance with Clause 22 of the Auction Procedure, are deprived of the right to obtain a permit in the cases provided for in Clause 30 and the third paragraph of Clause 33 of the Auction Procedure, the amount of the guarantee fee for this lot at repeated auctions is 40 percent of the initial price of the lot.

Payment of the guarantee fee must be confirmed before the deadline for accepting applications for participation in the auction.

After the end of the auction, information about the end of the auction is displayed in the electronic bidding system for the sale of permits, and an auction protocol is automatically generated for each lot.

The winner, on the basis of the signed auction protocol, applies to Derzhgeonadra with a proposal to conclude a permit sale agreement or a permit sale agreement with a postponing circumstance based on the results of the auction. Such an agreement is concluded between Derzhgeonadra and the winner no later than 20 working days from the day following the day of formation of the electronic auction protocol and is published by Derzhgeonadra in the system.

The contract is signed in accordance with the legislation on electronic document circulation with a qualified electronic signature.

If a foreign legal entity wins the auction, which at the time of signing the auction protocol does not have a representative office registered in Ukraine, such foreign legal entity is obliged to register its own representative office in the territory of Ukraine within four months from the date of signing the contract of purchase and sale of the permit with a postponing circumstance.

In this case, the relevant contract of purchase and sale of a permit with a postponing circumstance must be re-issued to the permanent representative office of the auction winner – a foreign legal entity within ten days from the day the auction winner – a foreign legal entity sends the relevant request to Derzhgeonadra.

The winner, within 30 working days from the date of conclusion of the contract of purchase and sale of a permit or the contract of purchase and sale of a permit with a delay, shall pay to the state budget funds in the amount of the difference between the sale price of the lot and the guarantee fee.

After payment to the state budget of funds in the amount of the difference between the sale price of the lot and the guarantee fee, Derzhgeonadra through a personal office confirms the fact that the winner has made payment under this contract and closes the auction.

The purchase of geological information about the subsurface area, for which the winner is granted a permit, is carried out in accordance with the Procedure for the disposal of geological information, approved by the CMU (Resolution 2018).

Compensation for the cost of geological information is carried out in accordance with the details of Derzhgeonadra, specified in the protocol of the electronic auction, by the winner of the auction within 30 working days from the date of conclusion of the contract of purchase and sale of a permit or the contract of purchase and sale of a permit with a postponing circumstance.

Payment of the remuneration to the operator through whom the winner acquired the right to participate in the auction is made by the winner within a period not exceeding 10 working days from the date of publication of the auction protocol by Derzhgeonadra in the electronic bidding system for the sale of permits.

Payment of the price of the package of auction documentation is made by the winner within a period not exceeding 20 working days from the date of publication of the auction protocol by Derzhgeonadra in the system of electronic bidding for the sale of permits.

Remuneration to the operator through whom the winner of the auction acquired the right to participate in the auction, is paid by such winner of the auction until the date of conclusion of the contract of purchase and sale of a permit or purchase and sale of

a permit with a postponing circumstance between Derzhgeonadra and the winner of the auction.

The guarantee fee or its part, equal to the sale price of the lot (if the size of the guarantee fee is greater than the sale price of the lot), paid by the winner, is transferred by the organizer (operator) to the state budget within five working days after the publication of the protocol. If the amount of the guarantee fee is greater than the selling price of the lot, then the difference between the part transferred to the state budget and the paid guarantee fee is returned to the winner within five working days from the day of receiving the permit.

Issuance of a permit and an agreement on the conditions of subsurface use is carried out within 30 working days in accordance with the terms of the permit sale agreement based on the results of the auction.

Obtaining special permits without an auction. Special permits are granted for the following types of subsurface use:

- Geological study of subsurface areas of minerals;
- Geological study, including research and industrial development of mineral deposits of national significance;
- Extraction of minerals;
- Geological study of oil and gas-bearing subsurface, including exploratory and industrial development of deposits, with subsequent extraction of oil and gas (industrial development of deposits);
- Geological study of amber-bearing subsurface, including exploratory and industrial development of deposits with subsequent extraction of amber (industrial development of deposits);
- Construction and operation of underground facilities not related to the extraction of minerals, including facilities for underground storage of oil, gas and other substances and materials, disposal of harmful substances and production waste, waste water discharge;
- Creation of geological territories and objects of important scientific, cultural, sanitary and health importance (scientific testing grounds, geological reserves, nature reserves, natural monuments, medical and health facilities, etc.);
- Performance of works (implementation of activities) provided for in the product distribution agreement.

The State Research and Development Enterprise "Geoinform of Ukraine" is engaged in the preparation of materials and drawing up a conclusion on the granting of a special permit in accordance with the procedure established by Derzhgeonadra.

A special permit without an auction is granted in the event of:

1. Extraction of minerals, if the applicant, on the basis of a special permit for the use of subsurface, at their own expense, carried out a geological study of the subsurface area and the calculation of mineral reserves, which was approved in accordance with the established procedure, and submitted documents for obtaining a special permit for the extraction of minerals of the corresponding deposit no later than three years after stock approval;
2. One-time expansion of the boundaries by no more than 50% of the area of the

subsurface area previously provided for use for the purpose of its geological study, including experimental and industrial development (including subsurface areas provided for the purpose of extraction, geological study, including experimental industrial development, with further extraction of oil and gas (industrial development) provided that the spatial boundaries of promising deposits discovered in the process of geological study go beyond the subsurface area provided for use and are confirmed by the relevant protocols of the State Commission on Mineral Reserves of Ukraine), placement of underground storage facilities, and also an increase in the volume of mineral extraction due to the expansion of the boundaries of the site, but not more than 50% of the reserves determined by the previously granted permit, provided that the adjacent site is not provided for use and/or not put up for auction;

3. Geological study of the subsurface at the expense of the State Budget;
4. Geological study, including research and industrial development, extraction of groundwater (except mineral) for all needs, except for the production of bottled drinking water, provided that the volume of extraction of drinking groundwater from water intakes exceeds 300 cubic meters per day;
5. Geological study, including research and industrial development and extraction of natural medical resources by medical and preventive and sanatorium-resort facilities that specialize in their use exclusively for medical purposes and have a medical infrastructure;
6. Construction and operation of underground facilities not related to mineral extraction, including facilities for underground storage of oil, gas and other substances and materials, disposal of harmful substances and production waste, waste water discharge;
7. Creation of geological territories and objects of important scientific, cultural, sanitary and health importance (scientific landfills, geological reserves, nature reserves, natural monuments, medical and health facilities, etc.), in terms of their geological study and preservation (except for oil and gas);
8. Operation of underground structures, related to the prevention of flooding of the natural environment due to the closure of mines;
9. Implementation of product distribution agreements;
10. Geological study, including research and industrial development of mineral deposits of national significance and mineral extraction ;
11. Geological study of oil and gas-bearing subsurface, including exploratory and industrial development of deposits, with subsequent extraction of oil and gas (industrial development of deposits) on the continental shelf and exclusive (marine) economic zone by the joint-stock company "National Joint-Stock Company "Naftogaz of Ukraine" and/or the economic company, 100 percent of whose shares belong to the joint-stock company "National Joint-Stock Company "Naftogaz of Ukraine", for a period of 30 years.

To obtain a permit without holding an auction, the applicant submits an application applies? to the authority for granting permits together with the documents specified in Appendix 1 of the (Resolution 2011), in paper or in electronic form (hereinafter –

Application). The Application, together with the documents specified in Appendix 1, is signed in accordance with the legislation on electronic document circulation with a qualified electronic signature. In electronic form, the Application and documents are sent to the e-mail address of Derzhgeonadra indicated on its official website, and after the entry into force of the Procedure for the functioning of the subsurface user's electronic account, they are submitted through the subsurface user's electronic account. The procedure for the functioning of the subsurface user's electronic account is to be approved by the Ministry of Environment.

Two copies of the application and the documents attached to it are submitted together with the application. In the application, the name of the subsurface area, its location in accordance with the administrative and territorial system of Ukraine (region, district, settlement, location reference), geographical coordinates of the subsurface area, the type of minerals, the type of use of the subsurface, the validity period of the permit, information about the applicant (name, location of a legal entity or surname, first name, patronymic, place of residence, registration number of the tax payer registration card of a natural person – entrepreneur or series and passport number of such a person (for natural persons who because of their religious beliefs, they refuse to accept the registration number of the taxpayer's registration card and have notified the relevant supervisory body about it and have a mark in their passport), information for contacting the applicant (phone number, e-mail address), current information (data) on the date of submission of the application, which makes it possible to establish the ultimate beneficial owner, – surname, first name, patronymic (if available), date of birth, country of citizenship (nationality), and in the event that the final beneficial owner is a foreigner who is a citizen (national) of several countries, all countries of their citizenship (nationality), series (if available) and document number (documents) certifying identity and confirming citizenship (nationality), in particular, but not exclusively, passports of citizens of Ukraine for traveling abroad, place of residence, registration number of the taxpayer's registration card (if available), nature and measure (level, extent, share) of beneficial ownership (benefit, interest, influence) or a justified reason for its (their) absence, as well as the basis for granting a permit in accordance with Clause 8 of the Permitting Procedure.

The application and the documents attached to it are submitted to the permit granting authority with stitched and numbered pages and a description of the attached documents, certified by the signature of the authorized person of the applicant. The application is certified by the signature of the applicant's authorized person, indicating the date and original number.

Information on the registration of documents received for granting a permit is posted on the official website of the authority for granting a permit within three working days from the date of registration.

The decision to grant a permit without holding an auction is made by the authority for granting a permit in accordance with the data specified in the application, within 30 calendar days after receiving all approvals provided for in Clause 9 of the Permitting Procedure, and the proposals of the Ministry of Environment, provided for in Clause 24 *ibid*. The specified decision is posted on the official website of the

authority on granting permission within five working days from the day of its adoption. The granting of a permit without holding an auction is carried out within 20 working days after payment in full of the fee for granting a special permit.

Granting of permits in the cases provided for in sub-clauses 1-8, 10, 11 of Clause 8 of the Permitting Procedure is carried out by the decision of the authority for granting permits.

In the case provided for in Clause 9, permits are granted by Derzhgeonadra at the request of the Interdepartmental Commission for the Organization of the Conclusion and Implementation of Production Sharing Agreements on the basis of the concluded product distribution agreement.

An integral part of the permit is the agreement on the conditions of use of the area, which is concluded between the authority for granting the permit and the subsurface user and contains the work program, which is drawn up as an appendix, and special conditions of subsurface use, which provide for:

- requirements for work efficiency;
- modern technologies of mineral extraction and processing;
- the procedure for extracting minerals, in particular with the aim of preventing negative environmental consequences and ensuring the safety of built-up areas;
- types, volumes and terms of execution of works on the subsurface area;
- grounds for termination of activities related to the use of the subsurface area.

The permit with the agreement on the conditions of subsurface use and its appendices shall be published on the official website of the authority for granting the permit no later than five working days after their signing. Exemplary agreements on the conditions of subsurface use are approved by the licensing authority, taking into account the economically justified deadlines for work on individual groups of minerals in accordance with Appendix 5 and the main types of work in accordance with Appendix 6, and are subject to publication on its official website.

For granting a permit without holding an auction, a fee is charged (except in the case of granting a permit provided for in clause 11) in the amount that is calculated based on the bidding price of such a permit at an auction in accordance with the regulation (Resolution 2004).

A fee of 10 percent of the bidding price of such a permit at an auction at sea depths of up to 100 meters and 1 percent of the bidding price of such a permit at an auction at sea depths of more than 100 meters.

A fee of 1 percent of the bidding price of such a permit at the auction shall be charged for the issue of permits without an auction for the purpose of fulfilling Production Sharing Agreements.

The applicant must pay the permit fee in full within 45 calendar days from the date of sending the recommended notice of the amount of such permit fee. During the period of martial law, notification of the amount of such a permit fee is sent to the e-mail address specified in the application.

In the event of non-payment of the permit fee within the prescribed period, the applicant, in respect of whom a decision was made to grant a permit in accordance with Clause 8 of the Permitting Procedure, loses the right to obtain it, and the relevant

decision is revoked. At the same time, the authority in charge of granting a permit may extend the term of payment of the fee, provided that the applicant submits a written request for the extension of the term of payment of the fee with a mandatory indication of the reason, but for no more than 15 calendar days.

The acquisition of geological information about the subsurface area, which is provided to the business entity for use, is carried out in accordance with the procedure determined by the CMU (Resolution 2018), according to the bank details of Derzhgeonadra, specified in the notice on the amount of the fee for granting a special permit.

Payment for secondary (processed) geological information is to be made within 45 calendar days from the date of sending the recommended notification of the amount of the special permit fee involved.

Permit re-issuance is carried out in the following cases:

- in the case of a legal entity obtaining a lease or concession of an integral property complex of a state coal-mining enterprise;
- in connection with the legal succession of a legal entity (subsurface user) as a result of reorganization by conversion.
- in case of return by the lessee or concessionaire of a complete property complex of the state coal mining enterprise from lease or concession.

The permit may be suspended by the permit granting authority directly or at the request of the Ministry of Environment, State Agency of Labour, Ministry of Health, State Economic Inspection, local self-government bodies, or the State Tax Authority in the case of one or more of the following:

- violation by the subsurface user of the conditions of subsurface use as provided for by the permit or agreement on the conditions of use of the subsurface area;
- the occurrence of a direct threat to the life or health of employees or the population as a result of works related to the use of the subsurface area;
- failure to comply within the prescribed period with the instructions of authorized bodies regarding the elimination of violations of legislative requirements in the field of subsurface use or environmental protection;
- the existence of grounds as provided for by the Law of Ukraine "On Sanctions";
- non-fulfillment of the conditions of environmental impact assessment conclusions and/or conclusions of the state environmental examination;
- absence of an environmental impact assessment conclusion and/or a conclusion of the state environmental examination of mineral extraction activities;
- the absence of information about the ultimate beneficial owner or information about its absence, and/or the presence of discrepancies between the information about the ultimate beneficial owner contained in the public access of the Unified State Register of Legal Entities, natural persons – entrepreneurs and public organizations, with information (data) that makes it possible to establish the ultimate beneficial owner, submitted by the applicant., and Additionally, in the case of a registered foreign representative office – information about the ultimate beneficial owner in accordance with the Law of Ukraine "On Ensuring Transparency in Extractive Industries" (Law 2018).

The permit may also be suspended by the permit-granting authority at the request of the Ministry of the Environment upon an appeal to the Ministry of the Environment of the State Environmental Inspection and/or its territorial bodies regarding non-fulfillment of the conditions of the environmental impact assessment conclusions and/or the conclusions of the state ecological expertise, and/or the absence of an environmental impact assessment conclusion and /or the conclusion of the state environmental examination of mineral extraction activities.

Following the suspension of the validity of the permit, the subsurface user is obliged to stop carrying out the works provided for by the permit on the section of subsurface as provided for his use.

Termination of the permit does not release the subsurface user from the obligation to carry out work on the subsurface area which is related to the prevention of an emergency situation or elimination of its consequences. The suspension of the permit is not a reason to interrupt its validity period.

The permit is renewed by the permit granting authority after the subsurface user eliminates, or rectifies, the reasons that initially led to its suspension.

In the event that the suspension and/or cancellation of a permit is recognized as illegal (unfounded) by a court decision, which has entered into force, the validity period of the permit, and, accordingly, the period of subsurface use, shall be extended by the licensing authority for the identical period of such suspension and/or cancellation.

The right to use the subsurface is terminated on the grounds and in the manner provided by the Code of Ukraine on Subsurface (Law 1994b), the Laws of Ukraine "On Oil and Gas" (Law 2001) and "On the Permit System in the Field of Economic Activity" (Law 2005).

The above-mentioned requirements (as per paragraphs 21 and 22 of the Permitting Procedure) do not apply to subsurface users who have been granted a permit on the basis of paragraph 9 of the same procedure (Production Sharing Agreement). In this case, the right to use the subsurface may be terminated, limited or temporarily prohibited (suspended) only in the case of termination (including premature) of the agreement on the distribution of products, which is carried out under the conditions and in the order provided by such an agreement. The right to use the subsurface during the implementation of the Production Sharing Agreement may be limited, temporarily prohibited (stopped) or terminated by the Cabinet of Ministers of Ukraine in the event of a direct threat to the life and health of people or the environment in the manner provided by such an agreement.

Features of the use of the subsurface during the implementation of the agreement on the distribution of products, including those related to the termination (suspension or limitation) of the right to use the subsurface, are established in the manner of and under the conditions as determined by the Law of Ukraine "On Production Sharing Agreements" (Law 1999a), and the corresponding agreement on the production sharing.

From the moment the investor eliminates the conditions, as a result of which the right to use the subsurface is limited, said such right is subject to restoration in full.

On granting, extending the term of validity, suspending the validity, renewing the validity, reissuing, cancelling the permit and making changes to it, Derzhgeonadra issues an order, and the Council of Ministers of the Autonomous Republic of Crimea – a decision.

Derzhgeonadra informs the Ministry of Environment about the receipt of applications and documents specified in Appendix 1 of the Permitting Procedure, about regarding the granting and extension of the validity period of permits, while simultaneously sending on copies of these documents no later than within seven working days from the date of their registration.

The Ministry of Environment, within a period not exceeding 15 working days from the date of receipt of the documents, sends to Derzhgeonadra proposals for the granting or extension of the validity period of permits together with the conditions under which it is possible to use the subsurface in the proposed subsurface areas, in terms of compliance with the requirements of environmental protection legislation or comments on the granting or extending the validity period of permits.

In case of failure to submit to the Ministry of Environment proposals for granting or extending the validity of permits together with the conditions under which it is possible to use the subsurface in the proposed subsurface areas, in terms of compliance with the requirements of environmental protection legislation within 15 working days from the date of receipt of the documents from Derzhgeonadra in their entirety, it is considered that the proposals regarding the granting or extension of the period of validity of permits are absent.

Proposals and comments of the Ministry of Environment regarding the granting or extension of the validity period of permits are mandatory for Derzhgeonadra to be taken into account when making decisions regarding the granting or extension of the validity period of permits.

The order of Derzhgeonadra on granting, reissuing, extending the validity period, making changes to the permit, suspending the validity, renewing the validity, cancelling, refusing to grant or extending the validity period of the permit is posted within five working days on the official website of the relevant body.

The record of granted permits and applications is kept by the State Research and Development Enterprise "Geoinform of Ukraine" in accordance with the procedure established by Derzhgeonadra.

At the written request of the state bodies specified in Clause 26 of the Permitting Procedure, the authority for granting a permit shall submit generalized information on the granting, re-issuance, suspension and renewal of the permit, cancellation of the permit, and changes to it.

Control and supervision of compliance with permit conditions is carried out within the limits of their powers by the permit granting authority, the State Environmental Inspection, the Ministry of Environment, the Ministry of Health, the State Tax Authority, as well as local self-government bodies.

3.1.3. Assessment of Mineral Reserves and Resources

The assessment of mineral reserves is carried out by the State Commission on Mineral Reserves of Ukraine (SCMR), which operates on the basis of the Statement on the State Commission on Mineral Reserves of Ukraine, which was approved by regulation (Resolution 2000).

The SCMR carries out scientific and technical activities related to carrying out, at the request of subsurface users or on behalf of the relevant central bodies of the executive power, the State examination of geological materials for the study and use of the subsurface and the assessment of mineral reserves; generalizes the application of legislation on issues that belong to its competence; develops proposals for improvement and adaptation to international standards, namely, implements the harmonization of the Classification of Mineral Reserves and Resources of the State Subsurface Register of Ukraine with the classification schemes of leading world organizations in order to create conditions for comparing mineral reserves calculated according to different systems.

The State examination of the materials of for the geological and economic assessment of mineral deposits is carried out in accordance with the Regulation on the procedure for conducting State examination and assessment of mineral reserves, which was approved by the regulation (Resolution 1994b).

Materials for the geological and economic assessment of mineral reserves are submitted to the SCMR by subsurface users or persons authorized by them. After receiving the materials of for the geological and economic assessment of mineral deposits, the SCMR issues contracts with subsurface users or with persons authorized by them to carry out work on examination and assessment of mineral reserves and performs undertake them within the term stipulated in the contract. The procedure for determining the cost of work on state examination and assessment of mineral reserves is established by the SCMR with the approval of the Ministry of Economy.

The conclusions of the SCMR on the assessment of the quantity and quality of mineral reserves, their industrial importance and the degree of their geological and technical-economic study are the basis for their recording in the SIMR.

The assessment of the quantity and quality of mineral reserves is carried out in accordance with the instructions for the classification of mineral reserves and resources of the State Subsurface Register by individual types of mineral raw materials, for example, deposits of ferrous metal ores (iron, manganese and chromium), which was approved by the regulation (SCMR 2002).

According to the above mentioned instructions, mineral reserves and resources are divided into the following categories.

Mineral resources – volumes of minerals and components of undiscovered deposits, estimated as possible for extraction and processing at the current technical and economic level of development of deposits of this type of mineral raw material. Assessment of mineral resources and components is an approximate determination of the quantity and quality of minerals and components based on the analysis of

favourable geological and economic prerequisites and positive results of geological, geophysical and other research studies.

Mineral reserves include the volumes of minerals and components that have been discovered and estimated at their place of occurrence based on the geological study of discovered (identified) mineral deposits.

The instructions of the SCMR on the application of the Classification of Mineral Reserves and Resources of the State Subsurface Register to deposits of certain types of minerals establish the following protocols: grouping of mineral deposits by industrial types; the distribution of deposits according to the complexity of the geological structure, the volume of the reserves, and the content of the useful component in the ore; principles of distribution of reserves according to their industrial value, technical-economic and geological study; requirements for the study of mineral deposits, the estimation of reserves and readiness for industrial development; principles of resource assessment of promising subsurface areas.

According to the degree of geological study investigation carried out, mineral reserves are subdivided into two groups: explored and preliminary explored.

Explored reserves are estimated in areas that are intended for priority development and preparation of the project for the first phase of the mining enterprise. In the contours of explored reserves, according to the degree of exploration of their morphological features, reserves of categories A, B, and C₁ are distinguished.

Reserves of category A are estimated in the areas of detaileding study and priority development of deposits of a simple geological structure, within which the shape, size and conditions of occurrence of ore deposits are established; the ratio and spatial position of the areas formed by ores of various natural types and industrial (technological) grades are determined; the low-grade and barren areas within the ore deposits are selected and outlined, positions and displacement amplitudes of discontinuity faults are defined. The outline of the reserves of category A is carried out by exploration works.

Reserves of category B are allocated within the areas of detaileding study and priority development of deposits of complex geological structure and in deposits of the first group of complexity; occur in blocks for which the dimensions, main features of the shape, internal structure and conditions of occurrence of ore deposits, spatial placement of low-grade and barren areas within established ore deposits, the positions and displacement amplitudes of large faults and zones of development of low-amplitude faults have been established. In blocks of category B, the basic patterns of spatial distribution of different types and industrial grades of ores in the contours of ore deposits should be established. The outline of reserves of category B is made based on the data of exploration works with only a limited extrapolation zone.

Reserves of category C₁ are allocated in the areas of detaileding study and priority development of deposits of very complex structure and in deposits of the first and second groups of complexity of the geological structure, in blocks, within which the sizes and characteristic forms of ore deposits, the main features of their conditions of occurrence and internal structure, the possible discontinuity of ore bodies, the

position of the main tectonic disturbances, as well as zones and areas of their intensive development are all characterized. Spatial placement and the ratio of different natural types and industrial grades of ores, placement of areas composed of low-grade ores, is established in general terms. The outline of reserves of category C_1 is determined on the basis of exploration works and extrapolation based on geological and geophysical data.

Preliminary explored reserves are those in which the volumes of minerals, the quantity, quality, technological properties, mining-geological, hydrogeological and other conditions of occurrence of which have been studied with to a level of completeness sufficient for the probable determination of the possible industrial value of the deposit. The main parameters of preliminary explored reserves, which affect the choice of methods of extraction and processing of ores, are estimated mainly on the basis of extrapolation of the data of direct measurements or studies carried out within the boundaries of the deposit on a scarce poorly defined or irregular grid. The extrapolation is substantiated by analogy with the explored field (deposit), as well as by evaluation of the available geological, geophysical, geochemical and other subsurface research data.

According to the degree of study of the morphological characteristics, internal structure and conditions of occurrence of the ore deposits, the preliminary explored reserves correspond to the **reserves of category C_2** . Category C_2 includes ore reserves in subsurface areas, within which the shape, size, internal structure and conditions of occurrence of ore deposits are estimated according to geological, geophysical, geochemical data and confirmed by a poor grid of intersections of geological exploration works. The outline of reserves of category C_2 is made on the basis of a justified extrapolation of the data of exploration products. In recently discovered deposits, where there are no reserves of higher categories, category C_2 includes areas of deposits in which the quantity and quality of ores were measured at several points although not located not on the same line transverse to the strike of the ore bodies.

According to the degree of geological study and reliability available, mineral resources are divided into two groups: prospective and predictive.

Prospective resources are volumes of minerals, quantitatively estimated based on the results of geological, geophysical, geochemical and other studies of subsurface areas within productive areas with known deposits of a certain geological and industrial type. Prospective resources take into account the possibility of discovering new deposits of the same geological and industrial type, the existence of which is justified by a positive assessment of ore occurrences, mineralization points, and geophysical, geochemical and other anomalies, the nature and prospects of which are proven. Quantitative estimates of parameters of prospective fields (deposits) are determined based on the interpretation of geological, geophysical, geochemical and other data or statistical analogy.

According to the degree of reliability of data on the conditions of occurrence and morphological characteristics of ore deposits, prospective resources are divided into categories P_1 and P_2 .

Category P_1 includes promising resources in areas of expansion of ore-bearing areas, which are adjacent to the limits of explored and previously explored reserves of discovered deposits, and in promising areas of the subsurface, where the existence of ore deposits, their shape, dimensions, internal structure and conditions of occurrence are estimated according to geological, geophysical, geochemical data and confirmed by individual sections of geological exploration works.

Prospective resources of the **category P_2** take into account the possibility of discovering new deposits in a known ore district, ore field, the presence of which is assumed on the basis of a positive assessment of ore occurrences of ore-bearing rocks, geophysical and geochemical and other anomalies, the nature and prospects of which are proven on the analogous discovered ore objects. Conditions of occurrence and morphological characteristics of mineralization are evaluated by analogy.

Predicted resources are the volumes of minerals that take into account the potential for the formation of deposits of certain geological and industrial types, which is based on positive stratigraphic, lithological, metallogenic, paleogeographical and other prerequisites established within promising areas where industrial deposits have not yet been discovered. The quantitative assessment of predicted resources is carried out on the basis of estimated (forecast) parameters by analogy with productive areas where there are discovered deposits of the same geological and industrial types.

Since 1997, the UNFC has been implemented in Ukraine. In particular, the regulation (Resolution 1997a) provides for the allocation of the following classes of mineral reserves and resources (Table 3.1).

Table 3.1 Classes of mineral reserves and resources of Ukraine (Resolution 1997a)

Categories by level of economic, social and industrial importance (axis E)	Categories according to the extent degree of technical and economic study and level of preparedness for development (axis F)		Categories according to the extent of geological study and reliability (axis G)	Class code according to the UNFC	Class UNFC-2009
1. Recorded reserves (1..) E1 E1.1; E1.2	Reserves in production (F1.1) approved for production (F1.2) or for industrial development (F1.3)	GEC*-1; (.1.); F1	explored reserves (.. 1); G1	111 proven	commercial reserves
	reserves recommended for development F2.1; F2.2	GEC-2; (.2.); F2	explored reserves (.. 1); G1	121 probable	
			preliminary explored reserves (.. 2); G2	122 probable	

Categories by level of economic, social and industrial importance (axis E)	Categories according to the extent degree of technical and economic study and level of preparedness for development (axis F)		Categories according to the extent of geological study and reliability (axis G)	Class code according to the UNFC	Class UNFC-2009
2. Assessed but not yet recorded reserves (2..) E2	development of reserves is expected, stopped or unprofitable	GEC-1; (.1.); F1; F1.3	explored reserves (.. 1); G2	211	possibly commercial reserves
		GEC-2; (.2.); F2 (F2.1; F2.2)		221	
			preliminary explored reserves (.. 2); G2	222	
3. The industrial value of reserves and resources is not determined; (3..); E3; E3.1; E3.2; E3.3	development of reserves and resources is not defined	GEC-3; (.3.); F3	explored reserves (.. 1); G1	331	Non-commercial reserves
			preliminary explored reserves (.. 2); G2	332	
			prospective resources (.. 3); G3	333	Resources of geological exploration
			forecast resources (.. 4); G4	334	
	residual (additional) reserves in the subsurface that are not mined	F4	explored reserves (.. 1); G1	341	residual (additional) reserves and resources
			preliminary explored reserves (.. 2); G2	342	
	residual (additional) reserves in the subsurface that are not mined		prospective resources (.. 3); G3	343	
			forecast resources (.. 4); G4	344	

* GEC means geological-economic conclusion which roughly corresponds to the feasibility study.

The conversion of reserves and resources of minerals to the codes of the UNFC requires a huge effort, since the reassessment of the volumes of reserves and resources must be carried out individually for each deposit or occurrence of minerals.

These works are ongoing, therefore reserves and resources of categories A-B-C and P are recorded in the SIMR.

3.2. The Main Factors and Criteria of Affecting the Investment Attractiveness of the Mineral Resource Base of Ukraine

The investment attractiveness of the deposit or occurrence, as a rule, is a complex criterion that can be considered in absolute and relative terms. Carrying out such an assessment involves the availability of an investor and the search for acceptable investment objects opportunities, while the methodology depends on the intended goal, which may be as follows: 1) assessment of the feasibility of capital investment in expansion and technical upgrading of existing mining companies; 2) selection of alternative subsurface objects for investments, including those that have not yet been developed; 3) purchase of securities of individual mining companies. The assessment of investment attractiveness is usually carried out in two stages:

- the first stage involves the establishment of quantitative thresholds of the project and selection of companies, deposits, etc., which finally forms produces a short list of possible investment objects opportunities;
- the second stage provides a rating/ranking for of the short list specified in stage 1.

Absolute parameters of investment attractiveness for the first stage are set from the list of indicators of monetary valuation of reserves and resources of minerals, which is the result of their geological and economic assessment at each stage of exploration. In general cases, this list includes the cost of reserves and resources, profitability, liquidity ratio etc. The position of an investor regarding the amount (level) of investments and expected time of their return is important in the assessment. In addition to the generally accepted indicators, additional indicators and conditions are used in exploration and mining projects, which are associated with the emergence of special components of assessments – namely geological risk and mining risk(s).

In view of above, a range of versions of the assessment of investment attractiveness, depending on the investor's requirements are used in modern practice, This is extremely painstaking and laborious work, which should take into account various criteria and factors, as well as the risks that exist in exploration works. The main assessment factors in the first approximation include the following technical and economic indicators of geological and economic assessment of deposits (Mykhailov et al. 2017; Mykhailov, Kurylo 2017):

- the need/demand for specific minerals in the world market and specifically the European market (Report on critical Raw Materials 2014);
- degree of geological, and technical and economic study of the deposits, which is carried out in accordance with domestic and international standards of assessment;
- geological-industrial type of deposit, complexity of geological structure of deposits – these are determined by conventional methods (simple, complex, very complex, too complex);
- the size of deposit, the scale of explored reserves, geological and economic (mining) reserves, their quantity and quality, grade in productive bodies and so on;
- geometric parameters of mineralization, including quantity, shape, size of ore bodies, their average thickness, continuity by/along strike and dip;

- the quality of mineral, its grade in geological reserves, complexity of deposit and the content of concomitant components, the form of appearance of useful components (chemical element, mineral, rock mass), presence of harmful impurities, uniqueness of raw materials;
- mining operating conditions, which determine the method and system of deposit development;
- technological properties of raw materials, optimal (in quality and cost) technological solutions of processing and beneficiation, depletion of ores, yield of concentrate(s), content of useful component(s) in concentrate, etc.;
- ecological conditions of deposit operation, assessment of the impact of current state of mining environment on the possibility of development, assessment of the impact of extractive activities on the environment, environmental costs;
- the amount of required investment, project costs for the development of deposit, capital investment (buildings, roads, mining, underground workings, concentrator, reclamation of disturbed lands, housing construction, etc.), total operating costs, operating costs per 1 ton of ore, costs for decommissioning, payment for special use of subsurface, payment for exploration work (exploration), deductions for repair and maintenance of roads, contributions to the innovation fund, depreciation of fixed assets, etc.;
- available infrastructure (roads, railways, power lines, etc.) and labour supply;
- degree of industrial development of deposit;
- annual production capacity (for ore, for relevant rocks, for rock mass), duration (LOM), ore extraction;
- concentrate price, annual profit from sales, gross profit, net profit;
- profitability of the project (unprofitable, low-profitable, medium-profitable, high-profitable);
- return on investment, payback period;
- liquidity (low-liquid, medium-liquid, highly liquid) established by the results of statistical analysis of mineral markets (demand, supply, prices);
- social and economic viability of projects;
- investment risk assessment;
- probability of assessment.

Regarding the assessment of risks and uncertainties of investments in exploration work, it this is carried out in accordance with domestic and international standards of assessment, it is based on statistical processing of initial data and stochastic modelling and should take into account the following main risk groups: geological, investment, financial, political, organizational, technological and others. The indicator of investment attractiveness takes into account availability of positive lines of evidences and the weight of each factor for the selected subsurface objects.

According to a certain list of classification and ranking features (which can be expanded and changed depending on the types of minerals) it is possible to model the aggregate indicator of "investment attractiveness", which takes into account availability of positive lines of evidences and weight of each factor for selected subsurface objects. That is, the mathematical substantiation and the method of determining the complex parameter of evaluation is foreseen, which takes into account the possibility, feasibility and profitability of different types of investments (short- or long-term).

3.3. Availability and Accessibility of Mineral Data of Ukraine

3.3.1. Geological Mapping Data

The current policy of Ukraine is to make the country more and more open to the western investors and research communities (Malyuk 2016). Recognising that access to geological information is important, especially in regard to potential for supplying raw minerals, the new procedures for availability of geological data was approved by the CMU (Resolution 2018). This affects all subsoil companies and investors by managing of private geological data and by streamlining the procedure for acquisition of state geological data. Also enhances transparency in the sector by creating catalogue of information on geological data which will be accessible online. Currently the process of amending the Code of Ukraine on Subsurface (Law 1999b) is in progress, which will affect the sublaws, such as mentioned one (Resolution 2018).

Geological mapping of Ukraine on the scale of 1:200,000 began in the late 1960s and a programme of mapping of the new generation of the State Geological Map-200 was launched in 2000. Each map sheet may be published in a set of up to 4 themes, including some or all of the following, in various combinations:

- Geological map
- Geological map of Quaternary or Pliocene-Quaternary formations
- Geological map of pre-Quaternary, pre-Cenozoic, pre-Paleogene or pre-Mesozoic units
- Geological map of crystalline basement
- Hydrogeological map
- Mineral resources and occurrences

New generation maps and descriptive memoirs are in the process of completion or have already been completed for more than 4/5 of the country (Fig. 3.2). Nine regional geological enterprises are engaged in the mapping, supported by more than six academic and industrial institutes. The work incorporates large volumes of field research, drilling, and analytical data.

The map sheets close to the western border of Ukraine or those that gave significant metallogenic importance are fully translated in English (see Fig. 3.2).

Each geological map of the given map sheet contains (Fig. 3.3):

- geological map in the scale 1:200 000
- geophysical maps (gravity and magnetic) in the scale 1:500 000
- auxiliary maps (tectonic, geomorphology, landmarks etc.) in the scale 1:500 000
- geological cross-section

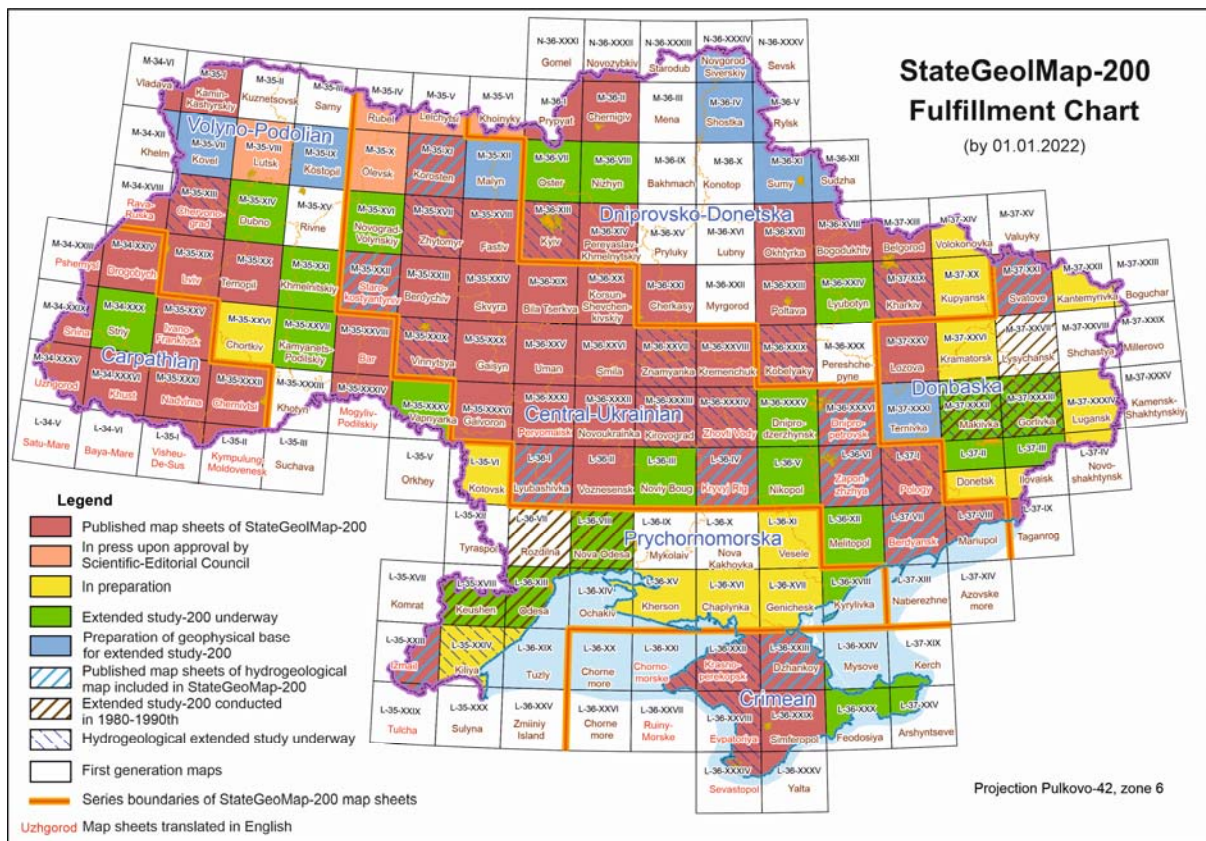


Fig. 3.2. Geological map sheets (may be combined where appropriate)

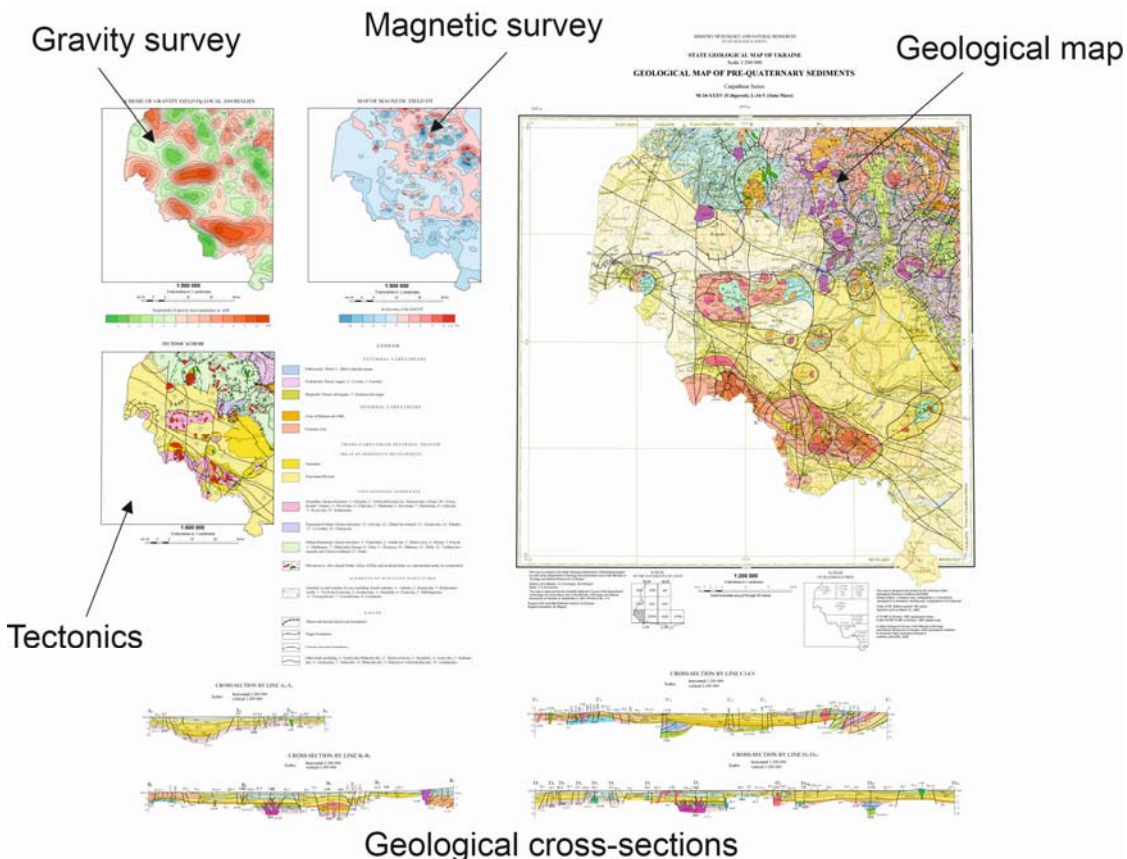


Fig. 3.3. Snapshot of one of the map sheets of the State Geological Map of Ukraine in the scale 1:200 000, map sheet M-34-XXXV (Uzhgorod), geological map of pre-Quaternary sediments (State Geological Map of Ukraine 2008)

Geophysical and geochemical data acquired by government agencies, either in Soviet times or subsequently, may be available through SRDE “Geoinform of Ukraine”.

The images below show low resolution gravity and aeromagnetic images of the Ukraine area from public domain global datasets.

3.3.2. Sources and Delivery of Geoscientific Data

The New Procedure (Resolution 2018) extends the scope of geological data to cover geochemical, hydrogeological, engineering-geological, geology-economical, technological, ecology-geological, geophysical, geographical, geodesic, aerospace, petrographic and paleontological information in hard copy and electronic form. It classifies geological data in the following categories:

- primary geological data – information or data obtained during subsoil use from exploration in the field, including specimens, samples, results of monitoring, usage and protection of subsoil; and
- secondary geological data – information or data saved in tangible or electronic form, obtained on all stages of geological exploration or from subsoil use from processing, interpretation and analysis of initial geological data.

The New Procedure envisages creation of a centralised catalogue of information on geological data maintained by the State Informational Geological Fund of Ukraine (Geoinform) in accordance with procedures approved by the Ministry of Ecology and Natural Resources.

All Information on geological data, irrespective of its ownership, must be provided to the Catalogue, including information on location of deposits or performance of works, name, type (initial or secondary), date of creation and owner of the geological information. Geoinform will also maintain records on the creation, acquisition, transfer of ownership or provision of the right to use geological data.

The New Procedure also required the creation of the State Depository of Geologic Information and Core Samples. Primary geological data owned by the state must be transferred to this depository.

Geological data can be provided to users, although this provision may be limited in accordance with (Law 1994a) and prohibited to companies that are subject to Ukrainian sanctions in accordance with the (Law 2014). Exporting geological data can be done according to Ukrainian law on foreign economic activities (Law 1991) and the Customs Code (Law 2012).

Geological data created or acquired at the expense of the state is owned by the state in accordance with the New Procedure. Access to the secondary geological information, which is a state ownership is free of charge, it must be published on the website of Geoinform in accordance with the New Procedure. Only while obtaining license, license holder is obliged to pay special fee as a compensation of state expenditures for geological works. This fee is 6% of the payment for the license.

Primary (unprocessed) geological information, which is state property, is also provided for viewing at its storage locations free of charge. Applicant has the right to make a digital copy of such geological information for processing or interpretation at his or her own expense. The digital image created as a result of making such a copy is the property of the state, and the right to (non-exclusive) use of the copy belongs to the applicant.

Primary geological information that is the State property, which is destroyed in the process of processing due to its physical properties (stone material), is provided to the applicant for research after compensation in advance the state's costs of obtaining it according to the fixed values determined by the regulation (Resolution 2022).

The draft law (Law 2021a) aimed to amend the Code of Ukraine on Subsurface (Law 1994b) has already been adopted in the 2nd reading by the Verkhovna Rada of Ukraine and is awaiting the signature of the President of Ukraine. This draft law envisages the creation of the Unified State Geoinformation System and the State Geological Portal, which will be the only official web-resource for providing information about geology and mining licenses in Ukraine. Since the beginning of Russia's war against Ukraine, however, the predecessor of this web portal has been closed to avoid Russian shelling of industrial targets, an access to the portal's resources is possible only for a limited number of people using special digital signature. Provision of geological information and access to available resources upon request is not allowed yet because Derzhgeonadra, as the administrator of geoinformation, which is state property, does not currently grant such permissions. Of course, this slows down investment, but for now it is the case. It is expected that after the end of the Russia's war, access to information will be restored and all databases will be available on the webservice www.nadra.gov.ua.

Specifically, it is foreseen that geological information is to be managed through the E-catalogue of geological information (metadata catalogue). The procedure for maintaining it is accepted, but this directory is currently empty. For 2023, the Derzhgeonadra has planned to allocate funds for conducting an inventory and filling with information on primary geological information by state-owned enterprises that are repositories of such information. Also, Geoinform was committed to place the metadata catalogue on the web portal in order to fill it with private owners through the special digital signature. That is, all these measures are to be implemented in the future whereas the first steps have already been undertaken.

The National geological mapping data were made available by Geoinform through an English-language digital portal "Mineral Resources of Ukraine" (<https://eng.minerals-ua.info>) jointly developed in 2017 with NGU, the Geological Survey of Norway, in the EIMIDA (European Integration of Mineral Data) project, funded by the MFA, the Ministry of Foreign Affairs of Norway.

Ukraine plans to provide standardized and harmonized, INSPIRE-compliant mineral data to the pan-European digital platforms on the whole range of minerals, with a special emphasis on strategic minerals. This is being achieved by permanent participation of SRDE "Geoinform of Ukraine" in various pan-European research projects initiated by the EuroGeoSurveys, the Geological Surveys of Europe. These

products already include pan-European digital portals developed in the context of several EU-funded projects such as Minerals4EU (2015; <http://minerals4eu.brgm-rec.fr>), ProSUM (2017; www.prosumproject.eu), GeoERA (2021; <https://geoera.eu>), and GSEU Project (2022-2027) devoted to the establishing the Geological Service for Europe which will be managing the common digital portal EGDI (European Geological Data Infrastructure, www.europe-geology.eu) applying the FAIR (Findable, Accessible, Interoperable, Reusable) data principles.

The European integration and geological data management are also expected to be accelerated through the recently established the EU-UA Strategic Partnership on Critical Raw Materials and Batteries, in follow-up an Action 9 of the Critical Raw Materials action plan (Communication from the Commission 2020), initiated with an MoU signed by the Vice-President of the European Commission Maroš Šefčovič and Prime Minister of Ukraine Denys Shmyhal at a high-level event held in Kyiv, Ukraine, on July 13, 2021 (https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3633). Recently at the European Commission Raw Materials Week the MoU had been signed between Derzhgeonadra and EBRD to support the digital modernization of the geological sector of Ukraine. The EBRD project, in its essence, should significantly move the issues of accessing and availability of geological information by creating convenient English-language geoinformation search engines using GIS, filling the information catalog, displaying geospatial data of unlicensed deposits and occurrences.

The draft law (Law 2021a) determined that primary and secondary geological information which is a state property is free of charge in Ukraine. Previously only secondary information was free. After taking into effect this draft law, all sublaws, such as (Resolution 2018) will be brought in line with the Code of Ukraine on Subsurface (Law 1994b).

According to the New Procedure (Resolution 2018), geological data created or acquired with the funds of companies and individuals is owned by these entities and SSGSU consent is no longer needed for transfer of private geological data. The only requirement is that the SSGSU be sent a notice no later than ten days before it is to take place.

Subsoil use agreements that are part of special permits for subsoil usage (“Special Permits”) include an obligation on the subsoil user to notify the SSGSU regarding creation, acquisition, transfer of ownership or provision of the right to use geological data in accordance with the New Procedure.

The New Procedure also requires that all privately owned secondary geological data in relation to the subsoil areas for which a Special Permit was terminated or expired be disclosed on the website of its owner or website of Geoinform within 3 years after any such event, and that the primary geological data owned by the subsoil user shall be transferred to the state.

This book is itself intended to be an additional source of geological information for modernising, updating and putting into English geo-information on Ukraine’s mineral potential. In parallel, re-writing of the Ukrainian Mining Law (The Code of Ukraine on Subsurface, Law 1994b) is underway, although this book was not linked to that

endeavour. As noted above, the efforts are being undertaken to make geo-information freely available on the Geoinform web site.

Publication of scientific papers, e.g. (Mykhailov et al. 2022) on minerals for green technologies and (Veklych 2019) on Quaternary formations, together with planned high-level “teaser” brochures on groups of Ukraine’s mineral commodities, will also provide valuable introductions to potential investors. One can also think about organising an investor conference to which mining companies and those in the financial / investment sectors would be invited, where they could hear a little about the geology, something about the infrastructure and laws and a lot about the investment possibilities in Ukraine.

So, promoting Ukrainian minerals is the question of timing for maximum impact and benefit. The war in Ukraine will eventually end, but no one knows when. If the promotion phase is left until after the war ends, it might be too late to have effect. On the other hand, if these efforts are made too early, they could be too theoretical and impractical, although mining and investment companies do need to prepare their corporate plans some years in advance.

3.4. Derivation of a Ranking Method for Relative Investment Attractiveness with Rules of Thumb

Above in Chapter 3.2 a long list of technical and economic criteria is given for geological and economic assessment of deposits (Mykhailov et al. 2017; Mykhailov, Kurylo 2017). For many preliminary decisions a much simpler way can be chosen. Further above the term “near-ology” was introduced. This term can also be used for the procedure to reach the right investment or go-ahead decisions by stepwise more detailed researches and investigations. In the following, a tool based on rules of thumb will be described to build up a merit order of projects, a relative ranking for projects at very different stages of knowledge.

To develop a comparable scale for relative investment attractiveness, to recognize future potential and to be able to apply the UNFC classification system with the three axes E Environmental-socio-economic viability, F Technical feasibility and G Degree of confidence a tool has to be designed to compare deposits, possible deposits and the potential of occurrences at very different stages of prospecting, exploration and investigation. This means mineral accumulations of potential economic interest at various stages of knowledge have to be brought to the same denominator. This can only be an economic evaluation resulting in certain characteristic parameters such as net present value (NPV), internal rate of return (IRR) or payback period (Wellmer et al. 2008). Whereas NPV and IRR are dynamic methods of economic evaluation, taking the time value of money into account, the payback period is a static method. In establishing a list of comparable investment attractiveness, a merit order, of course, all relevant commodities have to be evaluated with identical metal prices; money values for investment and operating costs have to be converted to the same time values, real prices and money values for a specific year, meaning inflation effects have to be corrected for.

The stages of an economic evaluation are shown in Fig. 3,4. This flow sheet is as valid for a deposit in the feasibility stage, where every cost data are to be researched in detail ab ovo, as for a prospect, where one has to work with many rules of thumb and assumptions. In this chapter suitable rules of thumbs helpful to come to a relative ranking of attractiveness of projects in various stages of knowledge will be described.

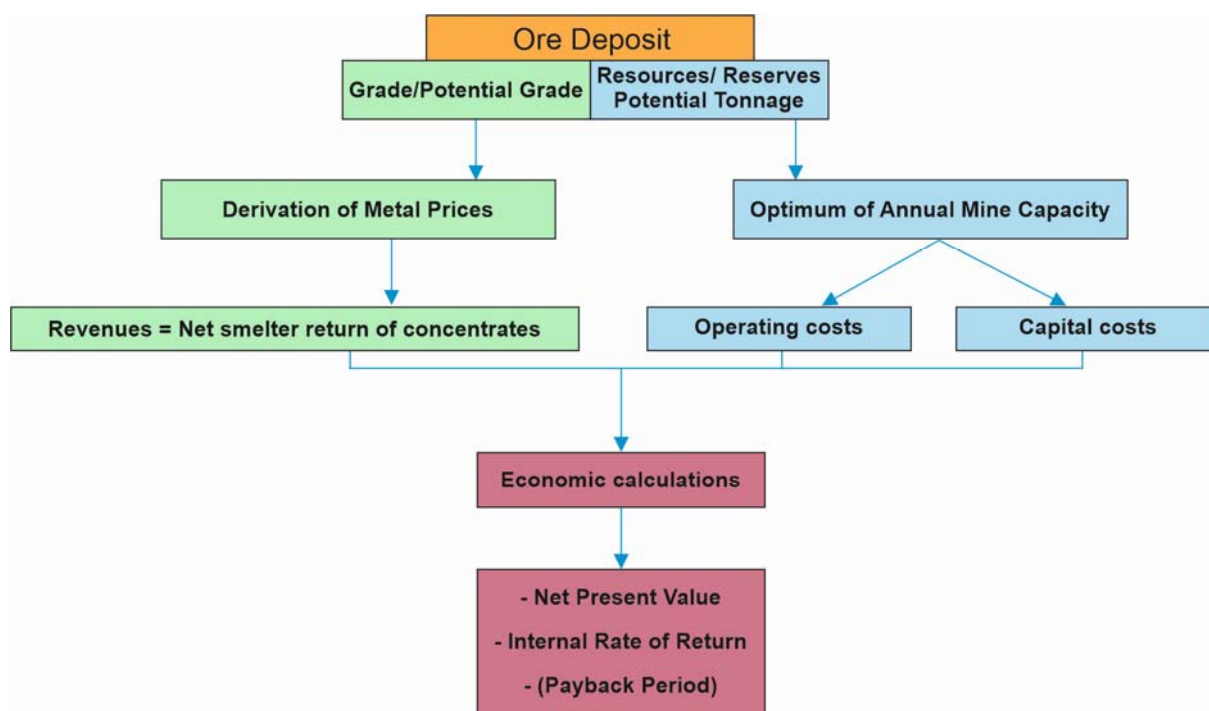


Fig. 3.4. Flowsheet of an economic evaluation of a mineral property (modified after Wellmer et al. 2008).

Derivation of cost data ab ovo means for example, costs for a shaft have be based on a quotation by a shaft sinking contractor, while mining costs for an open pit have to be derived from the investment costs of the equipment, the costs of labor, fuel, explosives, etc., the efficiency of blasting , hauling etc. In earlier stages of estimation one works with analogue costs of similar operations.

The starting points always are the grade and tonnages of reserves or resource. The estimation of grade and tonnage requires good geological judgement. In the feasibility stage there are strict guidelines in the Western World to determine reserves, for example the CRIRSCO or JORC-codes (e.g. JORC 2012, CRIRSCO 2019). To qualify as reserves these data have to be estimated with a relatively high accuracy with the help of statistical and geostatistical methods by a “competent person” (e.g. Wells 2017). In the prospecting and exploration stages for a relative ranking of investment attractiveness required is a vision to recognize a potential, i.e., a knack for possible grade or grade tenor and possible tonnages.

From grade and grade tenor data the necessary information for the revenues can be derived, from the tonnage data the necessary information for costs.

3.4.1. Revenue Data

First of all a *raw material price* has to be derived. For this purpose long-term price developments of real prices (meaning nominal prices corrected for inflation effects with the help of price indices (Wellmer et al. 2008, p.66, 225) have to be examined and long-term trends and price plateaus have to be recognized. Since 1918 or the end of World War I the real prices of the main metals did not rise in the long-term (Buchholz et. al. 2020, Wellmer 2022a). They fluctuated between lower and upper benchmarks (Fig. 3,5). Needless to say again that all projects concerning a certain commodity in a list of relative investment attractiveness have to be evaluated with the same assumed price.

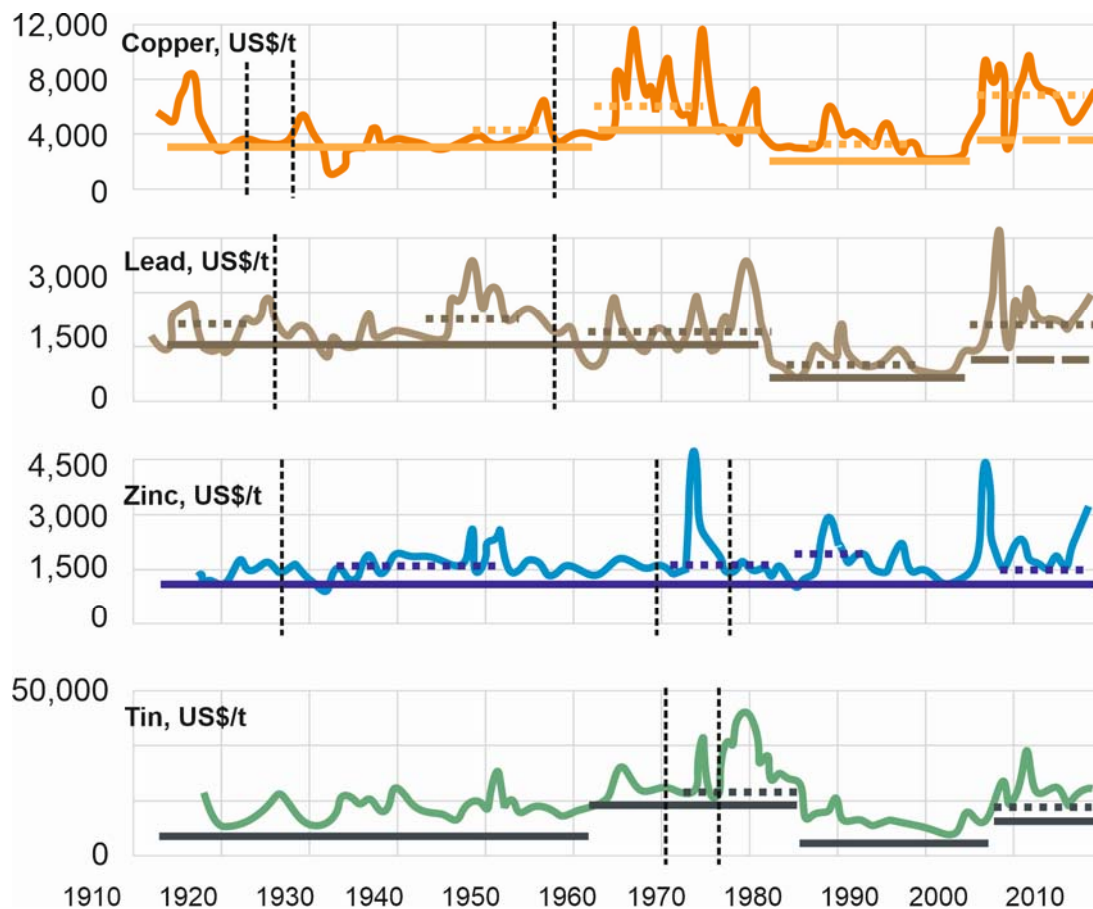


Fig. 3.5. Base metals: real prices, lower and upper real price benchmarks, and real total cash costs solid line for real price, solid horizontal line for lower real price benchmark, dashed line for upper real price benchmark, grey line for real total cash costs, real prices and cash costs deflated by using US Producer Price Index PPI, basis 2017, vertical dashed line indicates break in price specifications (modified after Buchholz et al. 2020)

Next the *revenue* has to be calculated. For certain metals like iron ore or tungsten unit prices are quoted, meaning the price for 1% metal in the concentrate. For base metals, however, the net smelter return (NSR) has to be calculated, that is the share for the mine of the sale out of the final product, a metal bar. For such NSR calculations formulae are used (Wellmer et al. 2008, p.72). Though for rule of thumb

calculations they can, however, be simplified. In the NSR formula the four variables concentrate grade, treatment charge, treatment losses and refining charge are replaced by one factor, the NF-factor (Table 1), multiplied with the metal price and the assumed recovery in the mill. So the rule of thumb calculation of NSR is as follows (Wellmer et al. 2008, p. 74):

$$NSR = \text{grade of the ore} \times \text{mill recovery} \times \text{NF-factor} \times \text{metal price} \quad (1)$$

Table 3.2. NF-factors (Wellmer et al. 2008, p.75)

Element	Percentage of net smelter return for mine = NF-factor	Recovery in the mill (%)
copper	65 (Europe) 75 (Pacific Basin)	90
zinc	50	90
lead	65	90
nickel	65	80
tin	94	60
gold (in copper mines)	95	80
gold (in gold mines, not heap leach operation)	98	90
gold (heap leach operation)	98	40
silver	95	80

3.4.2. Cost Data

Cost data for these rule of thumb calculations are analogue data derived from similar operations and adapted to the chosen capacity. Here the economics of scale have to be taken into account for up- and down-scaling. The operating and specific investment costs decrease with increasing capacity. Therefore, the determination of the right capacity, and thereby the life time of the operation, is a very crucial step at the beginning of estimating costs.

As an example for the economics of scale: if the capacity doubles, the investment costs would only increase by the factor of 1.5 (O'Hara 1980, Mular 1982, Wellmer et al. 2008, p.99), which will be discussed further down. Normally the decreasing operating costs and specific investment costs as a function of capacity or daily throughput are described with a power curve:

$$y = a \cdot cp^b \quad (2)$$

where a and b are coefficients, y stands for the operating or specific or absolute investment costs and cp is the mine capacity.

Therefore, an important step in the rule of thumb calculations is the choice of the right capacity cp .

Mine capacity. In 1977 the experienced Canadian mining engineer Hugh Taylor proposed a rule of thumb for mine capacities based on a sample of 30 mines (Taylor 1977). Taylor's rule, as it came to be known, was examined by Wellmer (1979, 1981) and McSpadden and Schaap (1984) whose results were in general agreement with

Taylor. Wellmer (1979, 1981) examined Canadian base-metal mines at the stage of investment decision, McSpadden and Schaap (1984) porphyry copper deposits worldwide. The US Geological Survey (USGS) investigated the use of Taylor's Rule for open-pit gold-silver and open-pit copper mining and heap-leach operations in the US and underground mining operations of massive sulphide deposits globally (Singer, Menzies, Long 1998, Long, Singer 2001). These studies were done on a limited number of cases, whereas Long (from the US Geological Survey) continued with a principle investigation, based on a much larger sample of mines: 796 open pit/underground operations and 400 underground mines (Long 2009, 2016). He derived at two formulae, one for underground mining and one for such bulk mining operations, being either normal open pits or underground block caving. Long's formulae (3) and (4) were critically examined in 2019 by Wellmer and Drobe (2019) who found that they can still be used and do not have to be adapted for technology changes for example.

Long's relationships between expected reserves/resources res_{exp} and daily capacity cp are:

$$\text{Open pit and block caving: } tonnes_{day} = cp_{op} = 0.123 \times res_{exp}^{0.65}. \quad (3)$$

$$\text{Underground: } tonnes_{day} = cp_{ug} = 0.297 \times res_{exp}^{0.56}. \quad (4)$$

Table 2 shows the suggested mine capacities for a range of tonnages from 0.1 million tonnes to 1 billion tonnes.

Table 3.3. Suggested mine capacities and ranges after Long (2009) and Wellmer, Drobe (2019)

Expected reserves/resources in million tonnes	Open pit+ block caving, daily capacity t/day	Open pit+ block caving: range, daily capacity t/day	Underground, daily capacity t/day	Underground: range, daily capacity t/day
0.1	220	200-250	180	150-200
0.5	620	600-700	460	450-500
1.0	980	900-1,000	680	650-750
5	2,800	2,700-2,900	1,700	1,600-1,800
10	4,400	4,300-4,500	2,500	2,400-2,600
25	8,000	7,900-8,100	4,100	4,000-4,300
50	12,400	12,300-12,500	6,100	6,000-6,200
100	19,500	18,000-21,000	9,000	7,500-10,000
250	35,000	33,000-37,000	15,000	13,500-16,500
350	44,000	42,000-46,000	18,000	16,500-20,000
500	55,000	53,000-57,000	22,000	20,000-24,000
700	70,000	68,000-72,000	27,000	25,000-29,000
1,000	87,000	85,000-90,000	33,000	31,000-35,000

Operating costs. Figs. 3 top and bottom show examples of typical power curves, here for underground lead-zinc mines (a, top) and open pit copper mines, excluding heap leach operations (b, bottom). From the derived power curves

$$y = 7.404 x^{-0.59} \quad (5)$$

for lead-zinc underground mines and

$$y = 2.068 x^{-0.477} \quad (6)$$

for copper open pit, excluding heap leaching,

whereby y are the operating cost and x the mine capacity, the operating cost can be calculated with the prior determination of the daily capacity, as shown above.

A comparison of the underground and the open pit example (Fig. 3,6) shows that the open pit curve flattens relatively soon, reflecting the observation that in open pit the operating costs per ton moved are rather constant. One just adds more trucks and shovels to increase capacity.

This opens the possibility to estimate the costs with rule of thumb more directly than with a power curve: With the waste to ore ratio and thereby the knowledge of total tonnes moved, the mining cost can be determined relatively accurately. There still remains the task of determining the milling cost separately. Again this can be done using power curves with data of existing operations. Knowledgeable mineralogists however, experienced in the science of geometallurgy (Hoal, Frenzel 2022, Wellmer 2022b) can estimate the milling costs with reasonable accuracy more directly. With examination of thin sections to determine the intergrowth and grain size, which has to be liberated, and with simple grinding and mill tests to determine the hardness of the ore, the Bond mill work index, one can find out, what the energy requirement, i.e., the major cost factor for crushing and grinding, is to achieve a reasonable recovery (Mular 1982, Wellmer et al. 2008, p. 104/105).

For total operating costs: To the combined mining and milling costs 25% have to be added for further technical costs, technical expenses and administration, the overheads (Wellmer et al. 2008, p. 104).

Investment costs. Whereas for operating costs in suitable data banks one can find in most cases enough comparable operations with cost data in one year or at least within a narrow time span to construct a power curve, this is more difficult for investment costs. Here another approach can be used: the 0.6 rule, first described by Mular (1978). According to Noakes (1993) the result of applying the 0.6 rule can be expected to have a margin of error of about 30%. The 0.6 rule is:

$$\frac{I_1}{I_2} = \left(\frac{cp_1}{cp_2} \right)^{0.6} \quad (7)$$

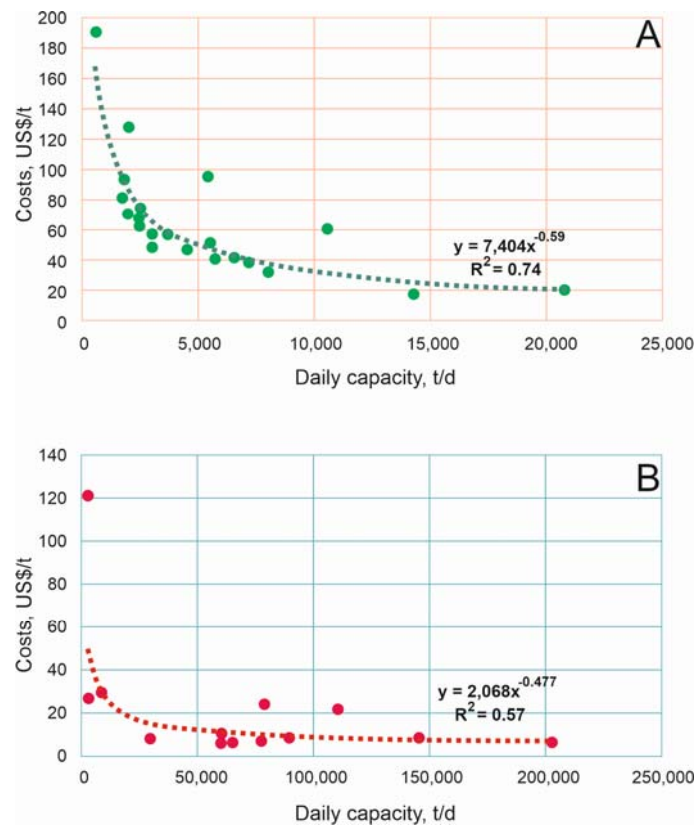


Fig. 3.6. Operating cost as a function of daily production capacity cp : A – for underground lead-zinc mines, B – for copper open pit mines, excluding heap leach operations (data source: (BGR 2018); modified after (Wellmer, Drobe 2019))

I_1 is the investment cost for capacity cp_1 , I_2 the investment cost for capacity cp_2 (Wellmer et al. 2008, p.99). Before one uses this formula one has to inflate the historical investment cost I_2 , bringing the money values to a common denominator, which is always the money value in an specified year. As stressed before, in a relative ranking of attractiveness all projects have to be evaluated on a money value based on the same year. For the adjustment of capital costs for inflation, capital costs indices are used. Inflation indices are always relative information. The absolute value has no meaning. An arbitrarily chosen year is set at 100 and the following years are related to the reference year. One suitable index for investment costs is for example the Marshall and Swift Mine and Mill Index (Wellmer et al. 2008, p. 91, 220). If one wants to construct one's own inflation index for capital costs as a rule of thumb one can construct it out from 55% wage index, 35% material cost index and 10% unchanged, taking into account productivity improvements and cost decreases arising from continuing technical innovations (Wellmer et al. 2008, p. 92).

The formula for calculating the inflation adjusted capital cost is:

$$\text{investment cost (today)} = \text{investment cost in year } y \times \frac{\text{index today}}{\text{cost index in year } y} \quad (8)$$

3.4.3. Economic Calculations

In economic calculations the yearly cash flows CF of a project are compared with the investment cost I . For the cash flow CF only real money streams are considered (no depreciation, which is an instrument to calculate taxes) (see cash flow box in Fig. 3.7).

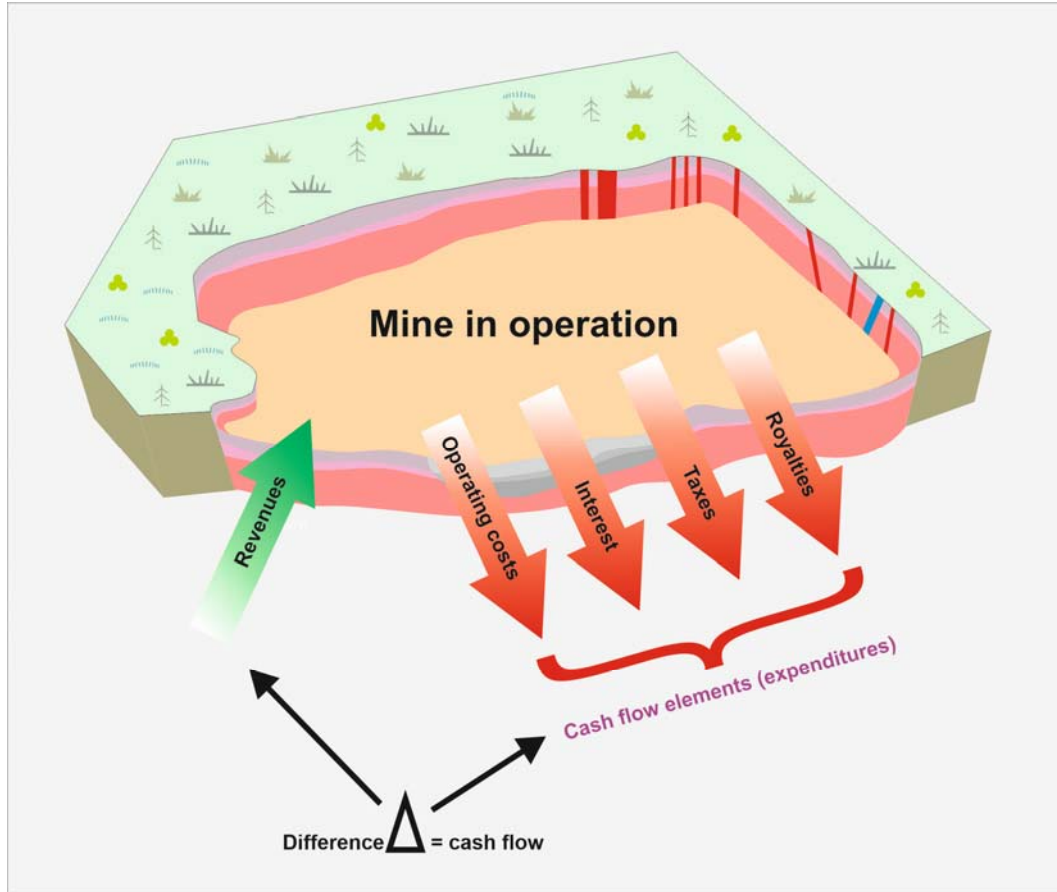


Fig. 3.7. Cash Flow box (modified after Wellmer et al. 2008, p. 127)

In standard economic calculations the time value of money is taken into account. Therefore, the economic calculations are called dynamic. Due to inflation and interest earned the mean the time value of money for example 10 years ago is different from the time value today, the present value. These time values can be accounted for by discounting factors q^{-n} (Wellmer et al. 2008, pp. 126, 225), whereby i is the chosen interest rate and n the number of years.

$$\frac{1}{(1+i)} = (1+i)^{-1} = q^{-1} \quad (9)$$

The standard economic method is the net present value calculation (NPV) where from the sum of the discounted net annual cash flows over the whole project life CF_n , the investment costs I are deducted (Wellmer et al. 2008, p. 130).

$$NPV(N) = \sum_{n=1}^N (CF \times q_j^{-n}) - I \quad (10)$$

The second method is the determined internal rate of return (*IRR*). This is the discounting rate for which the sums of the net discounted cash flows just equal the investment (Wellmer et al. 2008, p. 127, 138).

$$\sum_{n=1}^N (CF \times q_j^{-n}) = I \quad (11)$$

A third method is to calculate the payback period. The payback period is the number of years it takes to pay back the investment from the net cash flow. Normally the undiscounted cash flows are taken and, therefore, the method is considered as static, not dynamic method.

Whereas for feasibility studies the preferred method is the NPV determination, the *IRR* method offers shortcuts for rule of thumb calculations to quickly come to a relative ranking for the purpose of establishing a merit order of attractiveness with projects at very different stages of knowledge.

3.4.4. The Final Establishment of a Merit Order of Attractiveness for Projects with Very Different Stages of Knowledge

To be able to apply shortcuts we only have to make sure that the conditions are the same for all projects considered and thus we are able to work with constant cash flows. Therefore we consider an investment only with equity, no debt financing. Then we can avoid yearly changing debt payments and consequently yearly changing interest payments. Working with equal cash flows makes calculations rather simple. The CF_n in equation (11) then is constant and the discounting factors q_j^{-n} in equation (11) are the members of a declining geometrical sequence. The sum of this geometrical sequence is called annuity present value factor b_n and can be summarized by:

$$b_n = \frac{q^n - 1}{q^n \times (q - 1)} \quad (12)$$

This means from the ratio of investment I and the constant net cash flow CF over the years the annuity present value factor b_n can be calculated:

$$b_n = \frac{I}{CF} \quad (13)$$

With these annuity present value factors b_n one can go into the diagram of Fig. 3,8 to determine the interest rate i for the internal rate of return (*IRR*) as a function of the lifetime of the project. These interest rates are then the basis for the ranking of relative attractiveness, the merit order.

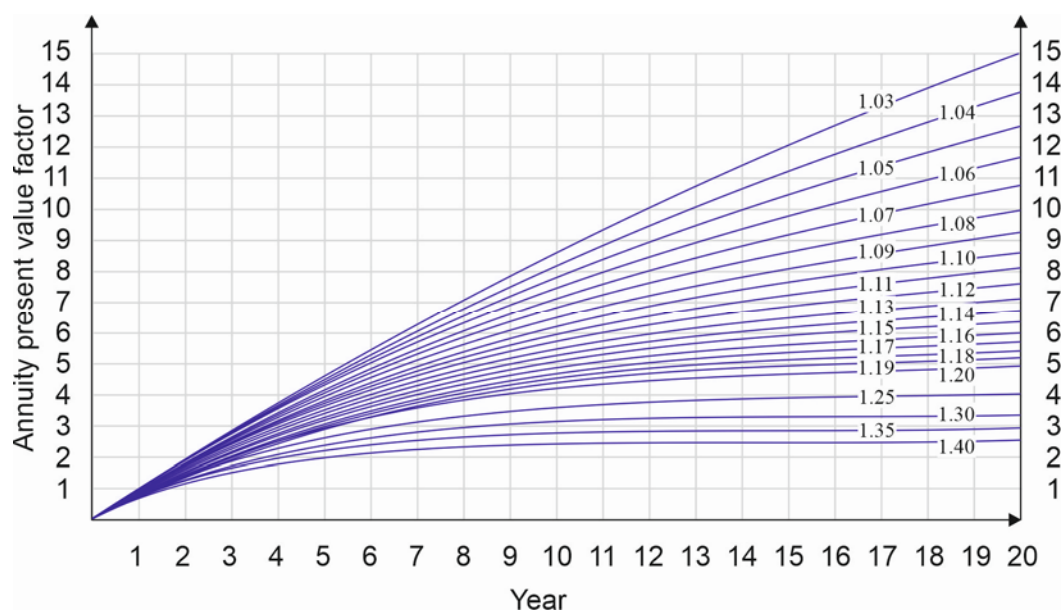


Fig. 3.8. Annuity present value factors b_n . The x-axis is the life time of the project in years.

If the projects have approximately the same lifetime one can also just work with the I/CF-ratio as criterion to establish a ranking list. There is a rule of thumb in some mining companies that an attractive project should not have as a first approach an I/CF-ratio exceeding 3 (Götz 2012, Wellmer, Drobe 2019, Wellmer et al. 2008, p.143).

3.5. From Prospective Geology to an Active Mine

Geology that indicates resource prospectivity capable of producing a positive return on investment, taking into account the factors described in section 3.3 above, is absolutely necessary, but not sufficient. This section takes the reader through the various processes that are commonly experienced on the road from prospective geology to active mining, and suggests how they might be applied in Ukraine.

The major mining companies spend large amounts of money on exploration. In the case of Rio Tinto, for example, whose net cash generated from operating activities was \$25.3bn in 2021, exploration and evaluation spend was \$726million (Rio Tinto 2021). This is a large number in absolute terms, but is less than 3% of net operating turnover. Rio Tinto is typical of the so-called Majors in relying heavily, for new projects, on the much broader spread of exploration work carried out by junior and mid-size exploration companies such that more and more grass roots activities are done by junior companies and they are also the predominant discoverers. Schodde points out (Schodde 2019) that in the period since 2010, in the “Western World”, 65% of all new discoveries were made by junior explorers. Interestingly, during the period 1958 to 1973 in Canada, the major companies spent 44% of the total exploration expenditure, but made only 15% of the discoveries, according to Wellmer, based on his analysis of data from the Economic Geology Jubilee Volume of 1981 (Wellmer 2022c). Of course, the differentiation between juniors, mid-caps and majors is not clear-cut, and an early stage discovery by a junior company can be

sold to a mid-tier company who takes the exploration work further, before selling the project, in whole or in part, to a larger operator, which takes it into production.

Furthermore, analysis of the exploration work carried out by the Majors indicates that it occurs mainly in their established mining areas where the geological, commercial and reputational risks are lower, or at least better understood, rather than in new, or frontier, locations.

The structure can be simplified as shown in Figure 3.9 which depicts the size of the area of interest along the horizontal axis and the layers of involvement vertically downwards. Thus the national geological survey organisations cover the greatest areas by size and generate the geological infrastructural data, such as geological maps, geochemical surveys and 3D models that are of interest to junior exploration companies, and soon to the smallest geographical area of an operating mine. As one progresses down the triangle towards the mine, the costs increase dramatically, as does the risk of a positive financial return on expenditure. Put simply, making geological maps is relatively cheap and low risk; carrying out greenfield exploration in parts of the mapped area can be done for a few million dollars at a higher level of risk, but opening a mine can cost hundreds of millions of dollars and carries huge risks both geologically and politically.

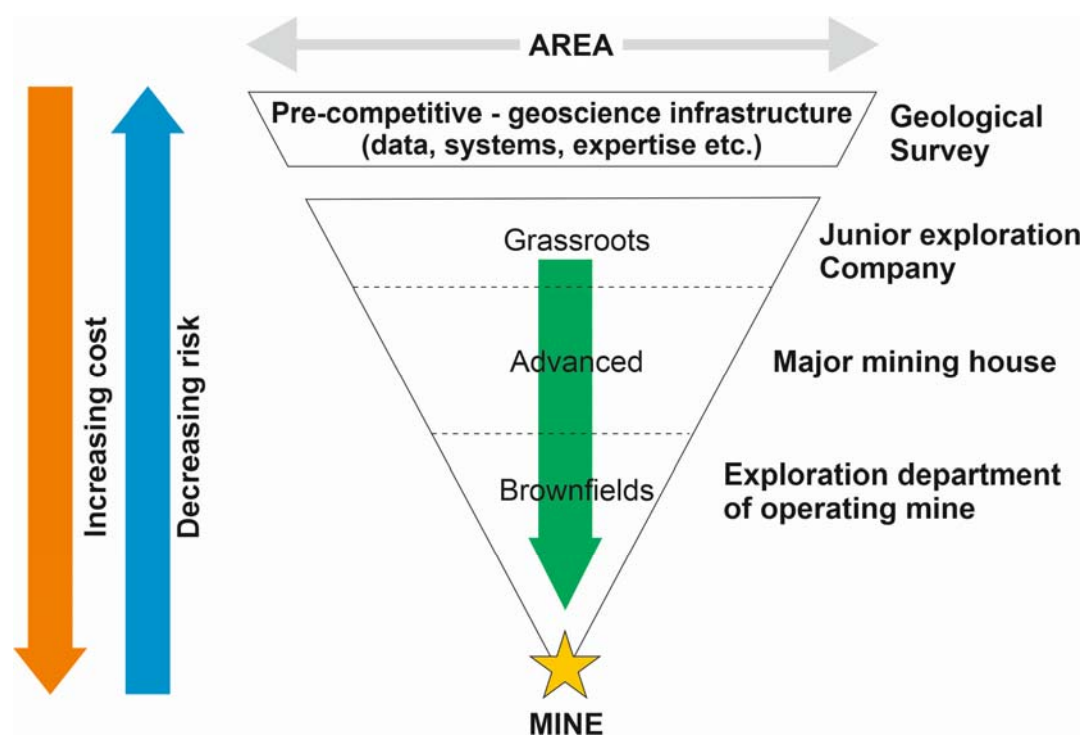


Fig. 3.9. Schematic of the mineral exploration value chain

Many projects fail to proceed through the different stages outlined above, for reasons of geology and / or the lack of finance. Given the importance of the junior sector in starting off the chain of events that might eventually lead to an operating mine, it is useful to examine in some detail the process that underpins this sector.

Most junior companies are set up and run by entrepreneurs who focus on a particular country, region or commodity in which they have knowledge or

experience. Some are attracted by popularity or opportunity, for example the recent high interest in critical minerals and battery metals; others prefer to look in as-yet underexplored regions. In either event, juniors will be interested in projects already started by others, and relinquished for reasons of, usually, running out of funds or failing to properly understand the geology in their licensed areas. Juniors will depend on obtaining the infrastructural geological data from the geological survey and, if available, from historical operators of the exploration area, but fairly quickly the junior company will need to raise funds to pay for the trenching, drilling, geophysics and laboratory work that is thought necessary.

At this stage, the company must turn to investors, either through private equity or a listing on a public stock market. In so doing, it is necessary to set out, usually in a prospectus, the investment case, in terms aimed predominantly at non-scientists such as high net worth individuals and fund managers. In so doing, the company must show, in addition to the prospective geological and market attractiveness of its intended mineral discoveries:

- That it has a competent and reliable management team, preferably demonstrated by good reputations in running previously successful companies in the same, or related, sectors.
- That it has security of tenure on its licensed areas that are unlikely to be appropriated or confiscated by the State in the event of a change in the political situation.
- That there is in place a mining law and other regulations that are fair and balanced to both the State and the investor, for example in allowing the import and export of profits and commodities without onerous tax penalties.
- That the country in which the exploration takes place can supply reasonably reliable services such as water, power, road or rail access to the licensed areas, has physical security and that suitably qualified and reliable local staff can be employed.
- That the country complies with international ESG (environment, social, governance) standards, in particular the absence of corruption in accordance with, for example, the UK's anti-bribery laws and the US Dodd-Frank Act.

Many of these features are encapsulated in international indices of mining attractiveness maintained by bodies such as the Fraser Institute (Fraser Institute 2020), with the inevitable result that it is easier to raise funds for projects that take place adjacent to existing and successful projects in established mining areas – giving a different meaning to the term “near-ology” used in section 3.3.

It is beyond the scope of this book to discuss these non-geological criteria of mining attractiveness as they apply to Ukraine, but it is necessary to address them in any consideration of mining promotion.

Noting that junior exploration is usually the starting layer for mining sector development, building on the State run infrastructure foundation of its geological survey, successful growth takes place when a junior project can demonstrate a viable resource and is able to sell its project to a mid-cap or even to a major company, making a capital gain in the process and returning part of this gain to its investors.

The return on investment can be significant in the event of a good discovery, ten-fold or more. But the failure rate is high, so many fund managers choose to spread their investment across many junior companies, operating in several countries and interested in different commodities. Anecdotally, an investment portfolio might go into a dozen juniors in the expectation that ten will fail but the two who succeed will generate order-of-magnitude returns.

As the projects move along the value chain towards an operating mine, the criteria for investment risk reduction do not diminish. Mid-cap companies must pay attention to their fluctuating share prices and will quickly abandon, and write off losses, on projects that are judged by the market not to be an asset, whether that is because of disappointing geological results or for non-scientific reasons. In the case of majors, a few errant exploration projects are unlikely to make much difference to share prices but executives are often very sensitive to the risk of reputational damage, so projects that might compromise health and safety or environmental protection are likely to be shut down without delay.

In summary, it is naive to assume that the presence of a mineral resource will automatically or quickly result in its exploitation unless several other factors are also in place; in particular the criteria that underpin positive investment decisions, many of which are unscientific or even logical.

3.6. Ranking of Mineral Resource Base of Ukraine by Investment Attractiveness

As a result of research, a preliminary assessment of the investment attractiveness of mineral resources for all types of minerals has been undertaken for the first time in Ukraine, which will serve as a basis for investment engagement. Attracting such investments is of great economic importance, and is a vital condition for further development of our country's economy and its defence capabilities.

In the first approximation, the investment attractiveness of Ukrainian strategic minerals can be assessed as follows (Table 3.2).

For individual deposits and occurrences, it is useful to present the results of the investment attractiveness assessment in the form of certificates of investment project, which contain its name and purpose, form of ownership, level of readiness of the investment project, license and other special documents, communications (electrification, gasification, water and sewerage), list of existing machinery, equipment, general condition (machinery, equipment, enterprises in general), number of employees, market position (local, regional), total required investments, method of attracting investments (financial investments, provision of credit resources), payback period of the project and its profitability.

Table 3.2 Investment attractiveness of the main strategic mineral occurrences of Ukraine

Types of raw materials	Examples of deposits (occurrences)
Traditional class: high level of investment attractiveness, low risk of investment ($\leq 30\%$), high competition	
Metallic minerals	
Iron	Inguletske, Valyavkynske, Novokryvorizke
Manganese	Nikopolske, Velykotokmatske, Fedorivske
Titanium	Malyshevske, Irshanske, Stremygorodske
Uranium	Vatutynske, Novokostyantynivske, Severynivske
Non-metallic minerals	
Kaolin	Glukhovetske, Turbivske, Velykogodomynetske
Foundry sands	Gusarivske, Bantyshivske, Chasiv-Yarske,
Building and facing stones	Golovynske, Lyznytske, Tokivske
Refractory clay	Chasiv-Yarske, Novoraiske, Veselivske
Highly promising class: high level investment attractiveness, low investment risks ($\leq 30\%$), medium competition	
Metallic minerals	
Rare earths	Novopoltavske, Mazurivske, Azovske
Zirconium and hafnium	Malyshevske, Tarasivske, Yastrubetske
Lithium	Shevchenkivske, Polokhivske, Stankuvatske
Scandium	Zhovtorichenske
Germanium	Coal of Donbas, Malobiganske
Non-metallic minerals	
Graphite	Zavallivske, Petrivske, Balakhivske
Potassium salts	Stebnytske, Kalush-Golynske
Abrasive raw material (garnet)	Slobidske, Ivanivske, Zavallivske, Loznenske
Quartz raw material	Gusarivske, Avdiivske, Velykoglibovytske
Piezo-optical raw materials (piezo quartz)	Volodarsk-Volynske
Promising class: intermediate level investment attractiveness, average investment risks (30-50%), low competition	
Metallic minerals	
Nickel and cobalt	Tarnuvatske, Devladiivske
Chrome	Kapitanivske, Lypovenkivske
Aluminium	Vysokopilske, Pivdenonikopolske, Biganske
Copper	Zhyrychi, Rafalivske, Prutivske
Tantalum and niobium	Mazurivske, Novopoltavske
Beryllium	Perzhanske
Gold	Sergiivske, Klyntsivske, Muzhyivske, Saulyak
Non-metallic minerals	
Phosphorites	Ratnivske, Osykivske, Zhvanske
Apatite	Stremygorodske, Novopoltavske
Fluorspar (fluorite)	Bakhtynske, Pokrovo-Kyreivske
Glauconite	Karachaiivske, Adamivske, Verbske
Flux limestones and dolomites	Olenivske, Novotroitske, Stilske, Karakubsk
Limestones for the sugar industry	Zamok, Lysogirka
Bentonite clays	Cherkaske, Kishtynske
Feldspar raw materials	Polonno-Baranivske, Yeliseivske, Andriivske
Stone-coloured raw materials	Kalyusyk, Prelutske, Beshuyske

Types of raw materials	Examples of deposits (occurrences)
With unclear prospects: low level investment attractiveness, high investment risks ($\geq 50\%$), no competition	
Metallic minerals	
Vanadium	Stremygorodske, Torchynske, Fedorivske
Lead and zinc	Beregivske, Biganske, Muzhyivske, Bilyaivske
Tungsten	Selishchanskiy, Kocherivskiy
Molybdenum	Verbinskiy, East Sergiivskiy
PGM	Prutivskiy, Zaliznyakivskiy, Kamenskiy
Strontium	Novopoltavske
Magnesium	Kalush-Golynske, Stebnytske, Zaturynske
Arsenic	Mykytivske, Kostiantynivske, Klyntsivske
Rubidium and cesium	Zhovtorichenske, Stankuvatske, Polokhivske
Non-metallic minerals	
Baryte	Beregivske
Boron	Bulganatske, Tarkhanske
Dawsonite	Kindrativska, Slovyanska
Bromine and iodine	Sivaske, Sasyk-Sivash
Mineral sorbents	Sokirnytske, Karadazke
High-aluminium raw materials	Dragunsk, Mariupolske, Perzhanske
Raw materials for mineral paints	Gigant Mine, Yasnopilske, Karachaiivske
Fluorine	Stremygorodske, Novopoltavske
Sulphur	Truskavetske

CHAPTER 4. METALLIC MINERALS

Taking into account the statements in Chapter 3, the degree of investment potential of metallic minerals may be divided into four groups:

- traditional, those which have been intensively developed in Ukraine for a long time, have significant proven reserves, and contribute significantly to the State budget (e.g., iron, manganese, titanium and uranium);
- highly promising, those occurrences with significant reserves or resources, but are not yet developed or alternatively, developed (e.g., rare and rare earth elements: rare earths, zirconium and hafnium, lithium, scandium and germanium);
- potential prospects, those reserves or resources not yet properly defined, so the certainty of their development is undetermined (e.g., nickel, cobalt, chromium, aluminium, copper, tantalum and niobium, beryllium and gold);
- those of uncertain prospects, occurrences and small deposits whose scale does not suggest a significant resource (e.g., vanadium, lead, zinc, tungsten, molybdenum, IPY, strontium, magnesium, arsenic, rubidium and cesium).

Naturally, the investment attractiveness of these groups decreases down the list; conversely the investment risk increases. Inevitably, minerals categorised into the first group have long been developed and exploited. So, in terms of the most interesting potential investments, these are likely to fall within the second group, namely: lithium, rare earths, scandium and germanium.

4.1. Traditional Raw Materials

Traditional metallic minerals of strategic importance to Ukraine include iron, manganese, titanium and uranium.

4.1.1. Iron

Iron is widely used, it accounts for up to 95% of world metallurgical production. In addition, the ferromagnetic properties of a number of iron-based alloys contribute to their widespread use in electrical engineering for cores of electromagnets, battery plates, for magnetic circuits of transformers and electric motors. Iron is also used as an anode in iron-nickel and iron-air batteries. Iron and cast iron powder is used as a sparking agent and fuel in pyrotechnics.

Iron ore deposits are known in more than 130 countries. Global ore reserves are estimated at 166.1 billion tons, of which 81 billion tons are iron reserves. In decreasing magnitude of iron ore reserves are Australia, Brazil, Russia, China, India, Ukraine and Canada. The world iron annual production exceeds 1.5 billion tons, slowly increasing in recent years. The largest producers of marketable iron ore are Australia, Brazil, China, India, Russia, South Africa and Ukraine. Countries such as Australia, India and Canada are constantly, albeit slowly, increasing their iron ore production (Table 4.1).

**Table 4.1. World mining iron production and reserves
(World Mining Data 2021; USGS 2020)**

Country	Production, kt of Fe					Reserves, billion tons	
	2015	2016	2017	2018	2019	Ore	Fe
Australia	500,994	531,075	548,297	562,137	568,965	48.0	23.0
Brazil	275,607	267,984	289,090	287,611	255,273	29.0	15.0
China	248,062	228,483	215,920	209,244	219,375	20.0	6.9
India	98,687	121,395	125,717	129,599	152,600	5.5	3.4
Russia	62,717	61,360	62,186	64,192	60,416	25.0	14.0
South Africa	47,324	43,196	48,809	48,277	47,064	1.1	0.7
Ukraine	42,817	40,241	38,768	38,751	40,451	6.5	2.3
Canada	28,194	28,506	30,683	32,181	33,020	6.0	2.3
USA	29,043	26,334	30,177	31,185	29,547	3.0	1.0
Iran	25,798	21,623	21,884	24,700	28,305	2.7	1.5
Sweden	17,097	18,206	18,741	18,405	19,367	1.3	0.6
Other countries	78,111	75,741	79,206	78,936	85,029	18.0	10.3
Total	1,454,451	1,464,144	1,509,478	1,525,218	1,539,412	166.1	81.0

Ukraine ranks seventh in terms of global iron ore reserves and production. Five iron ore basins (IOB) are distinguished in Ukraine namely: Kryvorizkiy and Bilozerskiy (high-grade hematite-martite and magnetite ores), Kremenchutskiy and Priazovsky (magnetite quartzites), Kerchenskiy (brown iron ores). The first three IOBs are of industrial importance.

As of January 1, 2021, 60 deposits are recorded in the SIMR, of which 26 are in production. Those of particular importance are: Inguletske, Skelyuvatske, Saksaganske, Valyavkinske, Gleyuvatske and Kremenchutske. Total reserves of iron ore are estimated to 25.5 billion tons (including reserve categories A+B+C₁ amounting to 18.1 billion tons, and in C₂ – 7.4 billion tons). In 2020, total resources were estimated at 138.2 billion tons; in 2020, with 163.3 Mt of ore mined (Mineral Resources of Ukraine 2021). These reserves and output provide a viable benchmark for future extraction including catering for the needs of "green energy" in Europe.

The main reserves of iron ore are confined to the structures of the Ukrainian Shield. A range of metallogenic regions and zones are distinguished (Fig. 4.1) namely: Odesko-Bilotserkivska (I), Kryvorizko-Kremenchutska (II), Middle Dniprean (III), Bilozersko-Orikhivska (IV), Azovian (V), and inside these – the iron ore fields and areas of magnetic anomalies: Bilotserkivsko-Volodarskiy (1), Seredniopobuzsky (2), Odesko-Annivskiy (3), Kremenchutskiy (4), Pravoberezhniy (5), Kryvorizkiy (6), Khersonskiy (7), Kobeliakskiy (8), Verkhivtsevskiy (9), Chortomlytskiy (10), Surskiy (11), Konkskiy (12), Bilozersky (13), Pavlogradskiy (14), Orikhivskiy (15), Molochanskiy (16), Vovchanskiy (17), Guliaypilskiy (18), Zakhidno-Pryazovskiy (19) and Skhidno-Pryazovskiy (20)

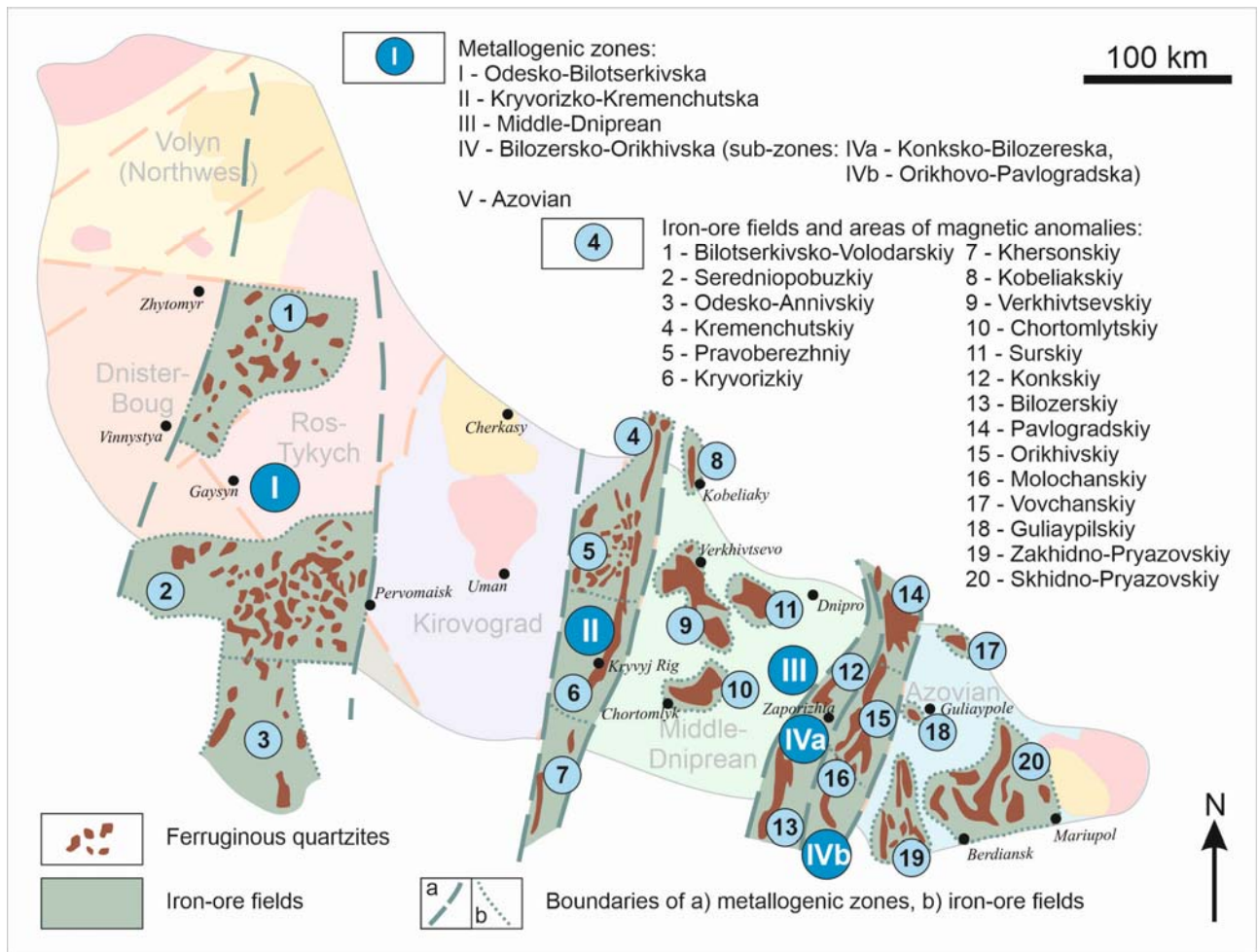


Fig. 4.1. Iron ore areas of the Ukrainian Shield (modified after Mykhailov et al. 2007). See Fig. 2.1-2.2 for details of geological background.

Iron ore is the basis of ferrous metallurgy in Ukraine. The main iron ore region of Ukraine is **Kryvyj Rig**, where deposits of ferruginous quartzites and high-grade magnetite and hematite quartzites of Paleoproterozoic age (banded iron ore formation) are being developed by a number of mining-beneficiation plants.

Iron ores of Kryvyj Rig have been known since ancient times. Their assessment began in 1781 (Russian academician V.F.Zuev), with the first estimation of reserves was made in 1873 and development began in 1875. Now the extraction, primary processing and beneficiation of iron ores of Kryvyj Rig iron ore basin are carried out by a number of mining-beneficiation plants (MBP), which develop the following deposits:

- PJSC Tsentralniy (TsMBP) – Velyka Gleyuvatka, Petrivske, Artemivske deposits, Ordzhonikidze mine;
- PJSC Pivnichny (PnMBP) – Pervomaiske and Gannivske deposits of ferruginous quartzites;
- PJSC Inguletsky (IMBP) – Inguletske deposit of ferruginous quartzites;
- PJSC Pivdenniy (PdMBP) – Skelyuvatske-Magnetitove deposit of ferruginous quartzites;
- PJSC "ArcelorMittal Kryvyj Rig" (PJSC AMKR) – Valyavkinske and Novokryvorizke deposits of ferruginous quartzites, Artem mine;
- PJSC "Sukha Balka" – high-grade iron ore in the fields of mines Yuvileyna and Frunze.
- PJSC "Kryvorizkiy Iron Ore Plant" – Ternivska, Gvardiyska, Oktyabska, Rodina mines.
- PJSC "Shymanivskiy Stil" – Shymanivske deposit of ferruginous quartzites;

- PJSC “Rudomain” – technogenic deposit, site # 2 of Pivdenniy quarry;
- PJSC “Ukrainian Mining Company” – Saksaganske deposit, Pivnichniy quarry (iron ores of IV and V ferruginous horizons)

The Kryvorizkiy IOB is composed of sedimentary and volcanic-sedimentary metamorphosed Paleoproterozoic formations of the Kryvorizka Series, which includes the following suites (from the lowermost): Novokryvorizka, Skelyuvatska, Saksaganska, Gdantsivska and uppermost Gleyuvatska (Fig. 4.2). The geological structure of the basin is described in numerous scientific publications (Belevtsev, Belevtsev 1981; Gursky et al. 2006a; Dovgiy et al. 2017; Kulish, Plotnikov 2005; Mykhailov et al. 2007; Rudko et al. 2010, 2012, 2013; Smirnov et al. 2010, 2012, etc.). The main productive sequence of the iron ore basin is Saksaganska Suite, which includes seven iron horizons from 20 to 145 m thick, composed of magnetite, silicate-magnetite, magnetite-silicate, magnetite-carbonate, magnetite-carbonate-silicate-carbonate-silicate-magnetite, carbonate-silicate, hematite-magnetite quartzites, and in supergene alteration zones – martite, disperse hematite-martite, hematite-martite ores. The iron ore interbeds are also known in Gdantsivska Suite.

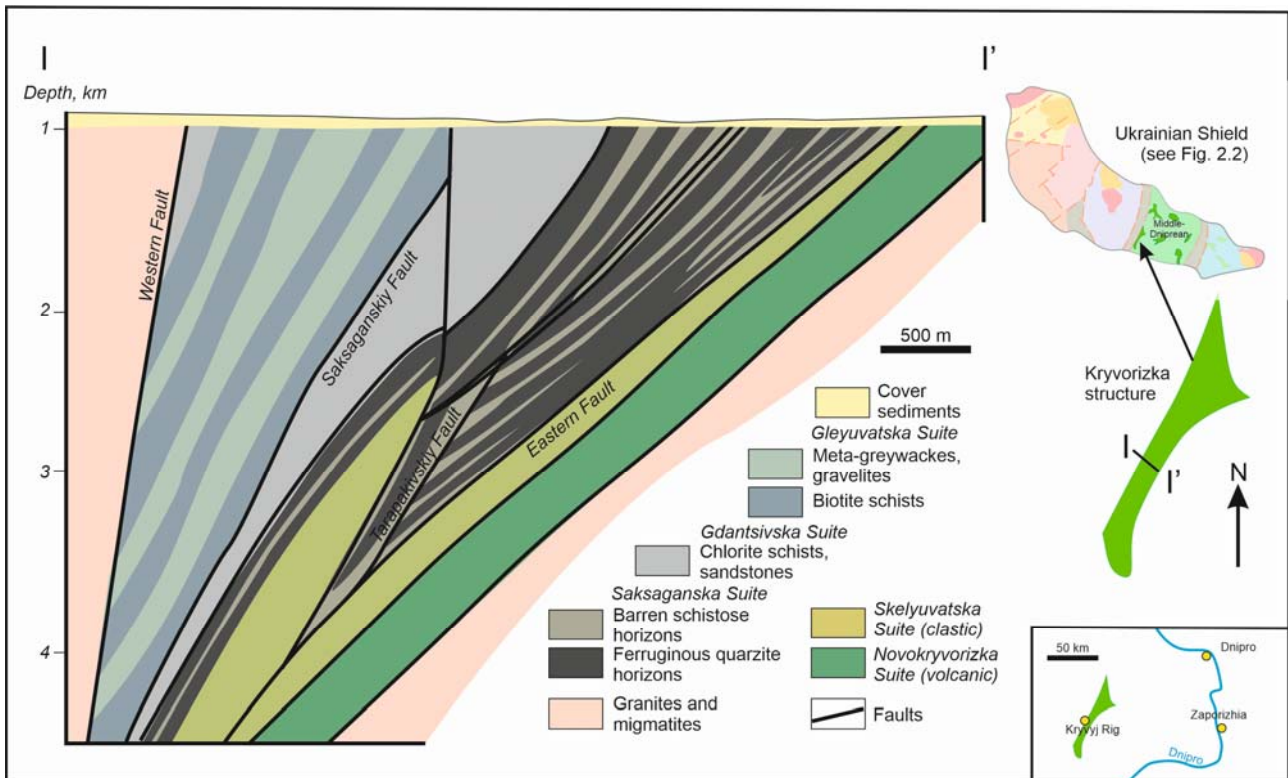


Fig. 4.2. Cross-section of the Kryvyj Rig iron ore district (modified after Mykhailov et al. 2007)

Several geological and industrial types of ores are distinguished namely: Saksaganskiy, Inguletskiy, Peromaiskiy, Skelyuvatskiy, Pravoberezhniy, Verkhivtsivskiy, Bilogorodskiy. The first three comprise high-grade ores (with an iron content 46% or greater), the other four are low-grade ores (iron content 20-45%).

The main iron ore deposits of the basin are as follows: Inguletske, Skelyuvatske-Magnetitove, Skelyuvatske, Valyavkinske, Novokryvorizke, Pivnichno-Valyavkinske Mine, Gigant-Glyboka Mine, Skhidno-Valyavkinske, Kirov, Rodina Mine, Velyka

Gleyuvatka, Oktyabrsk Mine, Frunze Mine, Yuvileyna Mine, Ternivska Mine, Gvardiyska Mine, Ordzhonikidze Mine, Pervomaiske, Gannivske, Petrivske, Zhovtorichenske and Artemivske (Fig. 4.3).

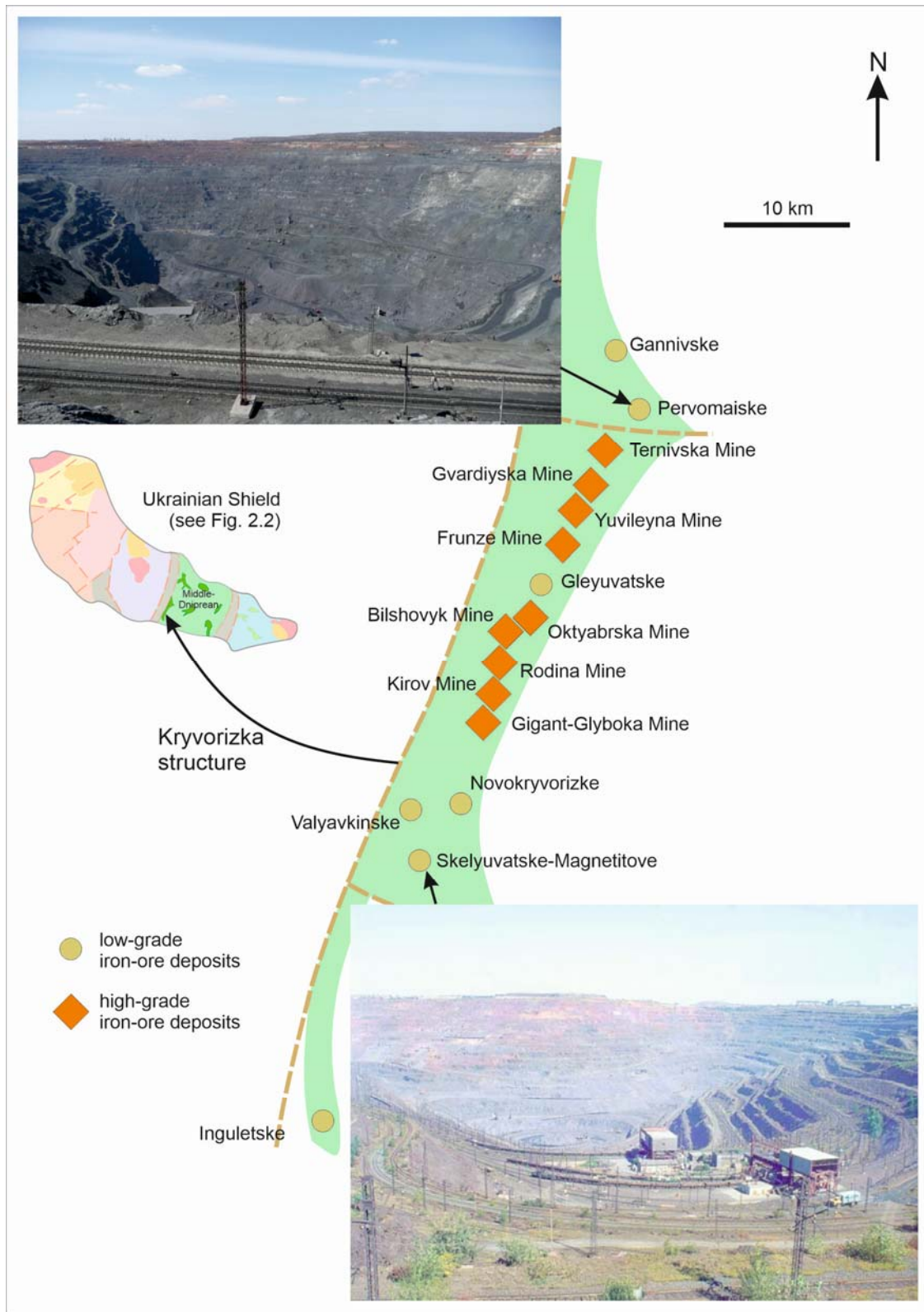


Fig. 4.3. Mining infrastructure of the Kryvyj Rig iron ore area (modified after Bobrov et al. 2002)

The main types of iron ores of Kryvyj Rig IOB are as follows:

- Easily beneficiated unoxidized magnetite quartzites with hematite, martite, etc., average content of Fe = 33.3-34.2%, mainly of Skelyuvatskiy type (Inguletske, Skelyuvatske-Magnetitove, Novokryvorizke, Pervomaiske, Valyavkynske, Gannivske, Velyka Gleyuvatka and other deposits);
- High-grade martite, hematite-martite; rarely magnetite, hematite-magnetite, goethite-iron-mica-martite ores of the Saksaganskiy type with 46-67% Fe (average 56.7-58.1%), P_2O_5 – 0.02% , S – 0.16%), represented by sheet-, lenticular-, columnar 10-100 m thick bodies;
- Heavily beneficiated oxidized ferruginous quartzites of supergene alteration of magnetite quartzites. Varieties include: goethite-disperse hematite (iron-mica)-hematite-martite, goethite-disperse hematite, etc.;

The composition of iron ores is dominated by magnetite, haematite, martite, iron mica, dispersed haematite, goethite, other iron hydroxides, quartz, carbonates, cummingtonite, biotite, chlorite, sillimanite, garnet, riebeckite and aegirine; secondary minerals include: albite, amphibole, apatite, ilmenite, sillimanite, pyrite, pyrrhotite; hypergenic – alunite, hydrargillite (gibbsite), kaolinite, limonite, chlorites, etc.

Oxidized ores comprise haematite, martite, goethite-martite, hematite-martite quartzites with ore layers composed mainly of grains and aggregates of hematite, martite (0.02-0.2 mm) and iron mica. The interestices are filled with quartz and carbonate grains and there are gangue layers composed mainly of quartz grains (0.02-0.1 mm) with an admixture of dispersed fine-grained hematite and iron hydroxides.

In summary, the iron ores of the Kryvyj Rig basin are characterized by an exceptional diversity of mineral and chemical composition, as well as structural and textural features of the ores. There are ores of different geological and genetic type (unoxidized, oxidized), different mineral composition (magnetite, hematite-magnetite, silicate-magnetite, magnetite-silicate, magnetite-hematite, carbonate-magnetite, silicate-carbonate-magnetite carbonate, hematite, martite, hematite-martite, magnetite-martite, limonite-martite and goethite-martite). The ores are characterized by a predominantly banded structure, in which ore layers (primarily magnetite, as well as hematite, martite, iron mica, cummingtonite and ferrous carbonates) alternate with barren layers of quartz, carbonates, apatite and other gangue minerals. These characteristics determine their onward processing and beneficiation (Mykhailov et al. 2022b).

The mining-beneficiation plants of Kryvyj Rig utilise the ferruginous (magnetite)-rich quartzites found mainly within the Saksaganska Suite of Paleoproterozoic Kryvorizka Series. These are mostly worked by open-cast excavations.

The Tsentralniy MBP carries out ore mining, processing and production of iron ore concentrate and pellets for the metallurgical industry. It is part of the Metinvest Group of Metinvest Holding LLC.

The mining complex of the company is represented by quarry № 1 based on the Gleyuvatske deposit (capacity of 6.0 Mt of magnetite ferruginous quartzites per year); quarry № 3 based on the Petrivske deposit (6.0 Mt); quarry № 4 based on the Artemivske deposit (4 Mt), as well as the Ordzhonikidze mine, Artem № 2 mine and

Gigant-Glyboka Mine which develop magnetite quartzites of Pivdenno-Magnetitove ore body (1.6 Mt).

The processing complex includes a crushing plant with a capacity of 28 Mt of ore per year, a concentrator with a capacity of over 6 Mt of iron ore concentrate per year, a pelletizing plant with a capacity of over 2.0 Mt of pellets per year, auxiliary shops and sludge storage.

Details of the iron ore mining at this and other iron ore companies are given in Table 4.2.

In 2020, the **Tsentrallyy** plant produced 4,840 kt of iron ore concentrate with an iron content of 66.3-68.0% and 2,840 kt of pellets with an iron content of 59.9-63.5%. The main consumers of the plant's production include the Kryvorizhstal, Azovstal and Dniprovskiy Metallurgical plants, as well as metallurgical plants in Poland, Romania, Slovakia and the Czech Republic.

**Table 4.2. Extraction of iron ore in 2020
(Mineral Resources of Ukraine 2021)**

Enterprise	Deposit	Individual and total production outputs, kt	
Tsentrallyy MBP	Velyka Gleyuvatka	4,942.0	12,825.0
	Ordzhonikidze Mine	1,362.0	
	Petrivske	4,478.0	
	Artemivske	2,043.0	
Pivnichniy MBP	Pervomaiske	2,674.0	8,610.0
	Gannivske	5,936.0	
Inguletskiy MBP	Inguletske	28,618.5	28,618.5
Pivdenniy MBP	Skelyuvatske-Magnetitove	29,830.0	29,830.0
PJSC "AMKR"	Artem Mine shaft field	566.0	25,269.0
	Novokryvorizke	9,734.0	
	Valyavkynske	14,969.0	
PJSC Kryvorizkiy Iron Ore Plant	Ternivska Mine	999.4	3,647.4
	Gvardiyska Mine	1,128.7	
	Oktyabrskaya mine	498.9	
	Rodina Mine	1,020.4	
PJSC "Sukha Balka"	Yuvileyna Mine	1,529.9	2,538.0
	Frunze Mine	1,008.1	
Poltavskiy MBP	Goryshne-Plavnynsko-Lavrykivske	12,886.0	12,886.0
Erystivskiy MBP	Erystivske	12,510.0	12,510.0
Zaporiskiy Iron Ore Plant	Pivdenno-Bilozerske	4,020.0	4,387
	Pereverzivske	367.0	

The Pivnichniy MBP is also part of the Metinvest Group and carries out a full technological cycle from iron ore mining to the production of iron ore concentrate (iron content 66%) and pellets (iron content 60.3-63.5%).

The raw material source of the company is the Pervomaiske and Gannivske deposits of ferruginous quartzites with total reserves of more than 3.1 billion tons of ore. These are extracted by opencast workings. The Pervomaiskiy quarry (see Fig. 4.3) is one of the largest in Ukraine, its length reaches 3000 m, width – 2500 m, depth

– 400 m (but longer-term is expected to reach 650 m deep). The Gannivskiy quarry is 5250 m long, 1200 m wide and 275 m deep, and it has an output of 10 Mt of ore per year.

The processing facility of the company includes three crushing plants, two concentrators, two pellet production shops and a number of auxiliary workshops. In the concentrators, crushed ore undergoes three stages namely grinding, enrichment (using magnetic separators) and combined desliming and filtration, which results in an iron ore concentrate an iron content of 66%. In the pellet production plants, the pellets have an iron content of 60.3-63.5%. In 2020, 4,780.4 kt of iron ore concentrate and 7,611.9 kt of pellets were produced.

The main consumers of the plant's production are the large metallurgical enterprises in Ukraine, Europe and in China.

The Inguletskiy MBP is the largest producer of iron ore concentrate in Ukraine with an iron content of 64% to 67%.

This MBP specializes in the extraction and processing of ferruginous quartzites of Inguletske deposit, located in the southern part of Kryvyj Rig basin. The field is being quarried by a cyclic-flow technology (the maximum size of a piece of blown ore is 1200 mm) and has a production capacity of 70 Mt of mined mass per year. From there, the ore enters the crushing plant with a production capacity of more than 36 Mt of ore per year. The ore reserves are estimated to be 1.2 billion tons. It too is part of the Metinvest Holding Group.

Ore enrichment takes place at two concentrators with an annual production capacity of over 14.5 Mt of concentrate per year with an iron content of 63.7-67.0%. The technological scheme of concentrators includes 4 stages of pre-grinding, 3 stages of grinding and 4-5 stages of magnetic separation. At each stage, waste is produced and the industrial product is further refined. Dry magnetic separation in a weak field is used as a pre-enrichment operation. At the factory № 3 process includes self-grinding of the ore mass, the crushing of raw materials up to 300 mm, two stages of grinding and three stages of magnetic separation.

A full cycle of heavily beneficiated ore with an initial total iron (Fe) content of between 32.6-36.7% results in a concentrate with total iron between 63.8-63.9% and a moisture content of about 10%. With further enrichment, employing magnetic flotation, concentrates with a total iron of over 67.0% is achieved. On average, the plant produces about 12.4 Mt of concentrate per year.

PJSC "InMBP" sells iron ore concentrate with iron content from 63.7% to 67.0%. The annual sales volume is approximately 14 Mt of concentrate. The main consumers are metallurgical plants (MP) which include: PJSC "MP Ilyicha" (Mariupol), OJSC "MP Zaporizhstal" (Zaporizhzhya), OJSC "Alchevskiy MP" (Alchevsk), OJSC "MP Azovstal" (Mariupol), PJSC "Enakiyevskiy MP"), as well as companies in China, Hungary and the Czech Republic.

The Pivdenniy MBP produces iron ore concentrate and agglomerate. Ore is mined in an open pit at the Skelyuvatske deposit with inventory reserves of magnetite quartzites of ~ 962.2 Mt and oxidized quartzites of ~ 53.6 Mt. The ore is transported

to grinding processing plants where machines CCG 1500/180, CMG 2200, CFG 2200 are installed.

The beneficiation cycle includes three stages of grinding and 4-5 stages of magnetic separation. At each stage, waste is produced, and the industrial product is further processed. The main method of enrichment is by means of a weak magnetic field. As a result, a concentrate with a mass fraction of Fe_{total} of 64.77-65.31% and a moisture content of about 10% is obtained from ore with an initial mass fraction of total iron of 35.01% and magnetic iron of 27.33%.

In 2020, the plant produced 12.798 Mt of concentrate with an iron content of 64.77-65.31%. The plant's production is supplied to metallurgical plants in Ukraine, Poland, the Czech Republic, Slovakia, and Romania.

The PJSC "AMKR" mines iron ores from the Valyavkinske and Novokryvorizke deposits. The mining and processing complex of PJSC "AMKR" consists of mining, crushing and concentrating plants.

Mining is carried out in two open cast quarries: № 2-bis (280 m deep) at the Novokryvorizke deposit, and № 3 (315 m deep) at the Valyavkinske deposit. The raw materials of the № 2 quarry comprises unoxidized ferruginous quartzites of the I and II iron-ore horizons of the Saksaganska Suite, and in the quarry № 3 from the IV iron-ore horizon of the same Suite. Mining is by means of drilling and blasting works. Of the primary quarry crushers, the primary crushing is to the size of not more than 1200 mm. The resulting 'conditioned', raw material can then be stored prior to further processing. However, most of this ore is transferred onto the next crushing plant.

At crushing plants № 1 and 2, primary ore with fragments up to 1200 mm in size pass through four stages of crushing and screening. Stage 1 reduces the mass aggregate to not more than 350 mm, Stage 2 to not more than 90 mm, Stage 3 to not more than 20 mm and Stage 4, to not more than 12.5% of the +20 mm grade. At processing plants № 1 and 2, beneficiation includes grinding (milling), wet magnetic separation, desliming and drying operations.

The finished product is a magnetite concentrate, in which the mass fraction of total iron sought is 65.3% but with a permitted deviation between -0.5% to +0.8%. The mass fraction of moisture in the concentrate should not exceed 10.5%.

The enrichment process imparts significant changes to the initial ore, in particular, the content of total iron doubles (from 32.1-36.3% to 65.0-65.5%). Other parameters which change, include a sharp increase in the amount of magnetite (up to 95-99%), whilst the vast majority of other minerals (e.g., hematite, martite, iron mica, cummingtonite, ferrous carbonates, quartz, gangue carbonates, apatite, etc.) are almost completely removed from the final product. This qualitative enrichment process is described in Mykhailov et al., (2022b).

High-grade ores are also mined underground by the enterprises of PJSC **Kryvyj Rig Iron Ore Plant** (i.e. the Ternivska, Gvardiyska, Oktyabrska and Rodina mines) and PJSC **Sukha Balka** (i.e., the Yuvileyna and Frunze mines).

The Kremenchutskiy IOB is a natural continuation of Kryvyj Rig OIB to the north. The ore-containing material of the Saksaganska Suite is up to 1300 m thick,

forms a submeridional strip 45 km long and 1-3 km wide. High-grade ores contain 58.5% Fe, low-grade ores are represented by magnetite (32.8% Fe) and cummingtonite-magnetite (27.4% Fe) quartzites. There are two ore fields, the northern Galeshchynske and the southern field of Gorishne-Plavnynske. The Gorishne-Plavnynske, Lavrykivske, Eristivske, Bilanivske ferruginous quartzite deposits and the Kremenchutske (Galeshchynske) deposit are of high-grade iron ores and are well explored. A number of deposits of low-grade iron ore (at Manuilivske and Kharchenkivske) were also explored. These explored reserves of industrial categories of the five main deposits are thought to contain more than 4 billion tons (Mykhailov et al. 2007).

The Poltavskiy MBP utilises two deposits (at Lavrykivske and at Gorishne-Plavnynske) with an annual capacity of 34 Mt of ore. The company has the capability of processing from raw ore mining to iron ore pellet production. Ore processing and the production of concentrate and pellets is carried out at the complex, which includes a crushing and concentrating plant. In addition, the company processes iron ore mined at the Eristivskiy MBP.

The Eristivskiy MBP is developing the Eristivske deposit, whose reserves exceed 600 Mt of ore and resources – more than 1 billion tons. Ore extraction is by opencast workings. The estimated production output is up to 27-28 Mt of ore per year.

The **Bilozerskiy IOB** utilises the ferruginous quartzite deposits of the Mesoarchean greenstone structures (GSS). Localities include Pivdenno-Bilozerske, Pivnichno-Bilozerske and Pereverzivske, of which only the Pivdenno-Bilozerske deposit is developed. The Zaporizkiy Iron-Ore Plant uses these ores. The Bilozerskiy IOB is one of the most promising IOBs after Kryvyj Rig. Reserves of high-grade ores at a depth of 900-1500 m are estimated at 475 Mt with total reserves at 737 Mt (Belevtsev et al. 1981).

The iron-ore deposits are confined to Bilozerska GSS. This GSS comprises a lower

Unit of greenstone volcanic and volcanic-sedimentary rocks of the Konkska Series (metabasalts, amphibolites, metasediments, quartzites) with a total thickness up to 1200 m, and an upper unit known as the Bilozerska Series. This upper Series is further subdivided into three suites. The lower, Mykhailivska Suite, is composed of quartz-sericite and quartz-chlorite-sericite schists and meta-sandstones; the middle (iron-ore-bearing), Zaporizka Suite comprises magnetite and martite-magnetite quartzites and various schists and the upper, Pereverzivska Suite, consists of meta-sandstones, meta-siltstones, metagraelites, meta-conglomerates, barren quartzites and chlorite-sericite schists.

High-grade ores are associated with the sequence of ferruginous quartzites (the Zaporizka Suite), which forms a productive horizon 150 m thick and up to 25 km long. The ore bodies are steeply dipping and traced to a depth of more than 1500 m. The ore body thickness varies from 2.5 to 10-30 m; locally, structural control combines layers to form an ore body up to 70-100 m thick (Fig. 4.4).

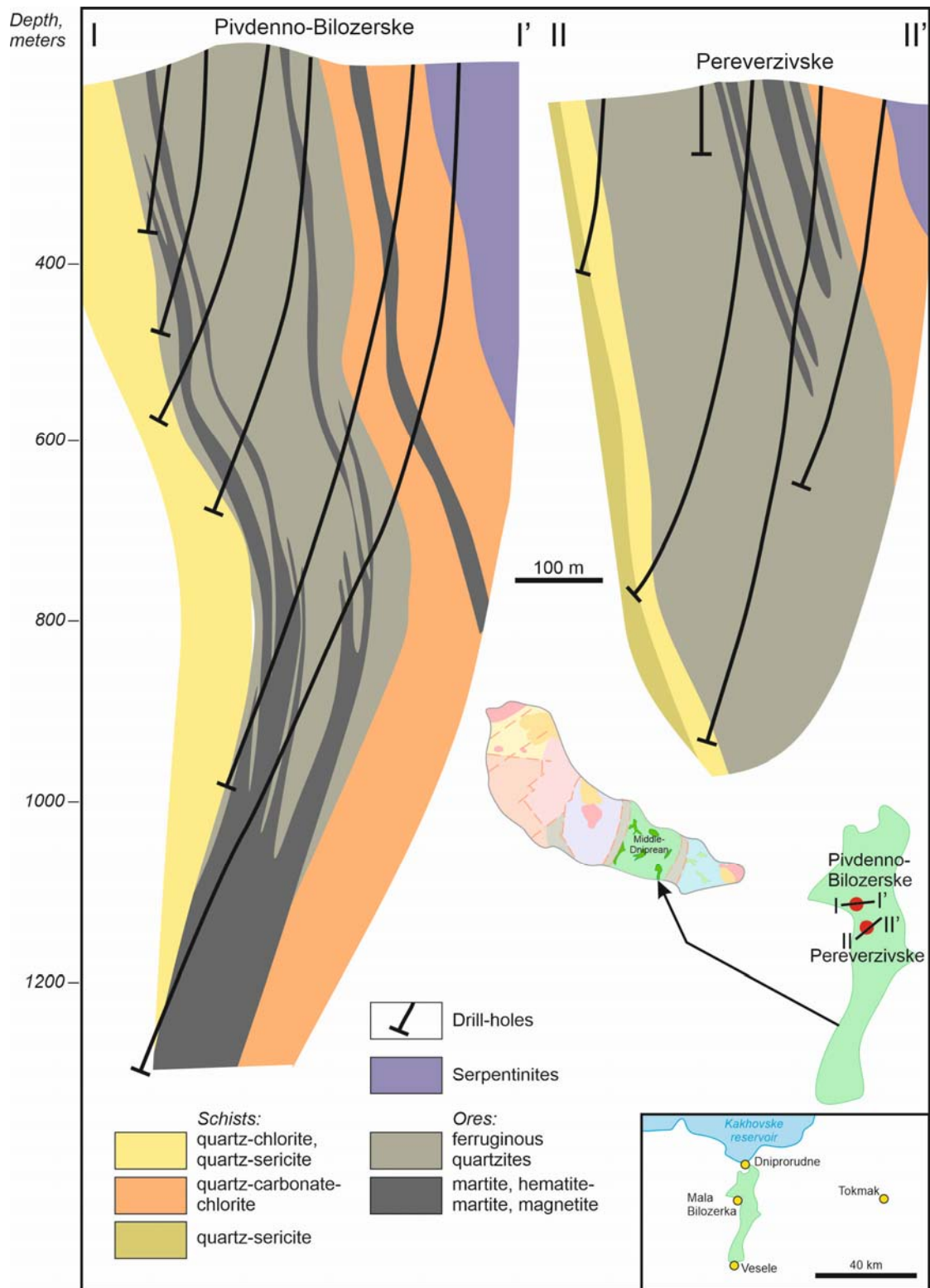


Fig. 4.4. Cross-sections of the Pivdenno-Bilozerske and Pereverzivske deposits (modified after Mykhailov et al. 2007)

The ore body occurs as sheets and lenses; however, this 'simple' bedform is often complicated by flexure bends, transverse folded structures and syncline hinges. High-grade ores occupy just over 10% of the total area of ferruginous quartzite. Mineralisation is accompanied by intense fracturing, cleavage, brecciation and crushed sequences. Ores are represented by martite (iron-mica-martite), disperse

hematite-martite (disperse hematite-iron-mica-martite), martite-disperse-hematite and disperse-hematite varieties.

In addition to high grade ores, considerable reserves of the Skelyuvatskiy-type, ferruginous quartzites are found in the Bilozerskiy IOB as oxidized (martite) with total predicted reserves from the surface to 1500 m deep of 8,100 Mt and promising resources of 8,800 Mt. There is also magnetite with estimated reserves from the surface to 1500 m deep for 13,650 Mt. Both the martite and magnetite quartzites occur in complex mining and geological conditions. In addition, they are covered by a thick layer of saturated sedimentary rocks, which complicates extraction and increases the cost of industrial production.

Pivdenno-Belozerske and Pereverzivske deposits are being developed by **PJSC Zaporizkiy Iron Ore Plant** with a production capacity of more than 4.5 Mt of ore per year. The company includes the Ekspluatatsiyna mine and Prokhodcheska shaft, a crushing and sorting factory, etc. After processing, the ore is sold as two grades; agglomeration iron ore with iron content up to 62% and open-hearth iron ore, with iron content up to 58%. In recent years, iron ore production has reached 4.5 Mt. The plant's production supplies metallurgical plants in Ukraine (Zaporizhstal), Poland, the Czech Republic, Slovakia and Austria.

Mining companies have explored reserves for 30-80 years, but much of the reserves that were explored in Soviet times are now situated in the protection zones of industrial facilities, under urban developments, MBP dumps, tailings or located at a depth of more than 500 m, which imposes difficult mining and complicated geological conditions. These constraints result in low production and profitability (Gurskiy 2008). Therefore, the realistic security of some companies does not exceed 10-15 years. Localities at risk are the Pivnichniy, Tsentralniy and Pivdenniy quarries, the Inguletskiy MBP, quarry № 2 of Tsentralniy MBP, the Ternivska, Gvardiyska, Rodina, Valyavkinska, Yuvileyna, Frunze and Kirov shafts, and the Inguletskiy, Zhovtorichenskiy, Dzerzhinskiy and Ilyicha Mines.

The Priazovski IOB has known but relatively undeveloped iron-ore reserves at Vasynivske, Kuksungurske, Guliaypilske and Mariupolske. The total forecast resources of the area are estimated at 8.1 billion tons (Gursky 2008).

4.1.2. Manganese

In addition to uses in metallurgy, a significant amount of manganese dioxide is consumed by the electrical industry in the production of manganese-zinc galvanic cells, MnO_2 is used in such elements as oxidant-depolarizer.

The world's manganese ore resources are estimated at 21,270 Mt. The predicted resource of manganese in the world's ocean seabed is almost four times higher than anticipated on the continents. World reserves of manganese ores amount to 10,407 Mt, the largest ore reserves occur in Ukraine (2,257 Mt), South Africa (1,045), Kazakhstan (354), Gabon (240), Georgia (185), Brazil (176), China (135), Australia (131) and Bulgaria (126). Proven world manganese reserves are amounted to 802 Mt. These, are concentrated in South Africa (260 Mt), Ukraine (140 Mt), Brazil (140

Mt), Australia (100 Mt) and other countries. Global manganese production is growing slowly; the largest producers of manganese ores in decreasing order include are South Africa, Australia, Gabon, Ghana, Brazil, China, India and Ukraine. In recent years production has significantly increased in South Africa, Gabon and Ghana (Table. 4.3).

Table 4.3. World manganese mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
South Africa	4,187	4,028	5,501	5,641	6,456	260
Australia	3,250	2,388	2,879	3,514	3,259	100
Gabon	1,876	1,573	2,266	2,875	3,158	61
Ghana	451	706	1,051	1,593	1,884	13
Brazil	1,226	1,199	1,344	1,281	1,452	140
China	2,484	2,150	2,508	1,180	1,350	54
India	729	802	860	920	970	34
Ukraine	547	492	651	683	686	140
Malaysia	216	294	515	530	475	n.a.
Ivory Coast	105	91	205	319	473	n.a.
Myanmar	28	116	137	208	429	n.a.
Other countries	908	811	853	886	833	n.a.
Total	16,007	14,650	18,770	19,630	21,425	802

The main criteria determining the manganese industrial value are the manganese content of the ores, the volume of reserves, the technological properties of the ores and the mining conditions. The metallurgical industry uses saleable ores with a manganese content of 25-56%. Oxide and oxidized ores are of the greatest industrial importance because they have a high manganese content (25-50%) and are easily beneficiated. By contrast, carbonate ores are of minor value due to their low manganese content (20-25%), heavy enrichment needs and the high cost of concentrates. Oxide-carbonate ores comprise a transitional category. Silicate-rich ores are difficult to beneficiate and therefore are mined only in limited amounts.

Despite Ukraine's significant reserves of manganese, ranking it second in the world, the nation is ranked only seventh in terms of production. This disparity is due to relative inferior quality of Ukraine's manganese ores compared to other countries. The problem lies with the carbonate ores (80.6% of the total amount of manganese ores) that are difficult to beneficiate, where the average manganese content is 20.7% and only a small fraction of relatively easily beneficiated oxide (12.2% of the total amount of manganese ores) and oxide-carbonate (7.2% of the total amount of manganese ores) ores, where manganese content reaches 28.6% and 25.0% respectively (Table 4.4). The average metal content in all inventory reserves of Ukraine is 25.8%. By comparison, ores mined by other countries have a manganese content of 35-62% (often 40-45%). Ukrainian ore concentrates contain between 37-45% of manganese with carbonate ores containing only 29-31% manganese. Foreign companies produce concentrates with a manganese content of not less than 48-50%.

This critical difference significantly reduces the competitiveness of the domestic manganese ore industry. The situation is exacerbated by environmental problems associated with the opencast method of exploitation, which leads to the loss of rich arable land. Therefore, it is important to objectively assess the domestic MRB of manganese, considering global factors, its analysis and evaluation, likely development trends and demand. These factors would provide a basis for targeted research and recommendations for the future of the industry.

Table 4.4. Manganese ore reserves and resources of Ukraine, Mt (Mineral Resources of Ukraine 2021)

Type of ore	Reserves			Resources	Content of Mn %	Production in 2020
	A+B+C ₁	C ₂	Total			
Carbonate	1,740.5	166.3	1,906.8	27.7	21.9	0.6
Oxide-carbonate	154.8	28.1	182.9	3.0	25.0	1.0
Oxide	262.3	2.9	265.2	27.2	28.6	2.0
Sludge	5.2	-	5.2	-		0.3
Total	2,162.8	197.3	2,360.1	57.9	25.2	3.9

Ukraine's main reserves of manganese ores are concentrated in the Nikopol manganese ore basin whose occurrences are known in the Carpathians (the Burshtynske deposit), in the Kerchenskiy basin, in Pobuzhye, in the Transcarpathians and other regions; however, these are not economically viable at present. Manganese ores are mined by Marganetskiy and Pokrovskiy MBP. Four mines and 7 quarries are developed. Ore is beneficiated by gravity-magnetic scheme at 4 concentrators which produce a marketable concentrate with a manganese content from 32.23% (PJSC Marganetskiy MBP) to 38.10% (PJSC Pokrovskiy MBP). Landscape LLC develops sludges from a man-made deposit known as the Maksymova sludge storage. Production is supplied to metallurgical, ferroalloy and other plants; some is exported to European countries. Descriptions of Ukraine manganese can be found in Gursky et al. (2006a); Gursky (2008), Mykhailov et al. (2007), Shnyukov et al. (1993) and Shumlyansky et al. (2003).

Table 4.5. Manganese ore types of Ukraine

Ore types	% of reserves	Average Mn content, %
Carbonate	80.6	20.7
Oxide	12.2	28.6
Mixed	7.2	25.0

Three types of ores are distinguished (Table 4.5). Available oxide ores are mostly exhausted, with some partly sterilised, being beneath constructions. Currently, mainly carbonate ores containing 3-13% CaO and 10-50% SiO₂ are being developed but require complex beneficiation processing.

The Nikopolskiy basin includes the Nikopolske (western and eastern parts), Velykotokmatske and Fedorivske deposits, which are associated with a platform pyrolusite-hydrogoethite-leptochlorite formation. They are located within an arcuate strip up to 250 km long and up to 20 km wide on the southern margin of Ukrainian Shield. In addition, several other promising sites are known in the western part of the Nikopolskiy basin. These are at Inguletska, Fedorivska, Vysokopilska, Pokrovska and Novovorontsovska, all with oxide-carbonate and oxide ores. The manganese ore

horizon lies in the Lower Oligocene sandy-clay sediments (Fig. 4.5). Since the beginning of the development of these deposits, a significant part of manganese ore reserves has been depleted. The high-grade easily beneficiated oxide ores have been intensively exploited, and consequently, their reserves decreased by almost half in the last decade. The harder-to-beneficiate, oxide-carbonate and carbonate ores were first mined in 1955; over the subsequent years, their production volumes did not exceed 15%. However, recently this output has increased to 29%.

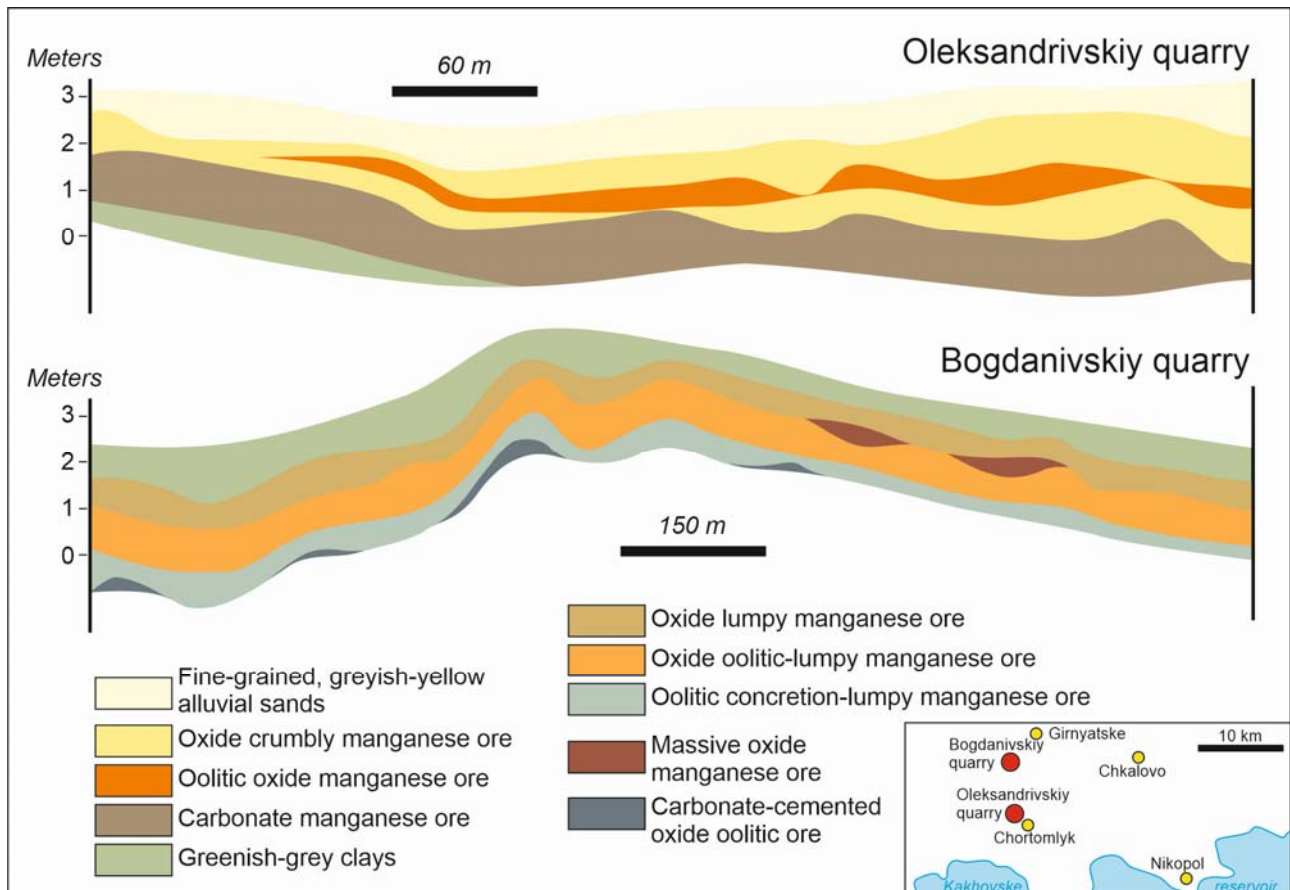


Fig. 4.5. Cross-sections showing the structure of the ore formation in the Oleksandrivskiy and Bogdanivskiy quarries (modified after Mykhailov et al. 2007)

The Nikopolske deposit. Discovered in 1883 by V. Domger, the deposit is located in the Bazavlutska Depression. Under development since 1886, the Nikopolske manganese-ore basin is one of the most studied and best understood in the scientific literature. The ore horizon dips gently to the south, with some complication due to flat folding. Its thickness varies from few centimetres at the margins to 4-5 m in the south and centre of the deposit, around 2-3 m on average, and the depth varies from 20 to 80 m.

The Oligocene deposits of the basin onlap upper Cretaceous-Eocene, or where these deposits are absent, rocks of the crystalline basement or their weathering crust. The ore-bearing Oligocene deposits are composed of three sharply distinct members: footwall sands, manganese ores, and hanging wall clays (Kuleshov 2017)

Zones of oxide, mixed oxide-carbonate and carbonate ores occur, due to progressive replacement of oxide ores by carbonate ores both from the shore of the

Oligocene sea into deeper parts of the basin, and from top to bottom through the ore bodies. Carbonate ores dominate the deposits in the Western and Eastern areas of the mineral field with particularly large reserves in the Velykotokmatske deposit (see below). There are two principal styles of carbonate ore: friable ores, with carbonate scattered in the sandstone-siltstone-clay host rocks as a thinly dispersed impurity with locally enriched regions; and solid or “rocky” ores forming nodules, lenses and rarely small beds within the host rocks or friable ores.

Geological, mineralogical, chemical and isotope data indicate a diagenetic origin for the carbonate ores of the basin, with some alteration during late diagenesis and catagenesis.

Table 4.6. Composition of manganese ores of Nikopolske deposit

Ore types	Content, %	
	Mn	P
Carbonate	17.22	0.188
Oxide	25.64	0.200
Mixed	24.58	0.208

The principal ore minerals are oxyhydrokurnakite (an intermediate product of the oxidation of manganese carbonates in the form of α -kurnakite containing a relative excess of oxygen and water, seen as brown earthy material), psilomelane, cryptomelane, vernadite, pyrolusite, manganite,

manganocalcite and calcium rhodochrosite. The average content of manganese and phosphorus in the different ore types is given in Table 4.6.

The deposits have been exploited by open pit quarrying and large areas are now worked out, though extensive resources remain. The western part of the Nikopolske deposit includes the Pivnichno-Zakhidna section (Shevchenkiyskiy and Zaporizkiy quarries), Bogdanivsky quarry, Chkalovska section (Chkalovskiyskiy quarries №1 and №2), Pivnichniy quarry, Chortomlytsko-Oleksiivska site (Oleksandrivskiyskiy quarry), Pokrovska site (Pokrovskiyskiy quarry), and Sulytska site.

The eastern part of Nikopolske deposit includes the Grushivsko-Basanska, Maksymo-Timoshivska, Zakamenska, and Novoselivska sections, the Comintern-Mariivska section under development and the exhausted Mykolaivska section. The manganese-bearing Oligocene ore layer is divided into three units, separated by the layers of nontronite clays: the lower (up to 1.6 m thick), with a low content of ore nodules; the middle, with oxide and oxide-carbonate ores; and the upper, with oxide, oxide-carbonate and carbonate ores. It dips to the south, up to 3 m thick in the lower parts of the Grushivsko-Basanska section. From north to south oxide ores change from oxide to oxide-carbonate and carbonate varieties. The ore minerals are cryptomelane, hydrocryptomelane, manganite, pyrolusite, todorokite, manganocalcite, rhodochrosite, dolomite, and manganosiderite.

The Velykotokmatske deposit. Located in the eastern part of the Nikopol basin, the Velykotokmatske ore layer is up to 3 m thick in the central part of the deposit. It comprises a sequence of sand-siltstone-clay rocks containing up to 50% ore minerals. From north to south oxide ores grade into mixed oxide-carbonate, and then into carbonate the latter accounting for 87% of the resource. The ore is represented by nodules, angular lumps, rounded concentric-layered formations, and solid layers. Oxide ores are composed of manganese oxides and hydroxides, with slab, pisolite, concretionary, solid, sandy, and earthy forms. Oxide-carbonate ores are represented

by layers of nodular carbonate ores (~0.2 m); alternating layers (10-15 cm) of carbonate ore with inclusions of manganite pisolites and clays with manganese-carbonate ores; carbonate ore masses; clumps of manganese hydroxides; oxide lump-earth ore with rare oxide nodules; lump ore with concentric-layered manganite pisolites and oolites, and manganese carbonate nodules. Carbonate ores are represented by lump and solid varieties, almost entirely composed of minerals of the manganocalcite – calcium rhodochrosite isomorphic series. Carbonate concentric-shell nodules are sometimes observed in solid ores.

The total reserves of the deposit are estimated to 1748.8 million tonnes, including 1578.2 Mt confirmed reserves, with average Mn content of 31% in oxide ores, 27.2% in oxide-carbonate and 23.4% in carbonate ores.

The Fedorivske deposit. Located in the southwestern part of the basin, the deposit is 98% low-phosphorus oxide and carbonate-oxide ore. The ores contain largely manganite and pyrolusite, with fewer other minerals and can be used to produce high-quality concentrates with Mn content of about 49%. The resources (C_1+C_2) are 34.1 Mt of ore with Mn cut-off grade of 16%, and an average industrial Mn content of 19.39%.

The Burshtynske deposit. Discovered in 1951 in the Fore-Carpathians and explored in 1952-1954, the deposit consists of Miocene manganese ore-bearing limestones, clays and marls in depressions up to 26 m thick, 4 km wide and 8 km long. The Mn content of unoxidized ores is 0.5-9.0%, with average 7.7% and in oxidized ores, up to 40%. Sections enriched in manganese form lenticular ore bodies 100 to 500 m in size and 1-6 m thick. The composition of ores is shown in Table 4.7. Total resources of metallic manganese amount to about 2 Mt with average content up to 9.5% Mn. However, the deposit is not of industrial interest due to its small size, the relative complexity of the structure, and low quality of the ores.

Table 4.7. Composition of manganese ores of Burshtynske deposit

Ore types	Mn content, %
Carbonate	0.5-30.0
Clay-carbonate	12.5
Mixed carbonate-oxide	30-40

Table 4.8. Mineral resources of Kerchenskiy Iron Ore Basin (Laznika 2006)

Commodity	Resources, Mt	Grade, %
Fe	600	35
Mn	57	3
V	11.4	0.67
As	2.2	0.13

The Kerchenskiy Iron Ore Basin.

The Kerchenskiy, or Kerch-Taman, iron ore basin in the northern Black Sea region is a typical example of marine sedimentary goethite-chlorite-siderite mineralisation. The field is credited with considerable

resources (Table 4.8), and Ge and Se were also recovered (Laznika 2006). It formed in a region of bogs, limans (linear river mouth lagoons) and shallow-water eutrophic lakes filled by Cimmerian (Middle Pliocene) marine sediments, with local uplifts that controlled the distribution of iron-manganese mineralization. The gabbro-anorthosite intrusions and Proterozoic jaspilites of the Ukrainian Shield served to supply Fe to the system.

The reducing environments of the bogs and lagoons favoured Fe concentration in the water, and subsequent mixing of waters with different salinities or Eh/pH then engendered precipitation of Fe as colloidal slimes and ferruginous oolites.

Three relatively distinct types of marine oolitic ore bodies can be recognised: (1) sheeted-lenticular ore bodies confined to synsedimentary and post-sedimentary synclines; (2) sheeted-lenticular inclined ore bodies on limbs of eroded anticlinal structures; and (3) ore bodies associated with mud volcanic breccias and confined to the so-called 'indented' synclines. 'Indented' synclines are sinks resulting from the redistribution of sedimentary material at deep interior levels, characteristic of mud volcanoes and tectonic folds in the Kerch area.

Flat lenticular deposits occur at Janis-Takilske, Eltigen-Ortilske, Komyshe-Burunske, Katerlezske, Baksynske, Kezenske, Osovynske, and Pivnichne, while Novoselivske, Baksynske, Bulganatske, Batalinske, and Achynske are examples of deposits associated with indented synclines.

The main carriers of manganese are psilolimestones and colloidal manganese hydroxides, iron and manganese carbonates, silicates, and isomorphic impurities in iron hydroxides. The average contents of Mn for the various ores are given in Table 4.9. The total manganese

Table 4.9. Average composition of manganese ores of Kerchenskiy Iron Ore Basin

Ore types	Mn content, %
"Tobacco"	0.68-1.19
"Brown"	0.87-2.22
"Caviar"	3.47-6.28
Carbonate concretionary	up to 13.93
Oxide concretionary	18-22

resources of the Kerchenskiy Basin are estimated at 40 Mt. The SIMR of reserves (A+B+C₁) records 8 deposits of iron ore that are not yet developed, with 382.2 million tonnes of "brown" ore and 799.8 million tonnes of "tobacco" ores.

In Pobuzhye, hypergenic Meso-Cenozoic iron-manganese deposits occur as laterite and hydromica (illite) weathering crust of Ukrainian Shield. In the **Khashchuvatske deposit** in particular planar, planar-linear and linear weathering crust is developed after Precambrian rocks, often enriched with Mn, confined to north-trending strip-like structures 4.0-15.5 km wide and up to 10 km long, with up to 14 horizons of oxide and hydroxide iron-manganese and manganese-iron minerals. Weathering processes extend to a depth of 40 m. The ores are easily beneficiated and the average MnO content is about 30%. The ore reserves of the deposit are not recorded in the SIMR. Other occurrences of the same type include Solontsivskiy, Zavallivskiy, Savranskiy, Grushkivskiy, Novoselivskiy ones. Prognostic resources in the Pobuzhskiy area amount to 758 million tonnes of ore in the P₁+P₂ categories, with a further 376 million tonnes of ore in the hypothetical P₃ category.

In addition, the **Prelutske** manganese ore deposit in the Trans-Carpathians occurs in a horizon of black quartzites and quartzite schists on the slopes of the ridge of the same name. Neither the shape nor size of the mineralisation have been established, and nor has any resource, although various researchers have made estimates ranging from 16 kt to 3 Mt. The thickness of the deposits varies from 1 to 5-10 m and they are characterized by a lenticular shape with sharp changes along strike of both thickness and content of ore minerals. They are composed of silicate-carbonate and oxidized

mineralisation, the manganese content of which ranges from 14 to 41%, with average 32.5%. The main minerals of silicate-carbonate mineralisation are rhodochrosite, rhodonite, while oxidized material contains mainly pyrolusite, psilomelane, vernadite, and manganite.

Prospects for the development of the manganese ore industry of Ukraine depend on the exploration of Fedorivske deposit, the study of occurrences in Carpathians, Kerchenskiy Basin, Pobuzhye, Trans-Carpathians, and the development of technogenic deposits.

Thus, the manganese ore industry of Ukraine is facing a real threat of a sharp decline in production, associated with both global market trends for manganese raw materials and problems of the remaining manganese resources (low grade ores, predominance of ores which are less easy to beneficiate, environmental problems, etc.) . Hence geological and economic reassessment of the manganese resources of Ukraine in modern market conditions is relevant and necessary, and should include the following elements (Mykhailov, Kurylo 2010b):

- quantitative and qualitative characteristics and indicators, including mining, processing and other costs, of existing facilities of the domestic base of manganese ore;
- the main characteristics of the world and domestic markets of manganese ore, which determine the economic value of deposits in modern conditions;
- the most promising objects of the domestic base of manganese ore raw materials and the limit conditions for the feasibility of their operation, taking into account economic, environmental factors and the introduction of modern technological processes;
- the main ways of investment support for a set of measures for the rational use of the domestic base of manganese ore.

4.1.3. Titanium

It is used in light high-strength alloys for aviation, aerospace, defence, shipbuilding, and the manufacture of medical devices. For example, titanium parts make up 5-7% of the Boeing-777 aircraft and 20-30% of the total mass of aircraft engines. Heavy helicopter rotors are made of titanium and in military aircraft the share of titanium can reach 25-30%. Titanium is also used in the manufacture of chemical reactors, pipelines, and equipment operating in aggressive environments, such as in chemical engineering.

World titanium reserves are estimated at 770 Mt, with more than 60% of these in Australia and China. Titanium production has been growing slowly in recent years, with China (with ~30% of world production), South Africa, Australia, Canada, and Ukraine being the largest producers. China, Ukraine, and Madagascar have increased production, while Australian production has decreased in recent years (Table 4.10).

Table 4.10. World titanium mining and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
China	1,067.2	1,196.0	1,242.0	1,932.0	2,306.9	230.0
South Africa	1,050.0	950.0	1,090.0	1,000.0	970.0	35.0
Australia	1,053.3	1,070.0	993.0	875.3	780.5	250.0

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
Canada	596.0	700.0	750.0	620.0	640.0	31.0
Ukraine	375.5	339.8	430.3	519.0	564.1	5.9
Mozambique	425.6	504.2	557.7	535.7	498.9	14.0
Senegal	240.3	238.1	280.3	287.9	281.0	n.a.
Kenya	319.8	339.5	345.6	340.2	262.7	0.85
Madagascar	102.7	152.1	230.7	214.0	258.8	8.6
Norway	277.3	260.0	238.2	176.4	211.3	37.0
Other countries	1,062.5	908.1	856.1	832.0	960.3	157.65
Total	6,570.2	6,657.8	7,013.9	7,332.5	7,734.5	770.0

Ukraine has a strong MRB of titanium, represented by two main types of deposits: placer mineral-sand type (Malyshevske and Irshanska Group of deposits) and hard-rock type (Stremygorodske, Fedorivske, Paromivske, Kropyvnyanske, etc.) (Fig. 4.6).

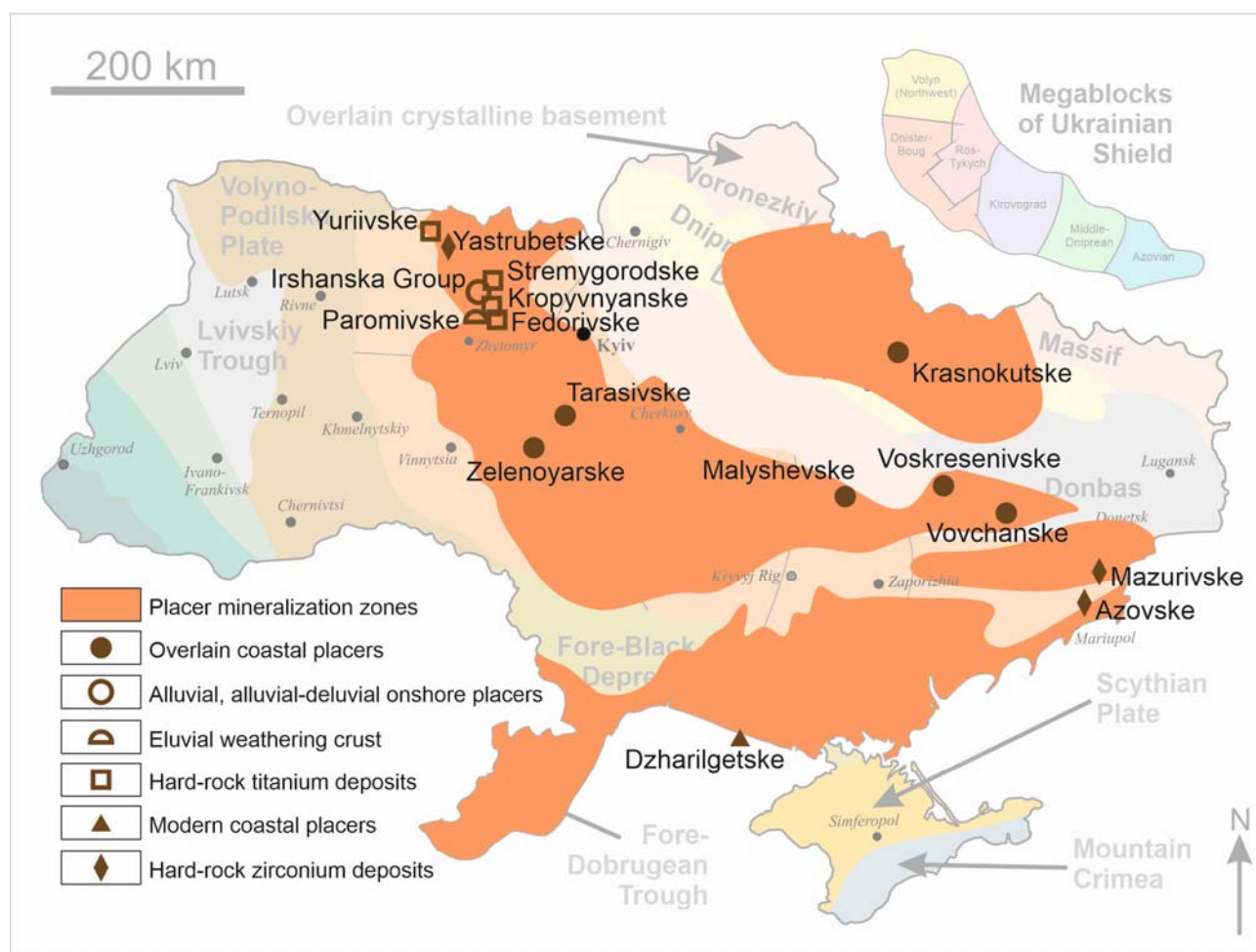


Fig. 4.6. Titanium and zirconium deposits of Ukraine (modified after Mykhailov et al. 2007)

In total, around 40 titanium deposits are known, of which 27 exclusively placer deposits are recorded by the SIMR, and 8 are being developed. Operating mines include Irshanskiy MBP (Irshanske, Lemnenske, Mezhyrichne and other deposits of Irshanska Group) and Vilnogirskiy Mining and Metallurgical Plant of the state enterprise United Mining and Chemical Company (Malyshevske deposit). Titanium

is also mined by Valky-Ilmenit LLC (Valky-Gatskivske); Demurinskiy MBP LLC (Vovchanske); LLC "Velta" (Birzulivske, Likarivske); Mezhyrichenskiy MBP LLC (Isakivska section of Mezhyrichne deposit); and Non-Ferrous Metals LLC (Western and Eastern sections of Balka Kruta deposit, which is a technogenic deposit of zircon-rutile-ilmenite ore sands of the Malyshevske deposit) (Mineral Resources of Ukraine 2021).

As of January 1, 2021, exploration is being carried out at the Yuriivska section (Titan Apatite Group LLC), the Krasnorichenske deposit (Zhytomyrburrozvidka LLC), the Selyshchanska section (United Mining and Chemical Company JSC), and the Paromivske deposit (Zhytomyrburrozvidka LLC).

Proposals for licensing are open for mining in Fedorivske, Stremygorodske, Kropyvnyanske, Zlobytske, Irshanske, Lemnenske, Torchynske, Ushytske, Ushomyrske, Voskresenivske, Krasnokutske, Pidlisne (Zhytomyr region); Nosachivske (Cherkasy region), Tarasivske (Kyiv region), the north-western part of Malyshevske and Verkhnyo-Irshynske (Dnipropetrovsk region) deposits, and for exploration over the Davydkivske deposit (Kharkiv region), the Yuriivsko-Koziivska, Vidoborzka and Pidlisna sites (Zhytomyr region), as well as the Korchakivskiy, Bilovodskiy, Khrapivshchyna (Sumy region), and Gaidarivskiy (Kharkiv region) occurrences (Investment Atlas of Subsurface User 2021).

The largest of the developed deposits is the ***Malyshevske (Samotkanske)*** Ti-Zr deposit in the basin of the Samotkan River (right branch of Dnipro River) in the Dnipropetrovsk region. The deposit was discovered in 1954 and has been under development since 1961. It is a coastal placer in Sarmatian sediments 19 km long, 2.5 km wide and 35 m thick, and includes several mineralised lenses up to 1518 m thick enriched with rutile (average content 24 kg/m³), ilmenite (77 kg/m³), and zircon (8-9 kg/m³). The deposit is developed by open-cast mining by Vilnogirskiy MBP and includes a drying plant and concentrator, where crushing, gravity separation and concentration using electric and magnetic beneficiation methods are carried out. The main products include rutile (over 95% TiO₂), ilmenite (over 63% TiO₂), zircon, staurolite, and silimanite concentrates.

The Irshanske deposit. This Ti deposit in the north of Zhytomyr region was discovered in 1951 and been operated since 1956. The average thickness of the productive sequence is 8.2 m, overburden thickness from 0.2 to 17 m and average content of ilmenite of 50.6 kg/t. Alluvial placers of ilmenite occur in Quaternary sediments, which were formed during the erosion of a Mesozoic weathering crust of ilmenite-bearing hard rocks of a gabbro-anorthosite. The deposit is being worked by Irshanskiy MBP, which produces ilmenite concentrate for use in titanium dioxide pigment and titanium sponge.

Hard-rock titanium deposits, associated with gabbroid massifs, are not currently being developed, but form a reliable basis for increasing titanium production in Ukraine. The largest is the Stremygorodske deposit in the Korsun-Novomyrgorodskiy pluton. Apatite-titanium ores have also been discovered in the Volodarsk-Volynskiy Massif (Kropyvnyanske deposit) and the Korsun-Novomyrgorodskiy pluton (Nosachivske deposit and Volkovskiy occurrence).

A number of complex titanium-apatite and titanium-zirconium targets are open to licensing proposals, including hard-rock mineralisation (Stremygorodske and Nosachivske deposits), mineral sand placer deposits (Tarasivske deposit, Yuriivsko-Koziiivska, Bilovodska, Korchakivska, Khrapivshchyn, Gaidarivska sites), and technogenic resources (north-western section of Malyshevske deposit) types (Investment Atlas of Subsurface User 2021).

The Stremygorodske deposit. Apatite-ilmenite mineralisation in the Zhytomyr region, discovered in 1954, is located in troctolites of the southern part of gabbro-anorthosite Chepovytskyi Massif (Korostenskiy pluton). The ore body has an oval shape in plan (2.3×1.0 km), elongated in the north-western direction, and funnel-shaped in cross-section. The central part is composed of plagioclase peridotites and melanocratic troctolites, while leucocratic troctolites, olivine gabbro, gabbro-monzonites and gabbro-pegmatites occur on the periphery. Apatite-ilmenite mineralisation is evenly interspersed, mostly in troctolites, with 6.9-8.17% TiO₂ and 2.8-4.5% P₂O₅ in the central part, and 3.36-5.9% TiO₂ and 0.65-1.5% P₂O₅ on the periphery. Ilmenite is seen as rounded, polygonal lamellar and xenomorphic grains, while apatite forms fine inclusions in ilmenite and olivine, and single dipyramidal-prismatic crystals up to several millimetres in size.

The bedrock is covered with a weathering crust up to 35-40 m thick (average 15.2 m), which contain 10.8% TiO₂ and up to 2.6% P₂O₅. Ilmenite and apatite concentrates with TiO₂ content of 49-51% and P₂O₅ 38.5-40.5% were obtained from these.

Table 4.11. Mineral reserves of apatite-ilmenite ores of Stremygorodske deposit

Commodity	Reserves, kt*	Category
Apatite	31,826.3	B+C ₁ +C ₂
Vanadium ores	222.9	B+C ₁
Fluorine in apatite	1,358.7	B+C ₁ +C ₂
Primary kaolin + gruss + weathered gabbro	32,354	A+B+C ₁
Gabbro-anorthosite	197,736 thousand m ³	A+B+C ₁
* unless other is specified		

The deposit is complex, with scandium, vanadium, fluorine, kaolin, gruss, weathered gabbro and gabbro-anorthosite in addition to the titanium minerals and apatite.

Three exploration wells with depths of 420-520 m were drilled at the deposit. The estimated reserves of apatite-ilmenite ores are given in Table 4.11. The average TiO₂ content is 6.91%; P₂O₅, 2.42%; vanadium,

0.2%; fluorine in apatite, 2.22%, and scandium 80 g/t. Information on titanium and scandium resources is confidential (Investment Atlas of Subsurface User 2021).

The Fedorivske deposit. A stratified gabbroic intrusion of in the western part of Volodarsk-Volynskiy Massif contains apatite-ilmenite mineralisation with titanomagnetite admixture layered with intercalated gabbroids. Significant V and Sc concentrations have been reported. Average TiO₂ content is 6.5%, with 2.9% P₂O₅ and 0.042% V₂O₅. Development by open pit is planned, with beneficiation to be carried out at the concentrator of the future Stremygorodskiy MBP (Gursky et al. 2006a).

The Nosachivske deposit. Apatite-ilmenite mineralisation occurs in the

Nosachivske norite massif in the Korsun-Novomyrgorodskiy pluton in the Cherkasy region, at the intersection of north-trending Tarasivskiy fault zone and east-trending Kanivsko-Novomyrgorodskiy fault zone. It is represented by a linear stockwork elongated in the north-eastern direction for 2250 m at a width of 200-780 m. The apatite-ilmenite mineralised bodies are sheet-like in shape, diluted by short apophyses and lenticular inclusions of xenoliths of barren rocks. One body is steeply-dipping, and the other is anticline-shaped. They are composed of apatite-ilmenite norites of the first phase, which are characterized by high concentrations of P_2O_5 , and ilmenite norites of the second phase, where higher content of TiO_2 is observed. The mineralisation is high quality and has good technological indicators for beneficiation. The deposit is complex, with the main components being TiO_2 and P_2O_5 , and accompanying minor feldspar raw materials.

Information on TiO_2 reserve tonnages is confidential. Table 4.12 provides information about the estimated P_2O_5 resources with average grades of 5.48% TiO_2 , 1.22% P_2O_5 , and 53.57% plagioclase, and additional resources with uncertain industrial value with average grades 5.17% TiO_2 , 1.27% P_2O_5 , and 55.62% plagioclase.

Table 4.12. Mineral resources of P_2O_5 of Fedorivske deposit

Commodity	Resources	
	Estimated, kt	Category
P_2O_5	85.20	B
P_2O_5	499.20	C ₁
P_2O_5	3,812.20	C ₂
Plagioclase	150,622.00	n.a.
Commodity	Uncertain, kt	Category
P_2O_5	1,361.18	C ₂
Plagioclase	59,459.64	n.a.

Again, information on TiO_2 reserve tonnages is confidential. Promising (P_1) resources of V_2O_5 in ilmenite are estimated to be 86.61kt with 4 396.75kt P_2O_5 , at grades of 0.22% V_2O_5 , 1.26% P_2O_5 and 4.75% TiO_2 . Further exploration may lead to increases in resources on the flanks and deep horizons of the deposit (Investment Atlas of Subsurface User 2021).

The Tarasivske deposit. This Ti and Zr deposit in the Kyiv region, discovered in 1961, is formed of ilmenite-rutile-zirconium placer sands in the Neogene sediments of the Novopetrivska Suite, which overlies Paleogene sediments of Buchatskiy, Kyivskiy and Obukhivskiy stages and is overlain by Quaternary sediments. There are three lithological and stratigraphic horizons, ore bodies are confined to the middle one. The main ore minerals are ilmenite, rutile, and zircon, Disthene, sillimanite, staurolite, tourmaline, andalusite, anatase, brookite, corundum, spinel, chromium spinel, baddeleyite, topaz, dumortierite, monazite, xenotime, cassiterite and other minerals are also found.

An industrial-scale beneficiation scheme of the zircon-rutile-ilmenite sands in the deposit was developed based on the results of technological studies, and in 2011 Micromine Consulting Services performed an independent assessment of the resources of Tarasivske deposit according to the JORC code.

Information on reserves and resources of titanium, zirconium and scandium ores is confidential but reported reserves of other minerals are given in Table 4.13.

Table 4.13. Mineral reserves and resources of Tarasivske deposit

Commodity	Tonnage, kt	Grade	Category
Disthene / sillimanite	74.9	3.43 kg/m ³	B
Disthene / sillimanite	294.2	3.43 kg/m ³	C ₁
Staurolite	14.7	0.51 kg/m ³	B
Staurolite	40.3	0.51 kg/m ³	C ₁
Vanadium ores	5.4	0.18-0.26%	C ₂
Scandium ores		19-100 g/t	

The deposit has been mined out, but potentially resources remain in the unmined pillars, if a way can be devised to remove these safely.

The Yuriivsko-Koziivska site. This deposit in the Zhytomyr region is represented by a Ti-Zr placer in Neogene Novopetrivska Suite and a sequence of variegated clays, which overlie the Paleogene Buchatska Series, Kyivska and Obukhivska Suites, and are overlain by Quaternary loams, sands, clays and soils 1.5-30.0 m thick.

The thickness of the productive Novopetrivska Suite varies from 0.5 to 16.5 m, with average 6.5 m. It has the form of a blanket-like layer of light-grey fine-grained quartz sands, sometimes with layers of coarse-grained, horizontally layered varieties, and in the upper part of the section, lenses of grey and variegated fine-grained sandstones with kaolinite cement, interbeds of cross-bedding sands, lenses of secondary kaolin and grey plastic clays 0.55-4 m thick. The dominant mineral component of the sands is quartz, which accounts for 86-100%, with feldspar, zircon, rutile, garnet, ilmenite, leucoxene, sphene, sillimanite, disthene, staurolite, tourmaline, hydrogoethite occurring in minor amounts. Titanium and zirconium minerals together vary from tenths to 108-200 kg/m³.

Table 4.14. Composition of sandy clays at Yuriivsko-Koziivska site

Mineral	Grade, kg/t
Ilmenite	22.32
Leucoxene	up to 5.88
Zircon	up to 1.34
Rutile	up to 0.67

A sequence of variegated clays with a thickness of 0.4 to 27.0 m is developed at some parts of the watersheds. In its lower part there are light-grey and ochre-yellow multi-grained sands 0.6-6.9 m thick, which gradually change upwards through the section to clayey sands and sandy clays. The Ti-Zr content of the sands is 0.54-20.84 kg/cm³;

the mineral composition of sandy clays is given in Table 4.14. The content of heavy minerals in the Quaternary alluvial sands is 1.08-48.2 kg/cm³.

Ore bodies are represented by two lenticular layers oriented approximately east to west, 6 to 13 km long and 0.4-1.5 km wide.

75 wells of a total length 2984.1 m were drilled at the site. Promising resources of category P₁ are estimated at 2,700 thousand tonnes of conventional ilmenite, with average content of 163.02 kg/m³, with a further 2,800 thousand tonnes at 65.53 kg/m³ in the P₃ category.

The Bilovodska site. A sequence of Ti- and Zr-bearing glauconite-quartz sands of the Buchatska, Kyivska and Mezhygirska Suites in the Sumy region, with an area of

62 ha and a total thickness of 30-32 m, which overlap the Maastrichtian chalk and are overlain by Beretska Suite. The sands consist of two sub-suites: the lower Zmiivska glauconite sands, with green clays 7-8 m thick at the base and the upper Sivaska, light fine-grained quartz sands 5.4-6.8 m thick (average 6.1 m), within which mineralization is confined. The Beretska Suite is overlain by Neogene clays and Quaternary loams with sand interbeds of a total thickness 8-11 m, with average 9.6 m. The average thickness of the productive sequence is 3.7 m, with average zircon content of 6 kg/m³, and 50 kg/m³ of conventional ilmenite. Resources of titanium-zirconium ores are preliminarily assessed by category P² but the information is confidential (Investment Atlas of Subsurface User 2021).

The Korchakivska site. An area of 750 hectares with similar geology is located 4 km south of Bilovodska site in the Sumy region. Here, mineralization is also confined to the upper part of Beretska Suite (Syvaska SubSuite) with a thickness of 3-18 m (average 9 m), and is covered with Neogene variegated and reddish-brown clays and Quaternary sediments with a total thickness of 3.6-16 m. The average content of ilmenite in the productive sequence is 51.4 kg/m³, with 7.6 kg/m³ rutile and 6.5 kg/m³ of zircon. Preliminarily resources of titanium-zirconium ores are assessed as category P₂, but details are confidential (Investment Atlas of Subsurface User 2021).

The Khrapivshchyna site. A third area of 170 ha with similar forms an extension to the north of the Korchakivska site and is located between the latter and Bilovodska site. Mineralization is confined to the upper sub-suite of Beretska Suite (Syvaska SubSuite) with a thickness of 5.3-13.5 m (average 10.4 m), and is composed of light grey and white fine-grained sands, up to siltstones, overlain by Neogene clays and Quaternary loams with a thickness of 3 to 15 m, averaging 10-12 m. The 5.6 m thick productive horizon, averages 7.8 kg/m³ zircon, 9.9 kg/m³ rutile, and 63 kg/m³ conventional ilmenite, within which a thickness of 4.3 m contains 8.6 kg/m³ zircon and 10.7 kg/m³ rutile. Preliminarily resources of titanium-zirconium ores are assessed in category P₂, but again the details are confidential (Investment Atlas of Subsurface User 2021).

The Gaidarivska site. An area of 971.4 ha in the Kharkiv region contains lenticular ilmenite-zirconium placers in the sands of Novopetrivska and Beretska Suites with an average thickness of 11 m beneath overburden of 27.5 m, the mineral composition is shown in

Table 4.15. Mineral composition of sands at Gaidarivska site

Mineral	Content, kg/m ³	
	Range	Average
Ilmenite	3.0-84.32	42.4
Leucoxene	1.06-44.78	n.a.
Rutile	0.2-7.20	6.8
Zircon	0.76-13.06	8.3

Table 4.15. The total length of wells drilled at the site is 521.5 m. Preliminarily resources of titanium-zirconium ores are assessed in category P₂, but the details are confidential (Investment Atlas of Subsurface User 2021).

The north-western part of Malyshevske deposit. At the border of Kirovograd and Dnipropetrovsk regions, an area of 3,309.8 ha contains coastal-marine Ti-Zr placer in grey fine-grained quartz sands of the Poltavaska Series, partly in Miocene Sarmatian sediments. The sands are composed of quartz, clay minerals, heavy minerals: zircon,

rutile, ilmenite, leucoxene, disthene, sillimanite, staurolite, tourmaline, spinel, chromite, and monazite. Reserves of titanium-zirconium ores are evaluated to category C₂, but the details are confidential. Reserves are estimated to be 1,407.8 thousand tonnes of disthene + sillimanite and 567.9 thousand tonnes of staurolite (Investment Atlas of Subsurface User 2021).

4.1.4. Uranium

Radioactive elements, especially uranium, are valued for their extraordinary ability to produce large amounts of energy by fission, which underlies their use for military and civil purposes, primarily as fuel for nuclear reactors.

World uranium reserves exceed 6 Mt, with the largest reserves in Australia, Kazakhstan, Canada, Namibia and Russia (Table 4.16) In recent years there has been a reduction in uranium production, from 72 thousand tonnes in 2015 to 64.4 thousand tonnes in 2019. Kazakhstan has the greatest uranium production (41.8% of world total). Namibia has increased its production, while production has declined in Canada and Niger.

Table 4.16. World uranium mining production and reserves (World Mining Data 2021)

Country	Mining, t					Reserves, kt
	2015	2016	2017	2018	2019	
Kazakhstan	28,072	29,113	27,500	25,595	26,895	906.8
Canada	15,659	16,666	14,394	8,225	8,370	564.9
Australia	6,668	7,352	6,736	7,737	7,726	1,692.7
Namibia	3,473	4,308	4,981	6,514	6,459	448.3
Uzbekistan	3,806	3,921	4,009	4,062	4,127	132.3
Niger	4,852	4,101	4,066	3,433	3,516	276.4
Russia	3,602	3,543	3,400	3,424	3,433	486.0
China	1,906	1,906	2,223	2,223	2,223	248.9
Ukraine	1,156	1,185	986	1,390	944	108.7
India	454	454	496	499	363	240.0
Other countries	6,001	2,089	1,611	981	362	1,042.8
Total	75,649	74,638	70,402	64,083	64,418	6,147.8

According to the 'Red Book' 2020, as of 1 January 2019 Ukraine has “reasonably assured and inferred uranium resources” of 186,896 tU recoverable at costs of USD 260/kgU or less, and resources of 72,916 tU recoverable at costs of USD 80/kgU or less, taking mining and processing losses into account.

The main uranium resources of economic interest in Ukraine are found in two types of deposits: metasomatite-type, monometallic deposits with ore grade around 0.1-0.2% U, located within the Kirovograd block of the Ukrainian Shield, and sandstone-type deposits with ore grade 0.01-0.06% U located within the 17,300 km² Dnipro-Boug metallogenic area. The latter contain molybdenum, selenium and rare earth elements in addition to uranium. The metasomatite deposits are suitable for underground mining while the sandstone type deposits are amenable to mining by in-situ leaching. In addition, the best estimate of Ukraine's undiscovered

(prognosticated and speculative resources) amounts to 277,500 tU.

Ukraine is one of the world's leading uranium mining countries, with uranium concentrate production of 500-800 tons per year. In total, 22 uranium deposits have been discovered in Ukraine, of which 4 are being developed (Fig. 4.7). There is no closed production cycle in Ukraine, so uranium ores are processed into the intermediate product and "yellow cake", with uranium content of 30-45%.

Producing uranium deposits in Ukraine are situated in two regions, Kryvyj Rig and Kirovograd. They occur in uraniferous albitite zones in the Ukrainian Shield and belong to the metasomatic class of deposit according to the IAEA (2018) classification scheme.

Globally, metasomatic or albitite uranium deposits occur in areas of tectono-magmatic activity affected by intense Na- or Na-Ca metasomatism that has produced albitized facies including albitite, aegirinite, alkali amphibole rocks and calcic-ferruginous facies along deeply rooted fault systems. Orebodies are of variable shape and size, composed of disseminated grains and thin veinlets of ore minerals.

Metasomatic uranium deposits worldwide contain as much uranium as unconformity-type deposits, although at typically lower grades. Albitite-type deposits are among the least well understood uranium deposits with a relatively sparse literature.

In both Ukrainian ore-bearing regions there are also some small uranium deposits of sedimentary type, palaeo-valley sandstone deposits within small Paleogene basins of continental sands and clays.



Fig. 4.7. Uranium deposits in Ukraine (modified after Mykhailov et al. 2007)

The main reserves in Ukraine are concentrated in Kirovogradska uranium ore area (UOA), where they are associated with the Precambrian structures of Ukrainian Shield (Severinivske, Michurinske, Kompaniivske, etc.). They are located in Precambrian gneisses and migmatites intruded by granitoids. Preliminarily estimated uranium reserves of the Kirovogradskiy UOA exceed 100 thousand tonnes, and resources are 200 thousand tonnes (Bakarzhiev et al. 1999).

The Vatutinske, Michurinske, Novokostyantynivske and Severynivske deposits are known in the Central Ukrainian UOA, and the Lozovatske, Pivdenne, Kalynivske deposits are known in the Pobuzkiy UOA. In addition, the Zhovtorichenske and Pervomaiske deposits, in Precambrian ferruginous rocks, were exhausted in the 90's, and there are uranium occurrences in ancient Precambrian conglomerates (Mykolo-Kozelske).

The Michurinske, Vatutinske and Novokostyantynivske deposits are operated by the Skhidniy MBP, Severinivske deposit is in reserve, other deposits are prepared for exploration. Operating uranium mines are located in Kirovograd (Ingulskiy) and Smolino village of Kirovograd region (Smolinskiy). The ore is processed by the hydrometallurgical plant in Zhovti Vody, Dnipropetrovsk region, the largest plant of this type in Europe.

The Michurinske deposit. This uranium deposit is located along the Kirovogradska fault zone in gneisses and migmatites of the Ingulo-Inguletska Series, and partly in Kirovogradski granites. It lies in a wedge-shaped tectonic block formed by north-trending faults, conformable to the gneiss-migmatite banding, and injections of Kirovogradski granites elongated in the same direction. The main ore-controlling structure is north-trending Main Eastern fault. Sodium metasomatites are developed in areas of numerous faults branching to the west off the Main Eastern Fault. Mineralization can be traced along strike for more than 1000 m, and down-dip for a few hundred meters, with the width of mineralization zone being up to 100 m.

The regions of sodium metasomatism are represented by core zones of aegirine-riebeckite or chlorite albitites, grading outwards into chloritized gneisses, migmatites or granites in the outer parts and then into unaltered host rocks (Cuney et al. 2011). Uranium mineralization in the form of lenticular and sheeted ore bodies is confined to the areas of strongly fractured and brecciated albitites. Of the ore minerals, uranium blacks (dispersed powdery mineralization of brownish-black colour, composed of uraninite, coffinite and/or ningyoite) and uranophane predominate; with about a third of ores represented by uranium silicates (nenadkevite, coffinite). Pitchblende (nastutan), uraninite and uranium titanates (brannerite, davidite) are of subordinate importance.

More than 15 ore bodies occur on the northern flank of the ore field with ores composed mainly of brannerite and oxidized uraninite; a new bismuth-uranium type of vein mineralization was discovered at the Obginniy occurrence, where U content reaches 15.5%, Bi 0.8-1.3%, and Pb up to 2%.

A swarm of younger mafic dykes crosses the albitites. The ore bodies are oxidized near the surface, and pinch out at depths of 150 to 550 m.

The Vatutinske uranium deposit is located in the western border of the Novoukrainskiy pluton, along a north-western extension of the Main Western fault, which dips steeply ($60-80^\circ$) to the south-west (Cuney et al. 2011). The area of the deposit is composed of Paleoproterozoic gneisses, shadow and striped migmatites, and granites of Kirovogradskiy complex. The bulk of ore-bearing albitites are located on the footwall side of Main Western Fault, in a strip more than 3 km long, 0.6 km wide, and more than 1.2 km deep. Albitites are divided into alkaline amphibole-aegirine and epidotechlorite varieties.

The host rocks dip south-westward at an angle of $60-70^\circ$. In the east, the deposit is bounded by the Eastern Fault. This fault zone contains large areas of mylonites, brecciated and fractured rocks. The mineralized albitites extend for up to 3 km, are up to 600 m wide and pinch out at the depth of 800 m. They are surrounded by zones of porous pyritized syenites (Cuney et al. 2011).

Uranium ores form three bodies of north-western extension with a dip to the southwest at an angle of $40-80^\circ$: the Skhidna, which is controlled by the Skhidniy fault; the Tsentralna, which contains the main volume of the deposit and has a complex branched shape; and the Pivnichno-Zakhidna, confined to flat-laying structures of extensive cataclasis. Ore bodies are of lenticular or complex shape, forming systems of connected en-echelon lenses which pass into each other (Fig. 4.8).

The main uranium minerals are oxides (uraninite, pitchblende, uranium black and uranium hydroxides), silicates (nenadkevite, coffinite, uranofan, betauranotil, boltwoodite), and titanates (brannerite, davidite). Disseminated, fine-clustered and fine-veined ores are distinguished, medium-, fine- and coarse-grained, massive (in granites), banded and spotted (in migmatites), and schistose (in gneisses).

The isotopic age of mineralization is 1800 ± 50 million years, its genetic type is hydrothermal-metasomatic.

Uranium is concentrated in two zones in the regolith: an upper zone with a pitchblende-coffinite association at the base of the Buchatski coal-bearing sediments, above the zone of sulphide enrichment; and a lower zone of ningioit-pitchblende-coffinite at the base of the regolith, at the contact with leached albitite. There are also uranyl phosphates (otenite, phosphuranylite, parsonsite, dumontite), uranyl vanadates (carnotite, tyuyamunite, sengerite, francevillite), and uranyl silicates (uranofan, betauranotil, boltwoodite).

The Novokostyantynivske uranium deposit covers an area of 1.5×1.5 km in the north of the central part of the Novoukrainskiy Massif, in the area of its contact with the Korsun-Novomyrgorodskiy pluton. The deposit is controlled by the northern part of the Novokostyantynivska tectonic zone, which extends for 30 km north to south. In the northern part of the deposit, the tectonic zone is represented by the Western and Sichniy faults, dipping $45-70^\circ$ to the southeast. In the central part of deposit, Sichniy fault is bounded on the north by submeridional Sienitoviy and Eastern faults. Within the fault zones mineralized breccias from tens to hundreds of meters in length and up to 10-15 m thick are developed. They are associated with 178 lenticular and stockwork-type ore bodies, grouped into three ore zones several hundred meters long

along the Western, Sichniy, and Eastern faults. Uranium ores are encountered in the wells up to 1200 m deep. They are located mainly in biotite, aegirine, actinolite-riebeckite or chlorite-epidote albitites, surrounded by altered syenites. Ore bodies are sometimes crossed by dikes of mafic composition (Cuney et al. 2011).

According to international experts, the reserves of the Novokostyantynivske deposit are about 76 thousand tonnes of uranium ore.

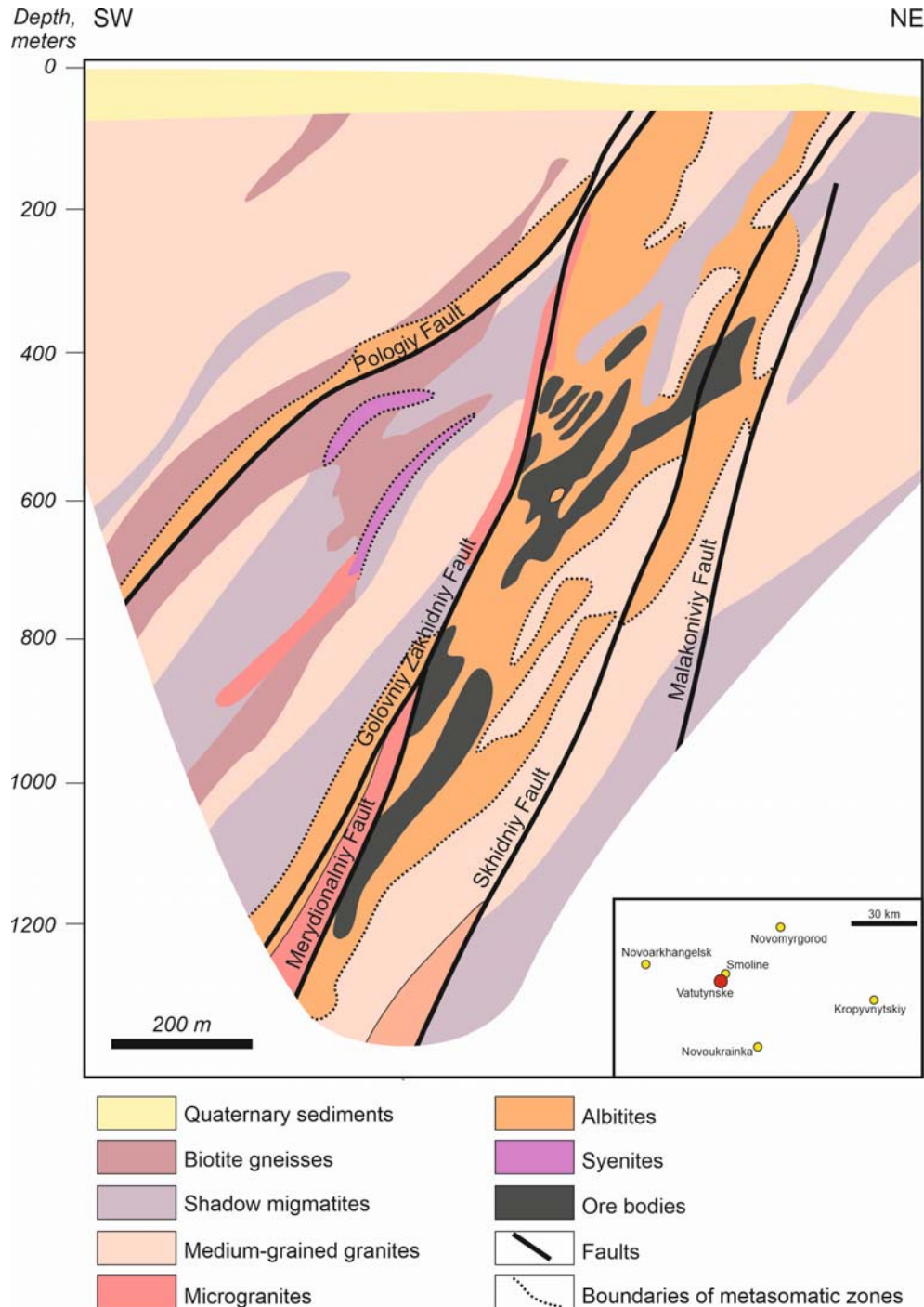


**Fig. 4.8. Cross-section of the Vatutynske deposit
(modified after Genetic types 1995)**

The Severynivske uranium deposit is controlled by a system of diagonal and north-trending faults of the Kirovogradska zone in the exocontact of Lelikovskiy Massif of

fine to medium-grained granites, as well as in the footwall, and partially hangingwall sides of the Severynivskiy Massif of porphyroblastic migmatites.

Two sections of deposit are distinguished: Pivnichno-Zakhidna and Skhidna. The first is confined to the system of faults in the south-eastern part of the Lelikovskiy Massif, where albitites with uranium mineralization are developed. Ore bodies form two complex sheeted and lenticular bodies of ore-bearing albitites up to 1 km long, with a thickness of tens to hundreds of meters, separated by a wedge-shaped block of barren rocks. The bodies strike north-west strike and dip northeast at 55-65°. Mineralization was traced to a depth of 1 km down-dip. Ore bodies are located in cataclastic zones along faults, swelling at the intersections of tectonic sutures with contact zones of different rocks.

The ores are disseminated aluminosilicate with ordinary and low-grade uranium content, with uraninite, silicate and oxidized varieties distinguished. The main uranium minerals are uraninite and yellow secondary silicates; less often brannerite, pitchblende, coffinite and oxidation products of brannerite are noted. Host albitites are hematite-carbonate-chlorite, hematite-carbonate-riebeckite-aegirine and hematite-carbonate-phlogopite in composition.

The eastern section is located between the eastern contact of the Severynivskiy Massif and the sequence of alternating migmatites and gneisses, in the footwall side of the Eastern fault zone. Mineralization is controlled by an arcuate structure, with the main part of ore-bearing albitites concentrated in the southern part. Extensive brecciation and silicification of rocks is characteristic, which complicates the morphology of ore bodies, producing numerous swellings and branches along strike and down dip.

Mineralization is confined to the junctions of faults of different orders, which led to the development of cataclastic zones within the ore-bearing tectonic block. Three groups of ore bodies are distinguished: Southern, Central and Northern, which form lenticular, spherical and en-echelon shapes. Host albitites are hematite-carbonate-chlorite in composition.

The following mineral types of ores are distinguished: brannerite, uraninite-brannerite, and oxidized. Uranium minerals include brannerite and its oxidation products, uraninite, pitchblende, uranium silicates and uranium black.

The Severynivske deposit has not yet been developed.

The Zhovtorichenske iron-uranium deposit is located in the central part of the syncline of the same name on the southern flank of the Kryvorizko-Kremenchtska synclinalorium zone, in rocks of the Saksaganska and Gdantsivska Suites. The width of the syncline ranges from 0.5 to 2.0 km, and the length in submeridional direction is more than 10 km. The main pre-ore faults dip almost vertically, intersecting host rock stratification at an angle of 5-25° with a displacement of up to hundreds of meters. Zones of brecciation and fracturing are developed mainly parallel to the host rock schistosity. These structures control development of metasomatic bodies up to tens of kilometres long and up to tens of meters thick (Cuney et al. 2011).

Uranium-bearing zones associated with sodium metasomatites are located within both limbs and the southern hinge of the Zhovtorichenska syncline and form sheeted,

lenticular and pipe-like bodies. Uranium mineralization is mainly found in albitites, but also in aegirinites and riebeckites. The Mykhailivsko-Olgivska ore zone occurs in the western limb of the syncline and includes 10 steeply dipping ore bodies up to 1 km long, which can be traced to a depth of 2 km. Three ore bodies up to 1 km along strike and up to several hundred meters down dip are developed within the eastern limb of the syncline. A mineralised ore zone with 10 ore bodies is located within the syncline hinge.

Uranium-bearing zones in the calcium metasomatites form layers that are generally conformable with, but sometimes crosscut, the metasedimentary sequences. They have no visible structural links with sodium metasomatic bodies. One of the zones, the Mykhailivska ore zone, is located within the western limb of the Zhovtorichenska syncline, and three in its eastern limb. They are hundreds of meters long, 400 to 900 meters deep and several meters thick (Cuney et al. 2011).

Several stratified zones of uranium mineralization occur within bodies of iron-carbonate metasomatites, including Mykhailivska, Main Western, Main Eastern, and Western Rivnobizhna. They are represented by veins with pitchblende, sulphide-pitchblende and malacon-apatite ores, as well as with bodies of metasomatites with a high content of Sc, V, Zr, Hf, TR. Six types of uranium ores are distinguished:

- uraninite, represented by iron-carbonate metasomatites with a fine dissemination of uraninite and sometimes pitchblende, in association with dolomite, iron-magnesium carbonates, and ankerite;
- brannerite, disseminated in amphibole-aegirine albitites with a low content of iron ore minerals;
- nenadkevite, in the Olgivsko-Mykhailivske body of albitites, magnetite-riebeckite schists, aegirinites and albite-riebeckite rocks, with uneven dissemination, bunch-like accumulations and veinlets of this uranium silicate.
- coffinite-pitchblende-brannerite, related to the oxidation of brannerite ores with the formation of chlorite, biotite, secondary carbonates and transformation of uranium minerals;
- sulphide-pitchblende, forming veins of up to a few centimetres in alkaline metasomatites of different composition; with sulphide content (pyrite, chalcopyrite, galena, sphalerite, and bornite) up to 1-2%. Other uranium minerals (brannerite, coffinite) are also present;
- malacon-apatite, represented by the early productive mineral association, which includes uranium minerals (brannerite, silicates and uranium oxides, uranium black), as well as monazite, xenotime, leucoxene, and iron hydroxides.

The infiltration deposits are confined to the paleo-valleys of the Dniprovskiy UOA, composed of Middle Eocene coal-bearing sediments of the Buchatska Suite. Ore bodies of the valley (Devladivske, Bratske, Novogurievskye deposits) and side-wall types (Sadove, Khutirskye, Tashlytske) are known. Mineralized coal-bearing sands predominate, sometimes mineralization occurs in coal-bearing clays and brown coal. Uranium is found mainly in the coal-bearing and clayey matter, sometimes uranium black, uranium-containing leucoxene and iron hydroxides are noted. Ore bodies as seen in plan have a complex isometric or elongated shape, and are multiple-level in cross-section, consisting of individual sheet-, lens- or roll-shaped ore bodies. The average uranium content is 0.015-0.030%.

Mineralization is controlled by zones of near-surface oxidation of local aquifers,

the lower limit of which does not extend below the water level in the Dnipro River (from +50 to +40 m). The following zones are distinguished: a) surface oxidation (meteoric water); b) soil oxidation (groundwater); c) soil-bed or bed oxidation (pressure infiltration waters); d) uranium mineralization, located under the lower surface of the soil oxidation zone or in the wedge of the soil-bed oxidation zone; e) epigenetically unchanged (non-oxidized) rocks.

Occurrences of uranium mineralization are also known in the formations of the lagoon-estuary (Surske and Chervonoyarske deposits) and lake-swamp complexes, where uranium mineralization is controlled by soil oxidation zones. It is confined to the upper parts of the Eocene coal-bearing sediments and commonly located in sandy brown coals, rarely in coal-bearing sands and clays. Reserves of deposits do not exceed 1-5 kt of uranium. Chervonoyarske, Safonivske, Novogurievsk and Surske deposits are the most favourable for testing by the underground leaching method.

Thus, the availability of large uranium reserves and the developed infrastructure of the uranium mining industry, still ensure the position of Ukraine as one of the most important uranium mining countries in the world. However, the relatively low uranium content found in most ores combined with expensive underground mining operations (sometimes at considerable depth) make doubtful the further important role of Ukraine in the markets of uranium raw materials due to the low competitiveness of the latter because of significant associated costs. Therefore, if deposits of new geological and industrial types (primarily "unconformity" and sandstone) are not discovered in Ukraine in the near future, we can expect a sharp reduction in uranium production from subsurface mining in the country.

4.2. Highly Promising Types of Raw Materials

Among the highly promising types of raw materials present in Ukraine are a number of rare and rare earth elements, namely the rare earths, zirconium and hafnium, lithium, scandium, and germanium. Some of them, namely rare earths and zirconium deposits, are of the complex-deposits type. Rare and rare earth elements are of strategic importance for modern sectors of the world economy, as they are widely used in the latest IT technologies, nuclear and jet technology, metallurgy, electronics, radio engineering, "green technology" and more. These elements include beryllium, lithium, rubidium and cesium, germanium, tantalum and niobium, zirconium and hafnium, scandium, strontium, cadmium, and the suite of rare earth elements.

The Ukrainian Shield is one of the most promising metallogenic provinces in the world in terms of rare metal and rare earth elements (Fig. 4.9), which are associated mainly with Paleoproterozoic alkaline and subalkaline intrusive complexes, carbonatites, and granite pegmatites (Kryvdyk, Tkachuk 1990, Zagnitko et al. 2017; Pavlyshyn et al. 2000).

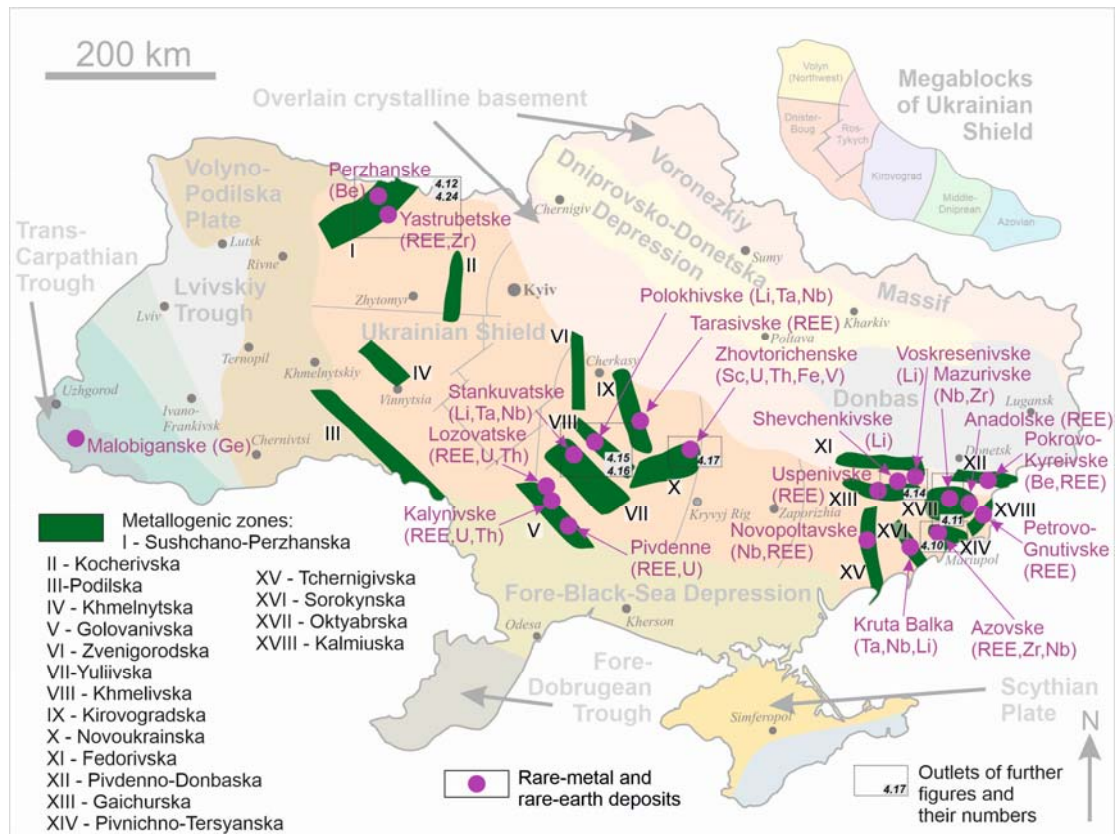


Fig. 4.9. Distribution of rare metal and rare earth deposits of Ukraine (modified after Mykhailov et al. 2007)

4.2.1. Rare Earths

In recent years, the topic of rare earth mineralization has become particularly relevant and has become of strategic importance for a number of industrialized countries (USA, EU, Japan, Australia, etc.), where rare earths are included in the list of critical minerals (Rare Earth 2020). This is due to two main factors.

First, the range of applications of the rare earth elements (REE) in modern high-tech processes, including "green technologies", has significantly expanded. Rare earths are used in the manufacture of permanent magnets, mobile phones, lasers, computer disks, batteries, electric and hybrid vehicles, luminophores for lighting, catalysts etc. They are also used in the manufacture of batteries for electric vehicles, monitors and flat-screen TVs, renewable energy equipment (e.g. solar panels, wind turbines, etc.), missile guidance systems, shipbuilding and submarines, and in hydrocarbons refining.

In addition, the global trend towards Green Energy Transition has significantly affected the priority of funding for exploration and mining, shifting it to finding alternative sources that will implement the chosen strategy through a smooth transition to carbon-free production in most areas. Second, in recent years China, as the main global producer of REE, primarily through the development of the unique Bayan-Obo deposit (Chao et al. 1997; Smith, Chengyu 2002), has imposed significant restrictions on rare earth exports, forcing many governments to step up prospecting and exploration of rare earths in their national territories.

These searches are aimed at identifying opportunities for the extraction of rare and rare earth metals, as the need for the latter is growing every year and is due not only to changes in the world economy but also the growing number of possible uses (Mykhailov 2010).

To date, the following countries have the largest known REE reserves (Mt): China (44), Brazil (22), Vietnam (22), Russia (12), India (6.9), Australia (3.3), Greenland (1.5), USA (1.4) plus others. In 2019, a total of 202.3 kt of rare earths were extracted in the world, including (kt): China – 132 (65% of world production); USA – 28 (13.8%); Australia – 17.6 (8.7%); Myanmar – 17.1; India – 4.2; Russia – 2.6; Brazil – 0.6, Malaysia – 0.114, Burundi – 0.068 (Table 4.17). There is a steady significant increase in REE production from 124 kt in 2015 to 202 kt in 2019, especially significantly production increased in countries such as Myanmar, India, Australia, USA and China.

Table 4.17. World REE mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Mining, t					Reserves, kt
	2015	2016	2017	2018	2019	
China	105,000	105,000	105,000	120,000	132,000	44,000
USA	3,678	0	0	14,000	28,000	1,400
Australia	10,916	13,872	17,264	18,556	17,613	3,300
Myanmar	230	2,730	5,000	20,400	17,100	n.a.
India	956	2,265	2,724	4,215	4,200	6,900
Russia	2,312	3,063	2,500	2,596	2,620	12,000
Vietnam	-	220	100	920	900	22,000
Brazil	1,040	2,900	1,700	1,100	600	22,000
Malaysia	565	1,876	302	86	114	n.a.
Burundi	-	-	31	631	68	n.a.
Total	124,697	131,926	134,621	182,504	203,215	111,600

Ukraine is the largest rare earth metallogenic province in Europe and has significant REE resources. There are known deposits of both traditional types associated with carbonatites (Novopoltavske) and mariupolites (Mazurivske), and non-traditional types: high-grade zirconium and rare earth-zirconium ores of nepheline-free syenites (Azovske, Anadolske, Yastrubetske); high-grade cerium ores (Petrovo-Gnutivske); feldspar metasomatites of uranium ore deposits (Severynivske, Lozovatske, Kalinivske, Pivdenne, Balka Korabelna); weathering crust (Khashchuvatske, Azovske); and monazite-containing placers (in Volyno-Podilskiy and Pryazovskiy areas of the Ukrainian Shield). This type of raw material, REE, is strategically important for the economy of our country, although its deposits are not yet developed (Gurskiy 2008).

Of these, the special permits (licenses) for exploration and mining are granted at Yastrubetske deposit (Yastrubetska section) to LLC "TsFR Group", and at Anadolske deposit in Pryazovya – to LLC "RM Minings". Licensing proposals are open for the Azovske deposit, Starodubivske and Dianivskiy occurrences in Donetsk region, and the Gurivskiy occurrence in Dnipropetrovsk region. The total reserves of rare earth

ores in Ukraine are estimated at 2.6 billion tons, TR_2O_3 reserves – at 2.2 Mt, and TR_2O_3 resources – at 3.4 Mt (Mineral Resources of Ukraine 2021).

Ukraine has advantages in the development of REE mineral resources, which are associated with the presence of complex deposits and ore occurrences, but their industrial development and additional research requires significant investment. A positive factor for our facilities is the developed infrastructure of the mining industry in almost all regions and the proximity to the European consumer market.

Numerous teams of explorers (SRGE Pivnichgeologiya, SE Pivdenukrgeologiya, SE Kirovgeologiya, Skhid SRGE) and scientists (IGMOF NAS of Ukraine, IGN NAS of Ukraine, Kyiv NU) have studied REE mineralization in Ukraine (Gurskiy et al. 2006a; Zagnitko et al. 2017; Mykhailov et al. 2007, 2021a; Mitskevich et al. 1986; Mineral Resources of Ukraine 2017; Melnikov et al. 2000). The results of exploration and research works are summarized in the provisions of the National Program for Development of MRB of Ukraine until 2030 (Law 2011a).

According to the item "Rare earths and yttrium", several hundred REE mineralization sites are identified in Ukraine, most of which are located in the Ukrainian Shield and adjacent areas. A rare-earth metallogenic province has been identified there, where mineralization of almost all known endogenous and exogenous rare-earth formations is found. In this province, three areas of rare earth mineralization are considered, where deposits and promising ore occurrences are known: Pivdenno-Skhidniy, Pivnichno-Zakhidniy and Tsentralniy. Novopoltavske apatite-rare metal ore deposit is recorded by the SIMR. Also, the Azovske deposit of rare earths is known, which was identified by the results of prospecting-exploration works.

The National Program provides the following steps for further development:

- preparation for test-industrial development of Azovske zirconium-rare earth deposit;
- assessment of resources of Shevchenkivske ore field, Anadolskiy occurrence and Khrystoforivska site;
- assessment of rare earth ores in weathering crusts of Sushchano-Perzhanska zone;
- geological assessment of promising ultrametamorphic complexes of Ukrainian Shield.

As of January 1, 2021, reserves of three deposits – Novopoltavske, Anadolske and Yastrubetske – were recorded by the SIMR. These are all complex deposits.

Carbonatites of Novopoltavske deposit, mariupolites of Oktyabrskiy Massifs, and alkaline metasomatites of Sushchano-Perzhanska zone are of particular interest. By the affinity to rock types, endogenous rare-earth mineralization can include: 1) zirconium-thorium-rare-earth mineralization in granites, syenites and pegmatites (Mykolaivske and Sabarivske deposits in Middle Dniprean megablock, Yastrubetske in Polissya, Uspenskiy occurrence in the Azov region); 2) yttrium-rare-earth-zirconium and cerium-lanthanum in alkaline syenites (Azovske, Anadolske, Petrovo-Gnutivske deposits of the Azov region); 3) uranium-thorium-yttrium-rare earth in potassium and sodium metasomatites (Lozuvatske, Kalynivske, Pivdenne – Kirovogradskiy uranium ore area (UOA).

There are four other important areas of potential development of endogenous rare earth mineralization:

1. Podilskiy, where it is associated with the granites of the Berdychivskiy and Zhytomyrskiy complexes, diorites and granodiorites of Zvenigorodskiy Complex;
2. Perzhanskiy ore field with Perzhanski granites, syenites and potassium metasomatites with zircon and britolite (Yastrubetske);
3. Kryvorizkiy UOA with potassium and sodium metasomatites, syenites of Korsun-Novomyrgorodskiy Complex;
4. Pryazovskiy with granites and pegmatites of Saltychanskiy, Anadolskiy, Kamyanomogylskiy complexes, carbonatites of Chernigivskiy Complex (Novopoltavske deposit), and syenites of Pivdenokalchykyskiy Complex (Azovske deposit).

The Novopoltavske complex carbonatite rare-metal-apatite deposit of the Azov area Zaporizhia region, is located in carbonatites of the Chernigivskiy Complex in the zone of the sub-meridional Orikhovo-Pavlogradskiy fault (Voinovsky et al. 2000; Glevaskiy, Kryvdik 1981). This deposit belongs to the phosphorus-rare-earth-rare-metal ore formation in carbonatites. The following associations of rare metal minerals are distinguished:

- 1) getchellite with baddeleyite in calcite carbonatites;
- 2) monazite-cerite-fergusonite in calcite and dolomite-calcite carbonatites;
- 3) pyrochlore-columbite with zircon in carbonatite phenites;
- 4) pyrochlore-zircon in syenite alkaline rocks.

Apatite carbonatites, nepheline and alkaline syenites constitute en-echelon steeply-dipping bodies from 10-20 up to 100 m thick, extending for the distance from a few hundred meters to a few kilometres. The bodies are composed of calcite and calcite-dolomite carbonatite ores, and are dyke- and stockwork-like in shape. Ore components are represented by apatite with minor monazite, pyrochlore, cerium fergusonite, columbite, getchellite, zircon, baddeleyite, orthite, aeschynite, and fersmite. The average apatite content in the carbonatites is 10%, sometimes reaching 30-50% in small phoscorite bodies.

Table 4.18. Minor REE content in apatite of Novopoltavske deposit

Element	Content, g/t
Y	150-600
Sm	250-400
Eu	40-150
Tb	40-100
Yb	10-20
Lu	0.3-0.7

The total REE content in the ores ranges from 0.17-4.6%; Nb_2O_5 – 0.06-0.3%; Ta_2O_5 – 0.002-0.003%; P_2O_5 – 4.3%. The main rare earth mineral is monazite, in which the REE content reaches 65%. Monazite has a low content of thorium (0.1-0.3%), which increases the value of the concentrate of this mineral. In addition, REEs are concentrated in apatite (average content 1.0-1.5%, maximum content 8-11%), where Ce (0.6-1.1%) and La predominate (0.1-1.6%), with minor REEs shown in Table 4.18. The Sr content usually does not exceed 0.5-0.7%, although sometimes it can reach 1.5-2.5% and even 5%. The age of mineralization is 2.19-1.99 billion years. In linear weathering crusts (up to 50-370 m thick) the content of useful components increases several times. Prognostic resources of the deposit by analogy with global examples of the same class, according to S.G.Kryvdyk (Mykhailov, Kryvdyk 2004), can reach 1 Mt of monazite (up to 500 kt of REE) and 200 Mt of apatite (up to 2 Mt of REE) to a depth of 500 m.

The weathering crusts are of high practical interest, where columbite and apatite are concentrated, the thickness of which in some areas such as adjacent to fault zones, can reach 300 m.

In addition to carbonatites, ore-bearing rocks in the Chernigivskiy Complex of the deposit can also include alkaline pyroxenites with ilmenite, as well as phenites. In the latter, the content of Nb_2O_5 is 0.15-0.37%, and zirconium up to 0.7-1.0%. Ore minerals are represented by columbite, pyrochlore-getchellite and zircon (Zagnitko et al. 2017).

Resources of hard-rock hosted complex ores (phosphorus, tantalum, niobium, fluorine) are assessed to be 384.7 Mt (Mykhailov et al. 2007). The deposit has been explored and prepared for mining. It is planned to develop the deposit to a depth of 600 m with a pillar 100 m high to support the unstable rocks of the weathering crust zone. Development is planned to be carried out from below, underground mining, by chambers with back-filling of the mined space.

It is estimated that extraction of REE from apatite alone can recover all costs for the development and operation of the deposit. PJSC “Volyn Mining and Chemical Company” received in the past a special permit for the extraction of rare metal-apatite ores of Novopoltavske deposit. Currently, however, mining at the field is not being carried out and the special permit has been cancelled.

The Mazurivske (Oktyabrske) deposit located in the Donetsk region belongs to the complex zirconium-rare-earth-niobium class. It is confined to the Oktyabrskiy Massif of nepheline syenites with pyrochlore-zirconium ores in albitites and mariupolites. The Massif is oval in shape, some 7-8 km long and 5-6 km wide, elongated in the north-eastern direction (Fig. 4.10). It is composed of subalkaline mafic and ultramafic rocks (gabbro, pyroxenites, peridotites), along with alkaline and nepheline syenites (foyaite, mariupolites).

In the north-eastern part of the Massif, four flat lying (from horizontal to 30-35°) plate-like bodies of mariupolites with a thickness of 1 to 79 m are found in gabbroids and pyroxenites (Zagnitko et al. 2017). The rock-forming minerals of mariupolites are represented by nepheline, albite, aegirine, and sometimes microcline; ore minerals present in the mariupolites and related albitite are pyrochlore, zircon, and britolite.

Mineralization is controlled by zones of extensive albitisation in three sites: Balka Mazurova (0.6×0.8 km), Balka Koshkodieva (0.4×0.5 km), and Balka Dolynikova (0.2×0.1 km). Ore bodies are flat vein-like in shape and up to 30 m thick, on which a strong kaolin weathering crust is formed in the upper part. Ore minerals in albitized nepheline syenites, mariupolites, and microcline-nepheline syenites are represented by zircon (0.1-1.8%) and pyrochlore (0.2-0.8%). Zircon crystals are mostly bipyramidal, 0.1-0.7 cm in size, but some isolated crystals 4 cm in size are also known. It is usually metamictic, opaque, brown-coffee-coloured zircon; skeletal and zonal forms are widely developed. The content of Hf in zircon is 0.62-1.05%, REE is 0.14-0.31%.

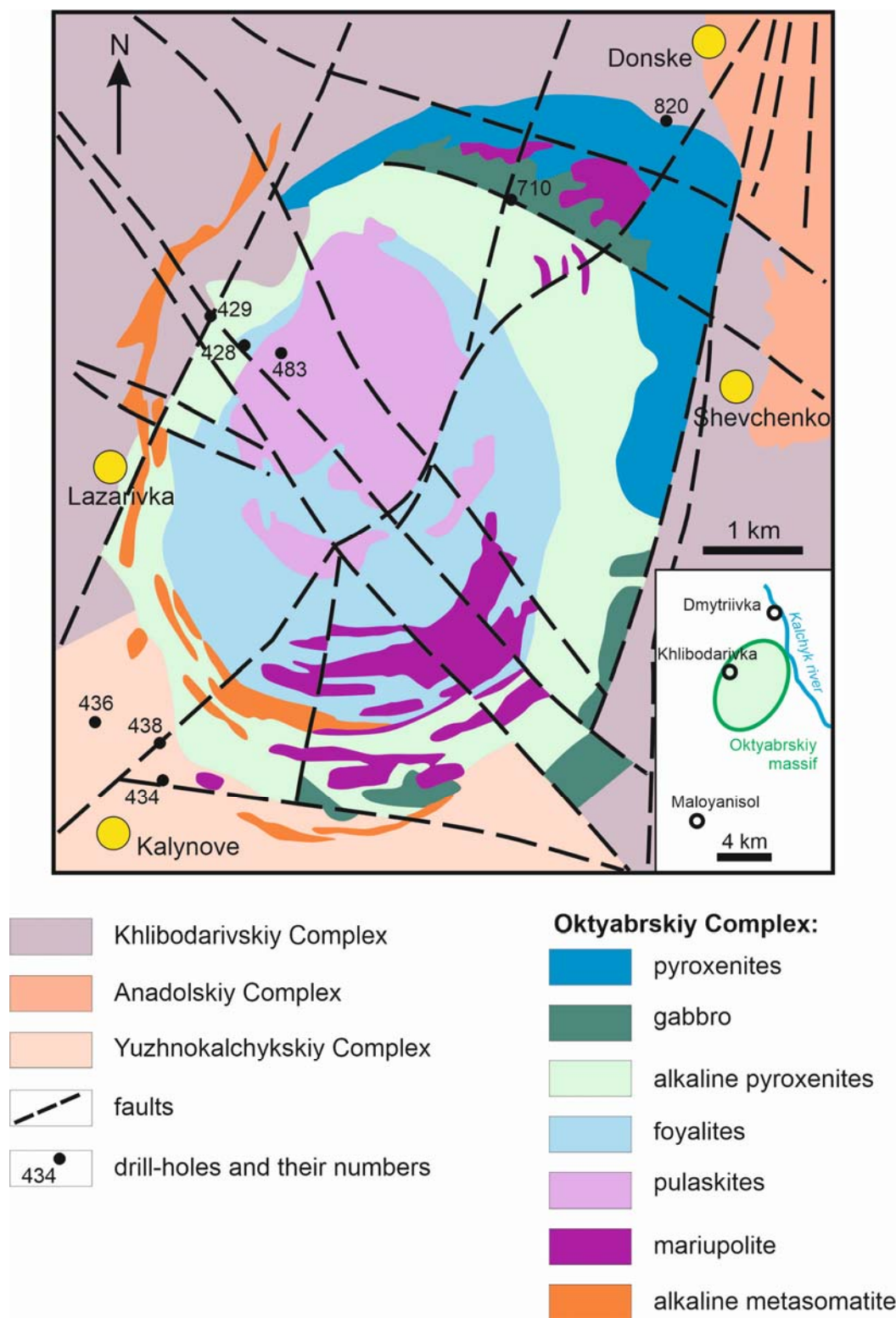


Fig. 4.10. Geological map of the Oktyabrskiy Massif (modified after Donskoy 2004)

The presence of pyrochlore determines the tantalum-niobium rare metal specialization of the deposit. It occurs in the form of octahedral crystals 0.02-0.08 mm in size, occasionally up to 0.5-1.0 mm, and is dominated by honey-yellow crystals, which form stream-like clusters. According to the peculiarities of the chemical composition, the mineral belongs to the niobium varieties with the content of Nb_2O_5 43.60-56.45%, Ta_2O_5 3.10-5.42%, REE – about 6%.

The REE content in ores averages 0.2%, in britolite – 65%, in pyrochlore – 1-5%.

Complex development of the ores as aluminous raw materials with the accompanying extraction of REE is planned under presently developed technological schemes (Donskoy 1983). Estimated resources of the deposit are 200 kt of TR_2O_3 .

The Azovske deposit of the Donetsk region belongs to a new industrial-genetic type, and has no world analogues. It is located in the northeastern part of the Volodarskiy Massif of the Azovian megablock; the Massif is composed of intrusive rocks of the Paleoproterozoic Pivdennokalchykyskiy Complex. It is confined to a series of syenite stocks, the largest of which is Azovski (1.3 km²), composed of alkaline feldspar, pyroxene-amphibole, quartz syenites and pegmatites of the Paleoproterozoic Pivdennokalchykyskiy Complex (Metalidi, Nechaev 1983; Melnikov et al. 2000). Amphibole syenites and alkaline metasomatites are widely developed. Nine ore bodies, represented by crescent-shaped lodes up to several meters thick, were found (Fig. 4.11).

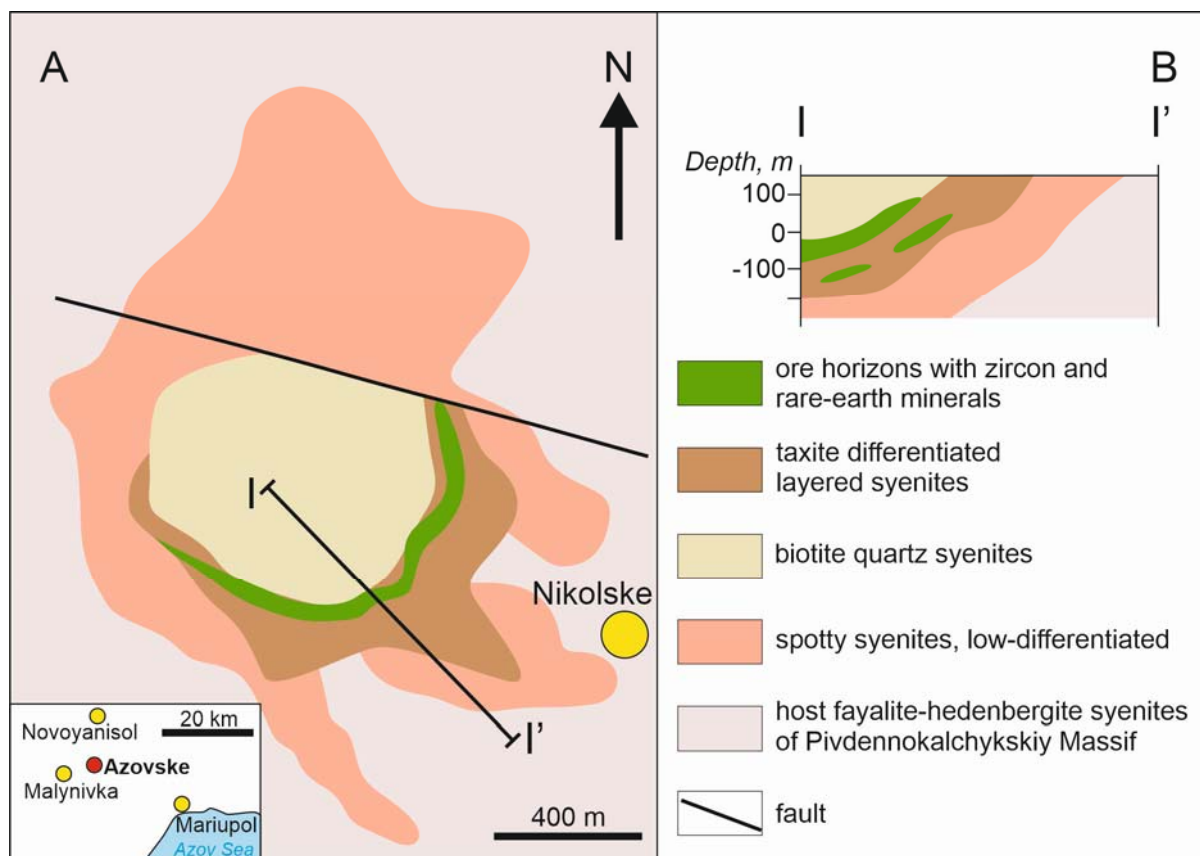


Fig. 4.11. Geological map (A) and cross-section (B) of the Azovske deposit (modified after Mykhailov et al. 2007)

The main ore body is 1640 m long and 32 m thick on average. Ore-bearing varieties are most often represented by meso- and melanocratic syenites (with ferrohastingsite, hedenbergite, fayalite), and less often by leucocratic ones. Ores are disseminated, ore minerals include: britolite (predominant), bastnaesite, orthite, zircon, monazite, chevkinite, itrialite, magnetite, rhabdofanite, fluorite. The average content of TR_2O_3 – 1.27%, ZrO_2 – 1.5% (Melnikov et al. 2000). The analytical content of a technological sample is shown in Table 4.19. In addition, U (0.0012-0.0142%) and Th (0.0035-0.094%) are present in the ore.

Table 4.19. REE content of technological sample, Azovske deposit

Element	% of the amount of REE
Ce	46.8
La	19.0
Nd	18.5
Pr	4.3
Sm	3.3
Dy	1.7
Er	0.4
Tb	0.3
Ho	0.3
Tm	0.1
Lu	0.1
Y	0.5

Zircon forms dense disseminations (1-3 mm), grain intergrowths, ore aggregates, and intergrowths with feldspars, amphiboles, and rare-earth minerals. Britolite (the main rare earth mineral) forms inclusions, intergrowths and aggregates of prismatic crystals, irregular in shape and up to 2-3 cm in size in pegmatoid areas. It occurs in paragenesis with zircon, orthite and rare chevkinite. Britolite is a complex rare-earth mineral, usually dominated by its essential cerium varieties, less so yttrium ones. Significant content of Y (up to 6-10% of the amount of REE) increases the industrial value of raw materials. Orthite is associated with zircon and britolite, and in the cataclastic areas, together with magnetite and fluorite, it fills veinlets in the feldspar mass.

Bastnaesite is observed in the form of individual

grains, bunch-like aggregates, inclusions in zircon, fluorite and vein minerals, and in pseudomorphs after britolite and orthite. Composition of bastnaesite is given in Table 4.20.

Prognostic resources of the deposit to a depth of 300 m are estimated at 56 Mt of ore with an average content of TR_2O_3 1.27% (with 0.4 cutoff) and Zr_2O_3 – 1.5%; some 710 kt of TR_2O_3 , of which 20% are provided by Y-lanthanides, as well as 840 kt of Zr_2O_3 .

Technological studies of the ores have shown the possibility of using the scheme of gravitational-magnetic beneficiation of their granular fraction and flotation enrichment of sludge. Processing of concentrates into selective rare earth products is possible at Prydniprovskiy Chemical Plant (Kamyanske town). The technology of hydrometallurgical refining allows transfer into solution of about 72-97% of REE, which then can be easily extracted by ion exchange technology. Zircon concentrate corresponds to the grade "zircon metallurgical concentrate", and the feldspar is suitable for use in the glass industry.

Unfortunately, the beginning of industrial development of the deposit is constrained by technological and economic difficulties. REE in the deposit are concentrated mainly in silicate form – britolite, which in terms of physical properties and REE content is less suitable than monazite, something which results in low rates of technological extraction. The obtained concentrate with a TR_2O_3 content of about 13% is not competitive compared to the standard world monazite concentrate, in which the amount of TR_2O_3 reaches 55%; a situation which requires additional technological research to be carried out.

Table 4.20. Composition of bastnaesite, Azovske deposit

Element	Grade, %
Y_2O_3	4.14
TR_2O_3	56.36
La	12
Ce	21
	Grade, g/t
Sm	105
Eu	1,070
Th	2,700
Yb	42
Lu	0.8

In recent years, SE Pivdenukrgeologiya has carried out additional prospecting and assessment works at the deposit and evaluated reserves and promising resources of complex zirconium-rare earth ores.

The Yastrubetske deposit of zirconium ores, which is similar to the previous one, has not yet revealed high-grade REE ores, although the syenites have the same set of minerals (britolite, orthite, bastnaesite) as in Azovske deposit. The Yastrubetske deposit is described below in the section "Zirconium".

The Uspenivskiy occurrence of the Azovian area is confined to the bodies of pegmatites and pegmatoid granites. It is located in albitized marginal parts. Host rocks are represented by quartzites and gneisses of the Osypenkivska Series. The thickness of ore bodies varies from a few centimetres to 59 m with a length of up to 300 m. The REE content is from 0.03 to 0.11%, Y – up to 0.015%. Productive weathering crust, discovered at a depth of 78-92 m, contains up to 5.45 kg/t of xenotime and up to 34 g/t of monazite, and has high radioactivity. The age of uranium mineralization in pegmatoid granites is 2.0-1.9 billion years.

The Anadolske deposit is represented by an ore zone that crosses the Anadolski granites and metamorphic rocks of the Zakhidnopryazovska Series to the southeast of the Oktyabrskiy Massif. The zone (0.7-3.0 m thick with a length of 1000 m) is gently dipping (30-45°) to the south-west and can be traced to a depth of 400 m. It is characterized by vein-stockwork fluorite-apatite-orthite mineralization with TR_2O_3 content – 0.1-16.7% (average – 9.23%). Ores are massive, spotted, coarse and thin-banded, with a high content of Fe_2O_3 , Fe and Ca, high – Mn, P and F, low – SiO_2 and Al_2O_3 . Rare earth minerals include orthite, cerite, bastnaesite, apatite and fluorite. Orthite forms bunches and lenses (up to 10-15 cm in size) of bundle- and fan-shaped aggregates of elongated prismatic crystals (0.5-1.5 mm) and contains 23.7% TR_2O_3 . Cerite forms inclusions of small xenomorphic and isometric grains (0.5-2.0 mm) in orthite aggregates, inclusion in fluorite, and contains 70.1% TR_2O_3 . Bastnaesite is confined to the intergranular areas of orthite and replaces the latter. The TR_2O_3 content in bastnaesite is 60%. Apatite and fluorite (2.9 and 0.8-1.12% TR_2O_3 , respectively) form thin layers in banded ores, which alternate with orthite layers, and chemically belong to the cerium varieties of apatite and fluorite. The ore reserves of the deposit are significant, industrial research at the Prydniprovskiy Chemical Plant has yielded positive results.

The Petrovo-Gnutivske occurrence is located in the valley of the Kalmius River northeast of Mariupol and is represented by a steeply-dipping fluorite-rare earth-carbonate vein (up to 3 m thick) hosted in fenitized granosyenites of the endocontact zone of the Kalmiuskiy Massif. The vein can be traced in the north-eastern (20°) direction for 1 km and to a depth of more than 150 m. It is composed of coarse-grained and massive aggregates of calcite, bastnaesite, parisite and fluorite. The host diallage syenites in the ore body footwall are phenitized (25-30 m thick). Phenites are represented by albitized potassium feldspar rocks with opal-like blue quartz and form a stockwork system of veins with a high (up to 11%) concentration of orthite. In the hanging-wall, granosyenites are transformed into apatite-sphene-albite-arfvedsonite-

aegirine phenites with zircon, chevkinite, ilmenite, magnetite and hematite developed.

This zone (up to 10 m thick) is cut by veinlets of titanite (containing 0.37% Nb₂O₃ and 1.28% TR₂O₃), fluorite and calcite. In the hanging-wall contact of the ore body the rims of fluorite-carbonate-aegirine composition are observed. Ore paragenesis is represented by the early association of fluocerite, bastnaesite, parisite, calcite, and the late association includes fluorite, galena, argentite, and other sulphides. The isotopic age of galena is 2.1-1.92 billion years. Sometimes the content of rare-earth fluorocarbonates reaches 15-20% with a content of TR₂O₃ 62.6% in bastnaesite and 52.3% in parisite. The ore has a selective cerium composition. In parisite La+Nd comprise 94.7% and Sm+Lu – 5.3%, and in fluorite the content of Y and heavy lanthanides – 87.6 and 98.3% of the total REE content.

Rare earth mineralization associated with feldspar metasomatites is known in uranium ore fields and deposits of the Kirovogradskiy UOA (Lozuvatske, Kalynivske, Pivdenne), where both albite and sodium-phosphorus metasomatites, with uranium-thorium-zirconium mineralization, are developed (malacon, monazite, orthite, xenotime), as well as apatite.

Table 4.21. Composition of the ore and xenotime in Balka Korabelna occurrence

Element	Grade. %	
	Ore	Xenotime
REE	up to 4.4	n.a.
Th	0.6	0.92
U	up to 0.2	1.64
Yb	0.092	8.5
La	0.177	0.2
Gd	0.05	2.7
Tb	n.a.	0.5
Er	0.092	6.7
Tu	n.a.	1.1
Dy	0.12	7.3
Ho	n.a.	2.0
Pr	0.055	0.2
Nd	0.197	0.7
Sm	0.046	0.9
Eu	n.a.	0.1
Ce	0.485	0.6
Lu	n.a.	1.6
Y	0.945	30

Characteristic rare-earth deposit variant associated with potassium metasomatism is represented by the **Balka Korabelna occurrence**, discovered in 1959. It comprises a steeply-dipping lenticular batch of northeast-trending intensively cataclased rocks in granitized gneisses and migmatites cut by pink pegmatite veins (up to 0.5 m thick). The zone is 70 m long and 40 m wide, and is traced to a depth of 50 m. The thickness of individual ore bodies reaches 20 m. The content of the ore is given in Table 4.21. Ore bodies are composed of fine-grained inclusions and segregations of monazite, xenotime and apatite in coarse-grained rocks consisting of biotite, feldspar and quartz with subordinate almandine and magnetite. The main ore minerals are monazite and xenotime, less abundant are

apatite and uraninite. The bulk of rare earth phosphates in ore bodies is confined to the sections of biotite rocks that have undergone microclinization.

Rare earth phosphates that occur in biotite in the form of single grains, during biotite microclination form segregations along the cracks of its cleavage and in contact with the microcline. Monazite and xenotime are concentrated mainly in magnetite, forming granular aggregates and individual crystals. Inclusions of

xenotime and monazite of irregular shape are observed in apatite, which probably represent the first generation of rare earth phosphates. Composition of xenotime is shown above in Table 4.21. Both high uranium (1.1% U) and low uranium (about 0.1% U) monazite grains are found. The isotopic age of xenotime and high-uranium monazite is 2045-1815 million years.

In connection with the carbonatite and alkaline complexes of the Ukrainian Shield, other potential sources of REE are also known (Malotersyanske pyrochlore-getchellite deposit in Middle Dniprean area; Perzhanske beryllium deposit with rare-earth mineralization; Proskurivskiy and Antonivskiy Massifs of alkaline rocks in Pobuzhya, etc.). Thus, the already known deposits of rare metals can not only meet Ukraine's needs in REE, but can also be a reliable source of foreign exchange earnings through the possible export of their concentrates (monazite, chlorides, oxides and fluorides of rare earths, xenotime, etc.).

The Khashchuvatske deposit, known since the early twentieth century as an iron-manganese source, this is an example of supergene rare-earth mineralization associated with a weathering crust. It is located in the weathering crust cap of the Umanski rare-earth granites, metasomatites, metamorphosed ultramafics, calcareous-magnesium skarns, chloritized and silicified amphibolites found in the Y-shaped junction zone of the Khmelnytskyi, Talnivskiy and Odeskiy faults. The weathering crust has a considerable thickness (20-100 m) and a clear kaolinite profile. The thickest crust (up to 100 m) is found in the form of pockets on metasomatites of granite exocontacts. Its feature is the increased iron content up to the formation of iron ores. Mineralization is represented by a body (13.7 m thick) of iron-kaolinite-hydromica ores, where REE are contained in the form of adsorbents on the surface of iron and clay minerals, partly in the form of separate minerals (churchite, rhabdofanite). Ores have a significant yttrium composition (Y_2O_3 – 85% of TR_2O_3). Churchite and rhabdofanite form small bunches, kidney-shaped and complex in shape, layers of coarse- and fine-grained, sometimes spherulitic structure. There is also rutile, zircon, spinel, barite, and apatite present. The chemical composition of the body in the weathering crust of metasomatites and calciphyres is characterized by high content of Fe_2O_3 (20.12%) and MnO (1.59%). Churchite and rhabdofanite extraction is possible by gravity separation scheme.

In addition to hard-rock deposits, large titanium-zircon-ilmenite placers are known in Ukraine, present in the Zhytomyr region (Gnilopyat, Sob, Rostavytsia rivers, Zhezhelivska gully) and in Pryazovia (Kalchyk River, coastal placers of Azov Sea), which can also be an additional source of REE. The average content of monazite is from 120-144 (Volyn) to 450-900 g/t (Pryazovia).

We have ranked the known occurrences of rare-earth mineralization according to their investment attractiveness (Mykhailov et al. 2021a). The industrial value of a deposit (occurrence) was determined based on the following criteria:

- degree of geological, technical and economic study;
- the size of deposit (occurrence), amount of reserves and resources;
- content of useful components (average, minimum and maximum values);
- thickness and depth of ore bodies;

- complexity of geological structure, mining-geological and mining-technical conditions of extraction;
- complexity of deposit, the presence of concomitant components;
- technological features of the ore beneficiation process.

According to the results of the ranking of domestic deposits and occurrences of REE, a group of the most investment-attractive targets has been identified, which includes the Novopoltavske, Anadolske, Azovske deposits, and the Balka Korabelna occurrence. Additionally, a group of targets with a high degree of investment attractiveness: Yastrubetskiy Massif, Perzhanskiy ore camp, Petrovo-Gnutivske occurrence, Budenivskiy, Portoviy, Vasylivskiy, Temryutskiy, Maloyanisolskiy placers; and a group with an average degree of investment attractiveness: Pokrovo-Kyreivske and Mazurivske deposits, weathering crust of Azovskiy Stock, as well as the Mykolayivskiy, Katerynivskiy, Maloyanisolskiy, Krasnyanskiy, Uspenivskiy occurrences have been determined.

4.2.2. Zirconium

It is widely used in the nuclear energy, in the production of ceramics, piezoelectric elements, refractories, abrasives, foundries.

World reserves of zirconium are estimated to be 62 Mt. The largest reserves are in Australia (67.7% of the world), as well as South Africa, Mozambique, China, and the USA. The world zircon production has stabilized at 1.5-1.6 Mt in recent years, with the largest mining countries being Australia, South Africa, China and the United States, which together account for 77% of world production (Table 4.22).

Table 4.22. World zirconium mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Extraction of ZrO ₂ , kt					Reserves, kt
	2015	2016	2017	2018	2019	
Australia	687.3	600.0	570.0	618.0	710.0	42,000
South Africa	377.8	377.4	361.8	303.6	340.0	6,500
China	140.0	100.0	116.0	150.0	140.0	500
USA	60.0	50.0	45.0	100.0	100.0	500
Mozambique	51.8	68.2	74.0	76.6	87.1	1,800
Senegal	45.2	52.6	81.7	93.6	80.7	n.a.
Indonesia	30.9	34.8	29.5	53.7	73.1	n.a.
Kenya	26.0	39.7	42.2	36.4	30.4	120
Madagascar	11.9	15.6	26.0	22.4	28.5	n.a.
Brazil	22.6	21.3	22.0	22.0	22.0	n.a.
Other countries	70.8	69.1	67.6	67.5	53.9	10,580
Total	1,524.3	1,428.7	1,435.8	1,543.8	1,665.7	62,000

Ukraine has significant reserves of zirconium, which are associated with both placer and hard-rock deposits. The SIMR records reserves of 3 hard-rock and 8 placer deposits, as well as 4 technogenic ore sands and one man-made deposit, represented by waste from enrichment of weathered ores (Mineral Resources of Ukraine 2021).

According to Western experts, the resources of zirconium (Zr_2O_3) in Ukraine reach 840 kt, and annual production is 18 kt.

Complex placer deposits Malyshevske ("UMCC" LLC, Vilnogradskiy Mining and Metallurgical Plant and LLC "Motronivskiy MBP") and Vovchanske (LLC "Demurginsky MBP"), as well as technogenic deposit Balka Kruta (LLC "Non-Ferrous Metals") are currently being developed, and the Trostyanetske deposit (Zhytomyrburrozvidka LLC) is being prepared for development (Mineral Resources of Ukraine 2021).

The main source of mined zirconium in Ukraine at present are placer deposits, represented by four types:

- 1) coastal-marine complex zircon-rutile-ilmenite (Malyshevske);
- 2) ilmenite alluvial continental (Vovchanske, Tarasivske, Krasnokutske, Zelenoyarske, etc.);
- 3) ilmenite and apatite-ilmenite eluvial in the weathering crust of hard rocks;
- 4) zircon-rutile-ilmenite placers of sandy beaches and shallow shelf (Yagarlytske).

The Malyshevske deposit is described in the section "Titanium".

The Vovchanske deposit located in the Dnipropetrovsk region is represented by a complex placer in the sandy Middle Sarmatian sediments, or partly in the sands of Poltavaska Series. The placer is composed of three subparallel deposits – Northern, Central and Southern, up to 15-20 km long, 50-1050 m wide, and 3-7 m thick, which are overlain by sediments 0.9-33.5 m thick. The ore sands are fine-grained quartz, well sorted, without clay. The main minerals are ilmenite ($80-100 \text{ kg/m}^3$), rutile and leucoxene ($25-31 \text{ kg/m}^3$), zircon ($7-9 \text{ kg/m}^3$), as well as disthene, sillimanite, staurolite, and tourmaline. The northern part of the Northern deposit is richest in zircon, where the content of zircon in the heavy fraction is from 20-50 to 70-90%.

The Tarasivske deposit present on the Ros River in Kyiv region is represented by a placer up to 20 km long, in coastal-marine, partially deltaic, sediments of the Poltavaska Series. These include white, greenish-grey sands, which in ore layers are brown, fine-coarse-grained. The distribution of ore minerals in the productive sequence is uneven. The highest concentrations were observed in the south-western part of the placer, where in some cases the content of the heavy fraction reaches $100-200 \text{ kg/m}^3$, and the total share of ilmenite, rutile, zircon is 75%; in addition, there are monazite, xenotime, cassiterite, baddeleyite, celestine ore minerals present. The thickness of ore-bearing sequence is from 0.5 to 30 m (average 7 m), overburden thickness ranges from 1.5 to 47.5 m (average 27 m), and the average content (kg/m^3) of zircon 10.4, rutile 12.0, ilmenite 23.0. The deposit can be considered as a reserve base of Vilnogradskiy MBP.

The Krasnokutske deposit in the Kharkiv region is represented by two layers in the sands of the Poltavaska Series with sublatitudinal extension, thickness 1-20 m (average 7 m), depth 0.8-57.0 m. Concentrate grades are shown in Table 4.23. The average content of zircon (kg/m) is 5.3, rutile is 7.0, and ilmenite is 10.0.

Table 4.23. Average grades of zirconium concentrates at some deposits

Mineral	Krasnokutske deposit, kg/m ³	Zelenoyarske deposit, kg/t	
		Entire deposit	Western flank
Bulk content	up to 286		
Ilmenite	up to 120		
Rutile and leucoxene	up to 14		
Zircon	up to 70		
Average bulk content		52.7	104.4
Zircon		4.4	7.2
Rutile		0.5	13.1
Ilmenite		18.3	34.0
Leucoxene		1.4	1.15
Sillimanite		7.5	
Staurolite		7.25	

The Zelenoyarske deposit in the basin of the Roska River is represented by three parallel lenticular bodies extending to the north-west for 13 km, and up to 1 km wide present in the sands of the Beretska Suite. The concentrate grades are given above in Table 4.23.. The thickness of ore sands is 38 m, overburden – 34 m..

The Mokro-Yalinska group of titanium-zirconium placers is located in the Azov region, in the eastern part of Konko-Yalinska depression. Deposits are confined to the sands of Poltavska Series that cover an area of about 50 km² in the upper streams of Mokra Yali River. Due to the low content of zircon and ilmenite, the reserves are classified as prognostic.

Hard-rock zirconium mineralization is represented by Azovske, Mazurivske, Yastrubetske deposits, which, unlike placer deposits, are not developed. Due to the complex composition of ores, which, in addition to zirconium, often also contain rare earths, niobium, tantalum, etc., and significant reserves, in the near future they may become attractive to investors and then become developed.

The Azovske and Mazurivske deposits are described in the REE section.

The Yastrubetske deposit is located in the south-western part of Perzhansky ore camp, and is related to the alkaline syenite massif of the same name. It comprises several crescent-shaped ore-bearing zones up to 2 km long and 5-120 m thick, enriched with zircon (Fig. 4.12). Besides zircon, there are also ilmenite, magnetite, apatite, orthite, bastnaezite, parisite, fluorite, britolite and others in the ore zones. The total content of REE in the individual bodies ranges from 0.07-0.3%, and sometimes reaches 1.24% (Gurskiy 2008).

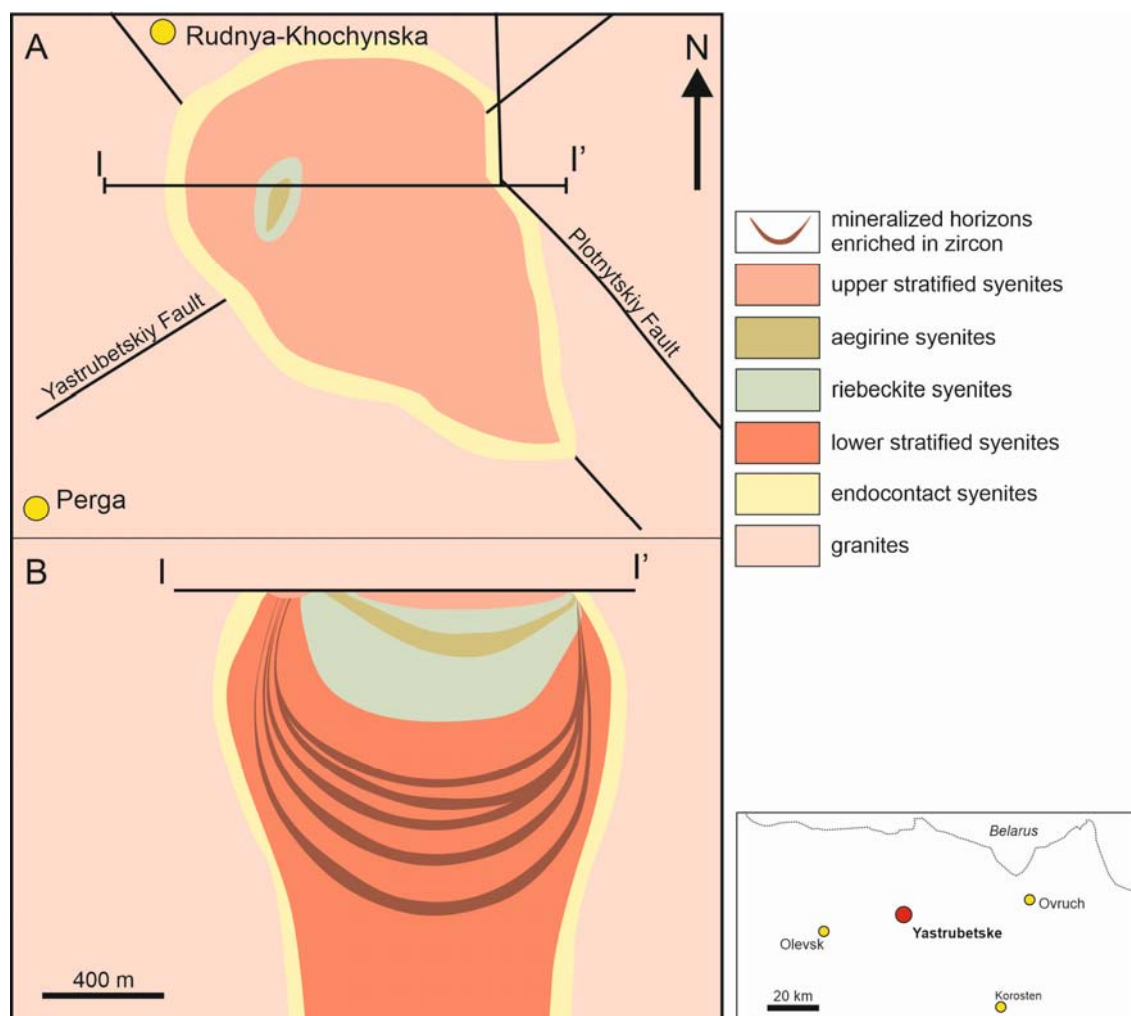


Fig. 4.12. Geological map (A) and cross-section (B) of the Yastrubetske deposit (modified after Mykhailov et al. 2007)

High-grade zirconium ores were discovered by drilling at depths of 500-1000 m, where they form several zircon-enriched horizons up to several meters thick (Zagnitko et al. 2017).

The main ore minerals are britolite and zircon, their composition is shown in Table 4.24. The composition of zircon is essentially yttrium, and britolite – yttrium-cerium. The deposit is considered to be large, but the considerable depth of known ore bodies (over 500 m) complicates any possible industrial development. It can be a source of concomitant extraction of non-metallic raw materials such as feldspar and fluorite.

4.2.3. Hafnium

It is used in nuclear energy for the manufacture of the control rods of reactors; radio engineering; in the manufacture of X-ray and television tubes; refractory and heat-resistant alloys for aviation, rocket engines, gas turbines; fire-resistant ceramics; manufacture of permanent magnets.

Table 4.24. Composition of some minerals of Yastrubetske deposit

Element	Grade. %	
	Britolite (Kryvdyk, Tkachuk 1990)	Zircon (Nechaev et al. 1986)
REE	up to 4.4	1.24
TR ₂ O ₃	50.2	
Y ₂ O ₃	10	
ZrO ₂	5-6	
Se ₂ O ₃	15-16	
La ₂ O ₃	6-7	
Gd ₂ O ₃	1	
Yb ₂ O ₃	0.6	
Tu ₂ O ₃	0.4	
Eu ₂ O ₃	0.1	
Hf		0.8
La		1.30
Ce		2.26
Pr		0.6
Nd		1.54
Sm		2.86
Gd+Eu		4.46
Tb+Y+Dy		65.86
Ho		2.66
Er		5.14
Tu		1.95
Yb		11.10
Lu		0.27

Industrial accumulations of hafnium in Ukraine are associated with complex zirconium deposits, as well as in alkaline igneous and metasomatic rocks of the Azovskiy and Korostenskiy plutons. The SIMR of hafnium ores is recorded in two placer deposits, Malyshevske and Vovchanske with 13.8 kt of hafnium oxide. The annual production was 267 tons of hafnium oxide in 2020 (Mineral resources of Ukraine 2021). It is extracted from concentrates of the Malyshevske deposit from the United Mining and Chemical Company and Motronivskiy MBP.

4.2.4. Lithium

This is one of the critical elements for the modern world. Most lithium is now used to make lithium batteries. It is estimated that the production of one battery for the Tesla Model S requires 63 kg of this metal with 99.5% purity. In addition, lithium is used in the manufacture of air conditioners, refrigeration equipment, common and dry batteries, galvanic cells with a hard surface. Lithium is also used in

the manufacture of glass and ceramics; in metallurgy, as chemical compounds. We can expect a significant increase in casting consumption in the near future.

Most of the world's lithium reserves are found in the brines of salt lakes of Bolivia and Chile, and in rare-metal granite pegmatites of the United States, Australia and Canada. A distinctive feature of many lithium deposits is their complexity. From the rare-metal pegmatites: tantalum, niobium, rubidium, cesium, tin, and beryllium are extracted in addition to lithium. Potassium, sodium, bromine, boron, and magnesium are extracted from the brines.

World lithium resources are estimated at 82.45 Mt, in particular (Mt): Bolivia – 21; Argentina – 17; Chile – 9; USA – 6.8; Australia – 6.3; China – 4.5; Canada – 1.7; Brazil – 0.4; Portugal – 0.25; Namibia – 0.09; other countries – 12.62 (including Congo (Kinshasa) – 3; Germany – 2.5; Mexico – 1.7; Czech Republic – 1.3; Mali – 1.0; Russia – 1.0; Serbia – 1.0; Zimbabwe – 0.54; Spain – 0.3; Peru – 0.13; Austria – 0.05; Finland – 0.05; Kazakhstan – 0.05). The world reserves reach 17 Mt, the largest are concentrated in Chile, Australia, Argentina, China and the United States; the

largest producers are Australia (54.3% of world production), Chile (25.2%), China (8.8%), Argentina (7.2%) (Table 4.25). In recent years, there has been a trifold increase in lithium production from 62 kt in 2015 to 189 kt in 2019 (3 times), with the largest increase in lithium production in the countries such as Australia, Chile, China, Argentina, Brazil, Canada.

Table 4.25. World lithium mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Mining, t					Reserves, kt	Resources, Mt
	2015	2016	2017	2018	2019		
Australia	24,140	29,640	98,260	114,920	103,000	2,800	6.3
Chile	22,500	31,240	32,520	38,850	47,770	8,600	9.0
China	4,350	6,000	14,700	15,300	16,600	1,000	4.5
Argentina	7,860	12,200	12,360	13,810	13,670	1,700	17.0
Zimbabwe	1,405	2,030	1,850	3,160	2,650	230	0.54
Brazil	308	440	533	600	2,390	95	0.4
USA	1,820	1,800	1,420	1,500	1,400	630	6.8
Canada	0	0	66	8,750	1,200	370	1.7
Portugal	204	307	604	914	710	60	0.25
Bolivia	0	10	20	10	160	n.a.	21.0
Nigeria	0	0	0	50	50	n.a.	n.a.
Namibia	0	0	0	600	0	n.a.	0.09
Other countries	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	12.62
Total	62,587	83,667	162,333	198,464	189,600	17,000	82.45

In terms of lithium, Ukraine is one of the leading countries in Europe (Bakarzhiev et al. 2000; Galetskiy et al. 1987; Eremenko et al. 1996; Ivanov et al. 2000). Lithium deposits in Ukraine are associated with early Precambrian rare-metal pegmatites of Ukrainian Shield. Three deposits have been encountered, the reserves of which are recorded by the SIMR (this information is confidential): Shevchenkivske (spodumene ores) of Sorokynsko-Shevchenkivskiy pegmatite belt in Donetsk region, Polokhivske (petalite ores) and Stankuvatske (Dobra section) deposits of Shpolyano-Tashlytskiy ore district in Kirovograd region. They are composed mainly of petalite and spodumene-petalite, occasionally of spodumene ores. The content of Li_2O varies from 0.25 to 2.23%, sometimes up to 6.55%, on average 1.0-1.25%.

Of these, “Ukrlitiyvydobuvannia” LLC has a special permit (license) for lithium mining at the Polokhivske deposit, and active proposals for licensing for the Shevchenkivske and Stankuvatske (Dobra section) deposits, and the Balka Kruta occurrence in the Zaporizhia region.

There are other lithium occurrences, for example, at Balka Kruta in the western Priazovye, at Lipnyazka and Nadiya in the central part of the Ukrainian Shield, and at Zhovtorichenske and Komendantivske in pegmatites of the Kryvorizko-Kremenchutska fault zone.

The Shevchenkivske deposit of spodumene ores is located in the northeastern part of Azovian megablock of Ukrainian Shield, in the Shevchenkivska graben-like structure with greenschist and amphibolite facies schists and gneisses of Neoproterozoic.

Paleoproterozoic Sorokynska Suite of Osypenkivska Series intruded by rare-metal pegmatites (Fig. 4.13).

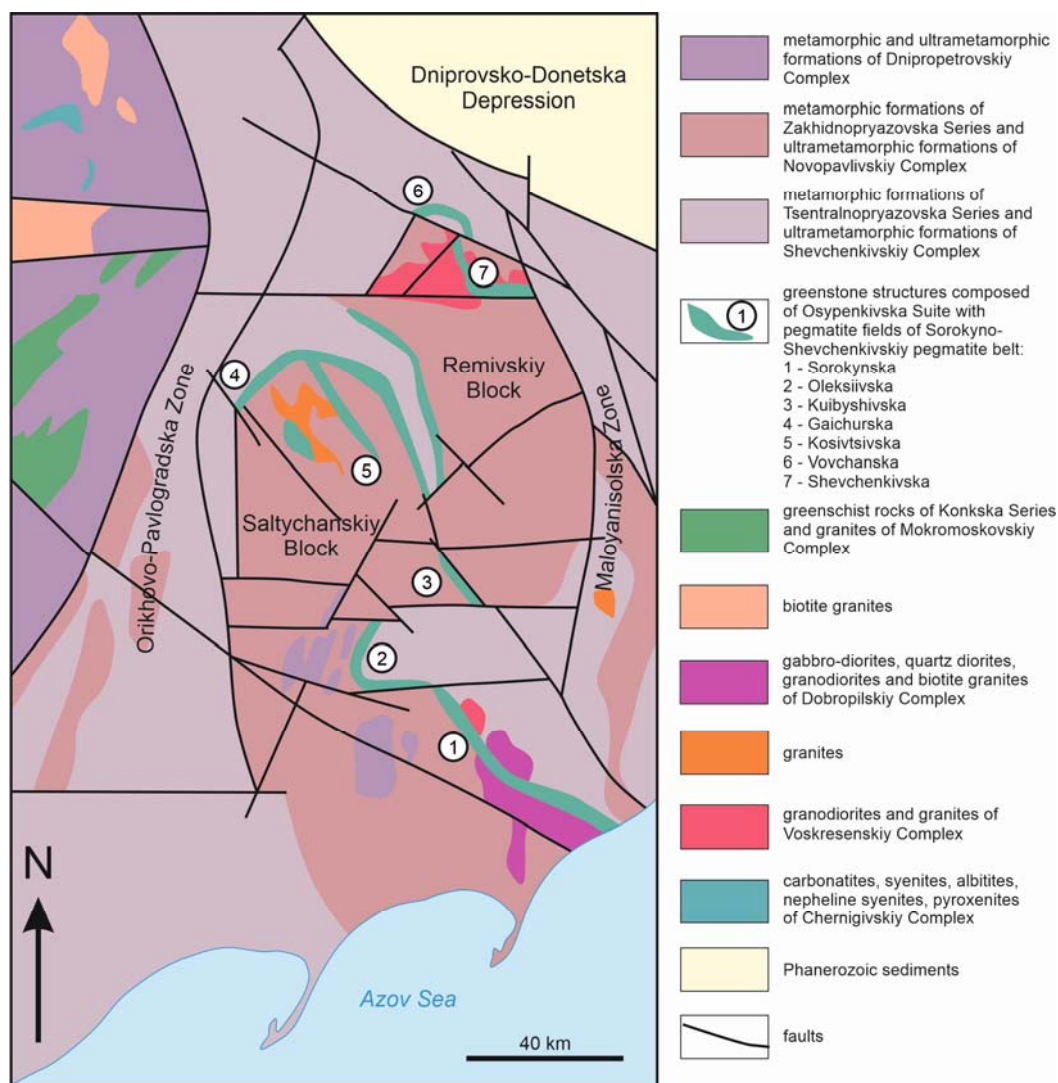


Fig. 4.13. Geological map of the Sorokyno-Shevchenkivskiy pegmatite belt (modified after Isakov, Bobrov 2000)

Six pegmatites have been identified, which form a single vein system of submeridional extension with a dip to the west at angles of 85-88°. The pegmatite veins pinch and swell and are 144-1076 m in length and from 2 to 84 m thick, mostly pinching out at a depth of 350-500 m (Fig. 4.14).

The discontinuous ore body 40 m thick and 600-700 m long holds almost all the lithium reserves of the explored part of deposit. Ore-bearing pegmatites typically have a zonal structure. From the outer zone: 1) contact quartz-albite fine-grained; 2) albite-microcline pegmatoid; 3) quartz-albite diverse-grained; 4) albite-spodumene; 5) microcline-spodumene; 6) petalite-spodumene; and 7) the innermost zone, of microcline. The composition of pegmatite bodies is simple: 90-95% of their volume is composed of the main rock-forming minerals – albite, microcline and quartz, 5-10% – of spodumene and, to a lesser extent, petalite, less than 4%. Rare lithium mica and phosphates, as well as minerals of niobium, tantalum, beryllium, and tin have

also been identified. The main carrier of lithium in the deposit is quartz-albite-spodumene (with microcline and petalite) mineral assemblage of the inner zones of pegmatite bodies. Spodumene forms crystals of 8-10 cm in size, petalite – fine-grained clusters up to 5-20 cm in size. Lithium oxide content is between 1.1-1.5%. More than 95% of the lithium reserves are associated with spodumene. The deposit comprises two types of ores, namely – spodumene (albite-microcline-spodumene) and petalite-spodumene. The content of lithium oxide in ores varies between 0.3-0.4% and averages 1.22%.

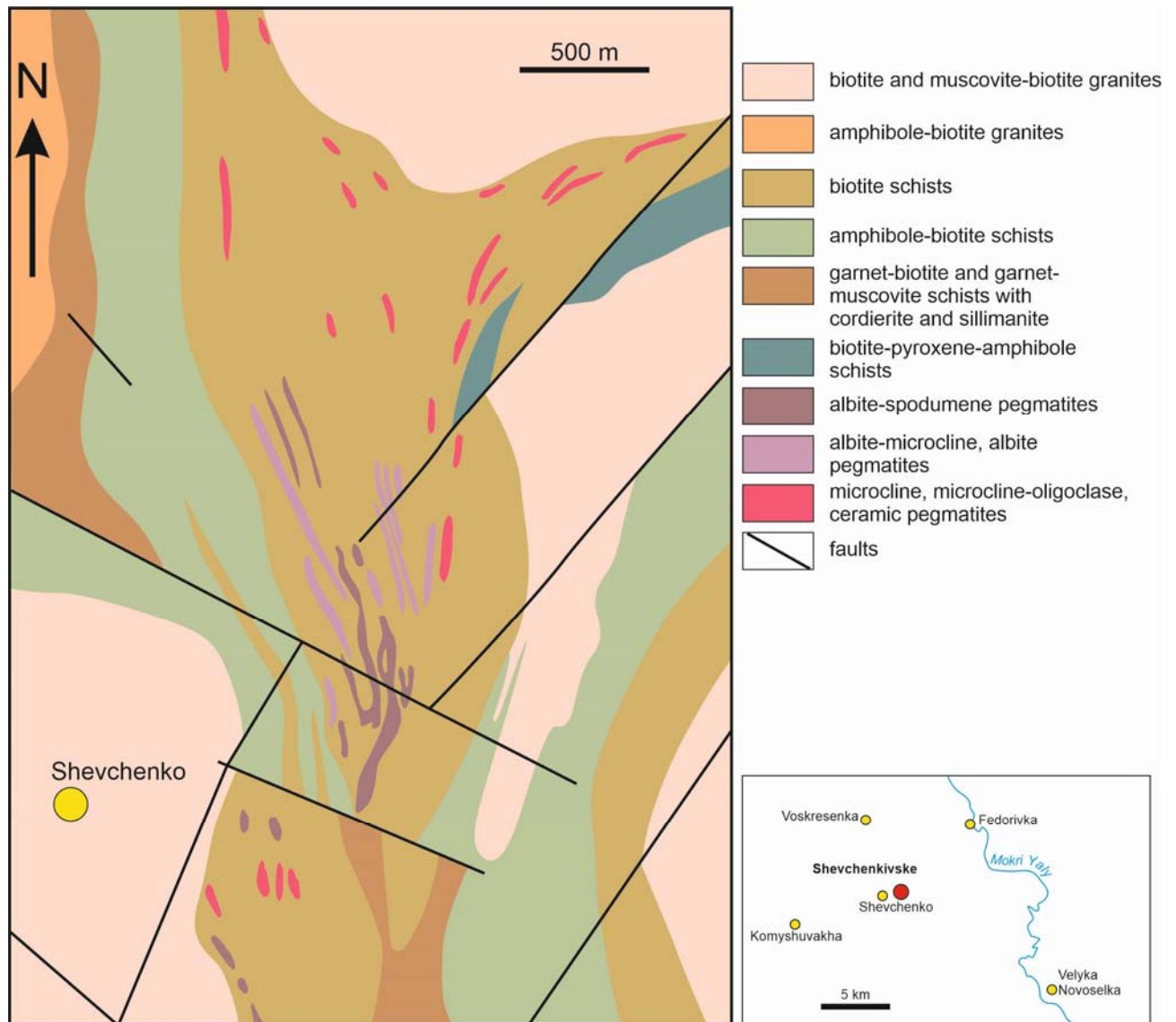


Fig. 4.14. Geological map of the Shevchenkivske pegmatite field (modified after Gursky et al. 20061; Gursky 2008)

In addition to the main component, rubidium, cesium, tantalum, niobium, beryllium and tin are present. In addition, rock-forming minerals, especially feldspar, can serve as raw materials for the ceramic and glass industries.

According to the results of the study of technological samples, the extraction rate of spodumene during enrichment is 88-92% with a total yield of concentrate averaging at 22.8%. This concentrate comprises around 4.9% of lithium and

corresponds to the grade "Spodumene concentrate; 4.0-7.0% Li_2O " of the Western European market.

Information on the reserves of lithium ore deposits is confidential. However, expert assessment along with proxies provided by similar deposits in the world, enables an estimate of lithium resources at approximately 30-35 Mt of ore and 400-450 kt of Li_2O . Approved reserves of quartz are estimated at 4,863.6 kt and mica – 527.2 kt. These assessments along with reserves of tantalum, niobium, and beryllium are provided in the Investment Atlas of Subsurface User (2021).

The Polokhivske deposit of petalite ores is located in a Paleoproterozoic syncline, which bounds the Korsun-Novomyrgorodskiy pluton in the southwest. It is composed of dislocated cordierite-biotite, garnet-cordierite-biotite, biotite, garnet and diopside-biotite plagiogneisses with injections of aplite-pegmatoid and two-feldspar diverse-grained biotite granites of Kirovogradskiy Complex. The deposit consists of three steeply-dipping ore bodies, which are conformable to the gneiss bedding and the linearity of granitoid injections (Fig. 4.15).

The largest and south-westernmost ore body is traced along strike for 550 m and down dip to a depth of 800 m. It has an average thickness of 60 m. The adjacent ore body, just to the northeast, has a thickness between 13 – 75 m and can be traced along strike for 350 m and downdip to a depth of 400 m. A third ore body of much smaller dimensions is not shown in Fig. 4.15. The average content of Li_2O (in%) in the largest ore body is 1.25, in the adjacent body – 1.21, and in the undepicted body- 1.04. The mineral composition of ore bodies is simple, they comprise four minerals (%): petalite (27.6-36.2), albite (26.3-28.0), perthite potassium feldspar (19.1-20.9) and quartz 15.8-21.7). The main carrier of lithium is petalite, which contains 91-95% of the total lithium in the ore. It forms fine-grained, monomineralic clusters of granoblastic texture up to 10-20 cm in size, or occurs in the form of scattered, small inclusions in the microcline-quartz-albite matrix. The composition of petalite is given in Table. 4.26.

The content of spodumene in the ores does not exceed 2%; It is unevenly distributed and generally found together with quartz mainly in strongly corroded relics of the original pegmatite. The composition of spodumene is given in Table. 4.27, whilst chemical and mineral proportions are shown in Tables 4.28 and 4.29.

Petalite concentrate can be obtained from the ores of Polokhivske deposit with ecologically safe gravitational beneficiation.

Information on the reserves of deposit is confidential. By the method of expert assessment, by analogy with similar deposits in the world, we can estimate its resources at about 65 Mt of ore and 800 kt of Li_2O .

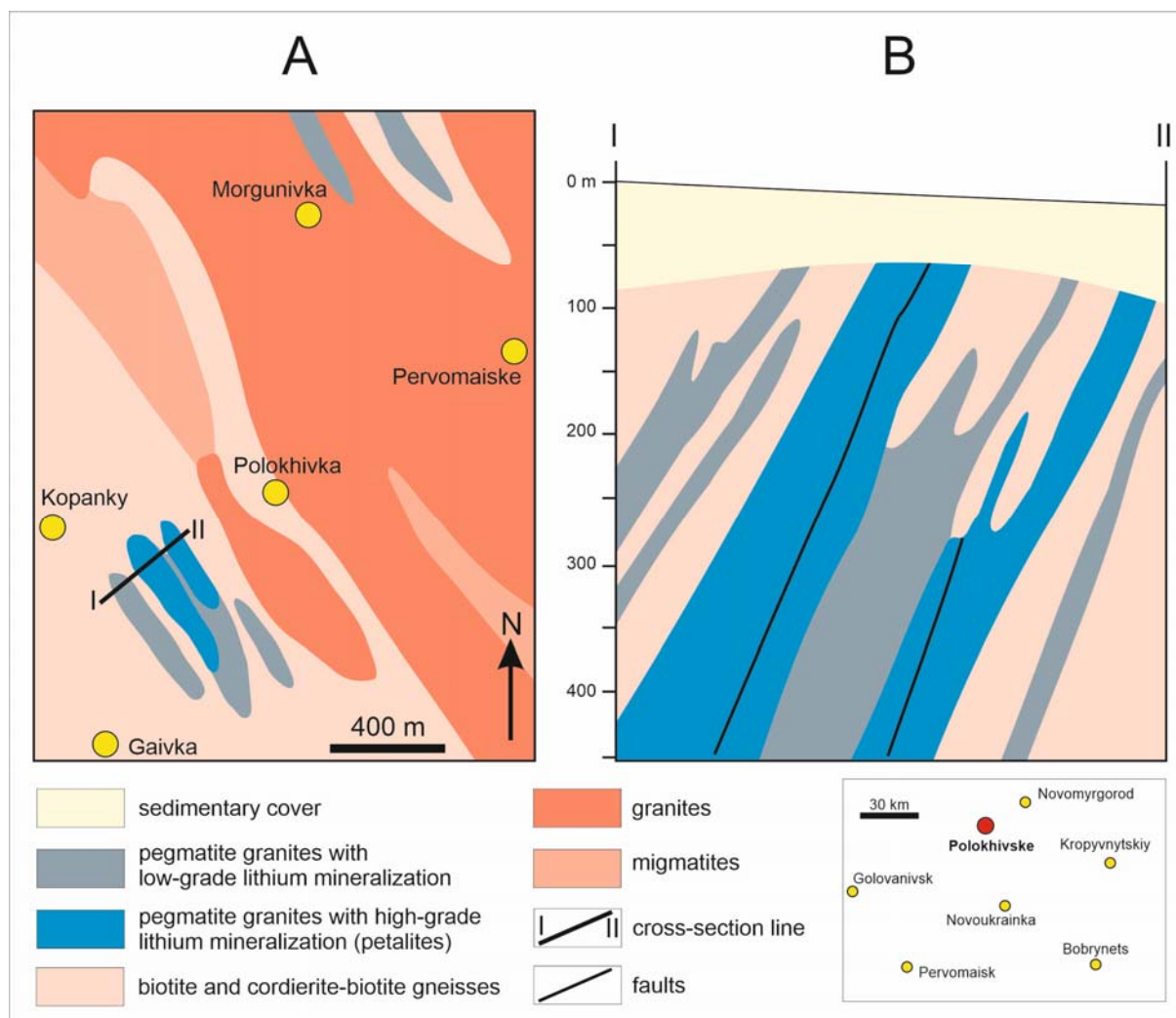


Fig. 4.15. Geological map (A) and cross-section (B) of the Polokhivske deposit (modified after Eremenko et al. 1996)

Table 4.26. Chemical composition of petalite in the Polokhivske deposit (drill-hole 26-90), (Wozniak et al. 2000)

Component	Samples by intervals				
	1	2	3	4	5
SiO ₂	78.34	77.82	77.90	78.36	76.58-77.64
Al ₂ O ₃	16.16	16.18	15.66	15.88	17.04-17.30
Fe ₂ O ₃	0.15	0.16	0.15	0.21	0.09-0.11
FeO	0.59	0.51	1.16	0.89	-
CaO	-	-	-	-	0.11-0.22
Li ₂ O	4.24	4.10	4.25	4.13	4.00-4.80
Na ₂ O	0.23	0.74	0.45	0.41	0.10-0.20
K ₂ O	0.20	0.43	0.32	0.21	0.13-0.18
H ₂ O ⁺	0.34	0.60	0.05	0.45	-

Sample interval analysis: 1 – petalite-albite pegmatite, depth 243 m; 2 – albite-petalite pegmatite, depth 301 m; 3 – albite pegmatite with petalite, depth 314.8-318.0 m; 4 – microcline-albite pegmatite with petalite, depth 321.5-324.5 m; 5 – technological samples.

Table 4.27. Chemical composition of spodumene in the Polokhivske and Stankuvatske deposits, % (Vozniak et al. 2000)

Component	Polokhivske deposit				Stankuvatske deposit
	1	2	3	4	5
SiO ₂	63.58	63.74	63.75	64.17	64.17
Al ₂ O ₃	26.34	26.89	27.06	26.99	27.18
Fe ₂ O ₃	0.84	0.25	0.10	0.34	0.09
FeO	0.72	0.57	0.72	0.26	0.48
CaO	0.34	Traces	0.06	0.12	0.03
Li ₂ O	6.70	6.99	7.10	7.04	7.14
MgO	0.08	Traces	Traces	0.08	-
MnO	Traces	Traces	Traces	0.04	0.05
Na ₂ O	0.46	0.96	0.46	0.67	0.84
K ₂ O	0.21	0.34	0.10	0.07	0.03
H ₂ O ⁺	0.56	0.04	0.44	0.08	0.57
Sum	99.83	99.78	99.79	99.86	100.58

Borehole and sample interval analysis: 1 – microcline-albite pegmatite with spodumene, drill-hole 26-90, depth 134 m; 2 – microcline-albite pegmatite with spodumene and petalite, drill-hole 26-90, depth 270-274.3 m; 3 – quartz-spodumene bunches in microcline-albite-petalite pegmatite, drill-hole 26-90, depth 303 m; 4 – quartz-spodumene bunches in albite-petalite pegmatite, drill-hole 7-92, depth 381.5 m; 5 – quartz-plagioclase zone with rare selenium spodumene grains at the contact with host amphibolite, drill-hole 32-91, depth 282.8 m

Table 4.28. Chemical composition of ores in the Polokhivske and Stankuvatske deposits, % (Eremenko et al. 1996)

Component	Polokhivske	Stankuvatske	
	Petalite ore	Spodumene ore	Petalite-spodumene ore
SiO ₂	74.94	72.03	72.12
Al ₂ O ₃	15.58	16.91	16.62
TiO ₂	0.22	0.27	0.36
CaO	0.32	0.35	0.47
MgO	0.08	0.14	0.09
Na ₂ O	3.66	3.67	3.86
K ₂ O	2.71	2.58	2.18
Li ₂ O	1.10	1.79	1.49
Pb ₂ O	0.04	0.10	0.10
H ₂ O ⁻	0.11	0.11	n.a.
H ₂ O ⁺	0.26	0.86	0.49
CO ₂	0.35	0.14	0.22
P ₂ O ₅	0.48	0.89	1.14
Sum	99.85	99.84	99.14
Ta ₂ O ₅	0.002	n.a.	0.006
Nb ₂ O ₅	0.002	0.006	0.006
SnO ₂	0.008	0.05	0.04
BeO	0.032	0.012	0.033

Table 4.29. Mineral composition of ores in the Polokhivske and Stankuvatske deposits (Eremenko et al. 1996)

Component (%)	Polokhivske	Stankuvatske	
	Petalite ore	Spodumene ore	Petalite-spodumene ore
Quartz	14.3	14.0	14.1
Microcline	23.5	18.8	14.8
Albite	34.0	31.1	33.9
Petalite	24.9	6.6	14.0
Spodumene	0.8	25.3	20.3
Triphylite	0.2	1.5	1.4
Apatite	0.8	0.1	0.3
Muscovite, garnet, calcite, cordierite, sillimanite	1.5	2.7	1.2
Component (g/t)			
Chrysoberyl, g/t	1,165	1,125	1,650
Cassiterite, g/t	90	450	400
Ferrocolumbite, g/t	55	500	500

The Stankuvatske deposit (Dobra section) of spodumene-petalite ores occur as two distinct deposits namely – Stankuvatske and Nadiya in the Kirovograd region and in the western outer zone of Lipnyazkiy granite dome (Fig. 4.16). The core of the dome comprises granites of the Kirovogradskiy Complex whilst the periphery comprises granite pegmatites. Lithium pegmatite bodies occur in orthoamphibolites and mafic-ultramafic rocks of the western border of the dome associated with amphibolite facies grade of metamorphism. The Stankuvatske ore may be traced for 2 km whilst the Nadiya ore for 1.6 km.

The deposit is composed of between 8-12 converging, steeply-dipping bodies of lithium pegmatites with a thickness of some measured in tens of centimetres with others as thick as 25-30 m. The combined thickness of the productive zone reaches 140-150 m, the thicker ore bodies being concentrated in the central parts. The content of Li_2O in individual ore bodies varies from 0.345 to 2.23%, an average of 1.26%. By contrast, the Polokhivske ore deposit comprises a complex, spodumene-petalite, with a spodumene content of up to 20-25%. Among the ore minerals of the Stankuvatske occurrence, petalite predominates, whilst in the Nadiya occurrence, spodumene is the major ore mineral. There are 4 types of ores: petalite (32%), spodumene (28%), spodumene-petalite (17%) and petalite-spodumene (23%). The presence of two lithium minerals is a factor that complicates the technology of ore beneficiation, as it necessitates the selective extraction of spodumene and petalite concentrates.

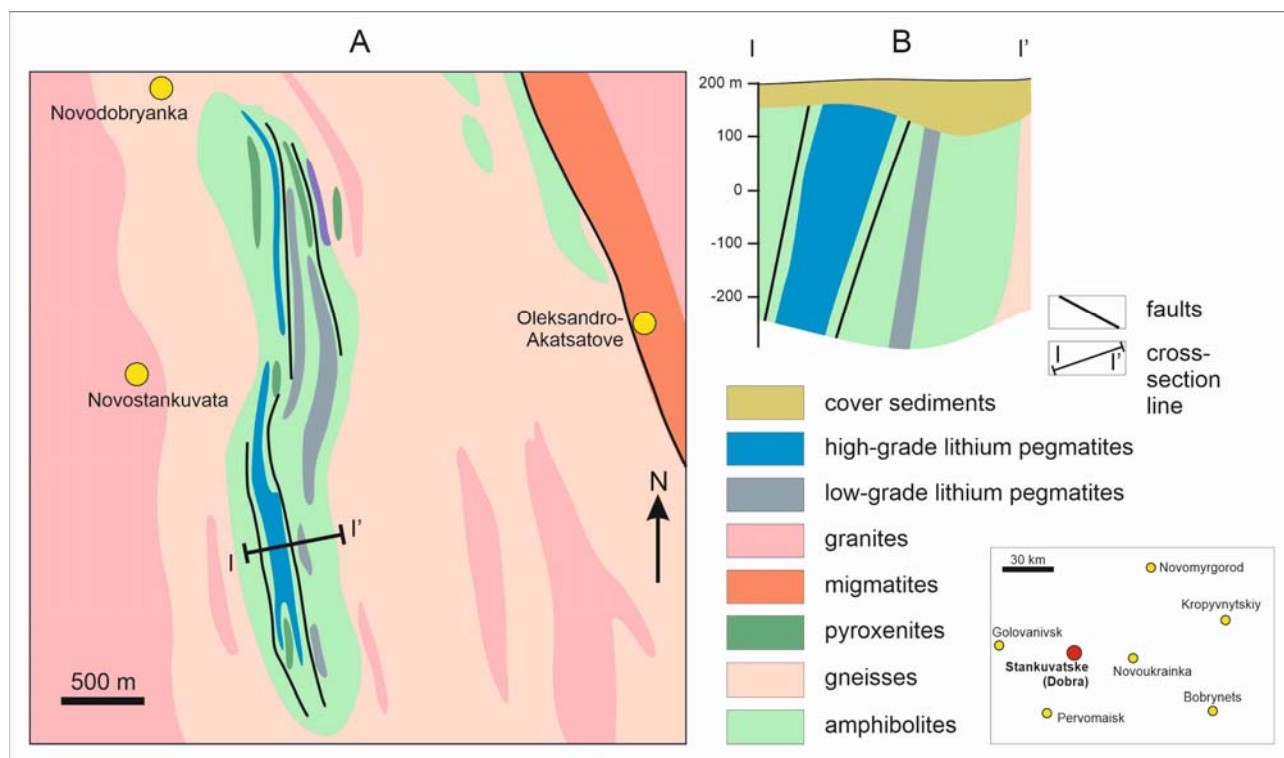


Fig. 4.16. Geological map (A) and cross-section (B) of the Stankuvatske deposit (modified after Eremenko et al. 1996)

Information on the reserves of lithium ore in deposits is confidential. However, expert assessment along with proxies provided by similar deposits in the world, enables a resource approximation of 60 Mt of ore and 750 kt of Li_2O (Investment Atlas of Subsurface User 2021).

The Balka Kruta occurrence in the Zaporozhye region is associated with pegmatites located in the Archean metamorphic rocks of the Sorokynska zone of the Azovian megablock (Panov et al. 2000). There are three ore zones; the details of useful components is provided in Table. 4.30 (Investment Atlas of Subsurface User 2021).

Table 4.30. The content of useful components of ore zones of the Balka Kruta deposit (%)

Zone	Ta_2O_5	Nb_2O_5	Li_2O	Rb_2O	Cs_2O	REE
First	0.001-0.268	0.001-0.036	0.008-4.0	0.006-0.094	0.001-0.041	-
Second	0.001-0.176	0.0015-0.022	0.02-6.55	0.005-0.395	0.001-0.129	up to 0.009
Third	0.001-0.0188	0.001-0.009	0.02-1.43	0.001-0.096	0.001-0.033	up to 0.007

Zoning within the ore bodies is a characteristic with quartz-albite bodies and spodumene confined to the upper horizons, and almost barren microcline bodies towards the lower. There are two types of pegmatites (Zagnitko et al. 2017). The first is characterized by the presence of a barren zone of block microcline and quartz (50% by volume) and a quartz-albite-spodumene zone (30% by volume). The second type is represented by large lenticular and plate-like bodies of variable thickness, with quartz-albite (up to 25%) and quartz-albite-spodumene zones (up to 60%). The vast majority of the commercially viable deposits belong to the second type. The main ore mineral is spodumene, but beryl, tantalum niobates, lithium phosphates, kukeite, and

holmquistite are also of economic importance. The Ta/Nb ratio varies widely. It is believed that the pegmatites of the deposit belong to the albite and albite-spodumene type (Suyarko et al. 2008).

As a result of the geological exploration, reserves are estimated for the main minerals – lithium, tantalum, niobium, cesium, rubidium in pegmatites and mica rocks, as well as for the associated feldspar in the amount of 809.8 kt, quartz in the amount of 582.6 kt and mica in the amount of 205.1 kt (Investment Atlas of Subsurface User 2021).

Thus, the total resources of lithium deposits in Ukraine could be as much as 2.0 Mt, potentially making Ukraine one of the leading countries in terms of resources of this metal. The likelihood is that Ukraine can meet all future needs for green technologies.

4.2.5. Scandium

It is widely used in rocketry and aerospace, metallurgy, laser and nuclear technology, chemical industry, electronics, oil cracking, in the production of solid oxide fuel cells, light alloys, ceramics and as radioactive isotopes. There are numerous other applications.

Scandium belongs to the strategic types of raw materials; together with REE, it is a metal of the XXI century. So, despite fluctuations in its value, it is predicted there will be an increase in demand over the coming years. As a rule, scandium is extracted as by-product in the processing of complex iron, uranium, titanium, tin, tungsten ores, bauxite, laterite and phosphorite. Single scandium deposits are almost absent with few exceptions (the Iveland and Tørdahl deposits in Norway; the Befanomo deposit in Madagascar).

World reserves of scandium are estimated at 0.5 to 1.8 Mt. They are concentrated in the United States, China, Australia, Norway, Russia and Ukraine. Deposits of scandium-containing ores are also known in Finland, Sweden, Kazakhstan, Kyrgyzstan, France, Austria and in Madagascar. World production of scandium varies from 4 to 20 tons per year. In recent years, the level of production and the price of scandium have fluctuated significantly determined by the world market (Scandium World Market 2020; World scandium reserves 2019; Review of the scandium market 2020).

Ukraine scandium reserves place the nation first in Europe and globally, is one of the world leaders. Reserves estimates are based on the complex iron-uranium-vanadium-scandium Zhovtorichenske, apatite-ilmenite Stremygorodske, Torchinske hard-rock deposits and the Zlobitske ilmenite placer deposit, and resources – in ilmenite and rutile placers. Scandium reserves are recorded by the SIMR for 13 complex deposits: Malyshevske, Valky-Gatskivske, Vovchanske, Zhovtorichenske, Stremygorodske, Fedorivske, Trostyanetske, Zlobytske, Torchynske, Irshanske, Lemnenske-Zakhidne and Lemnenske-Skhidne. Of these, 6 deposits are being developed (Mineral Resources of Ukraine 2021).

The Zhovtorichenske deposit in the Dnipropetrovsk region, is probably the most

interesting example of the complex iron-uranium-vanadium-scandium mineralization. Initially, since 1934, the deposit was developed as an iron ore locality. In 1976, scandium ores were discovered there. The mineral occurs within quartz-sodium metasomatites with uraninite and brannerite and vanadium-scandium ores, which are located in diopside quartzites, actinolite schists, partly dolomitized rocks of the Kryvorizka Series (Zagnitko et al. 2017). The ore zone is approximately 100 m long with a thickness does not exceed a few tens of metres (Fig. 4.17).

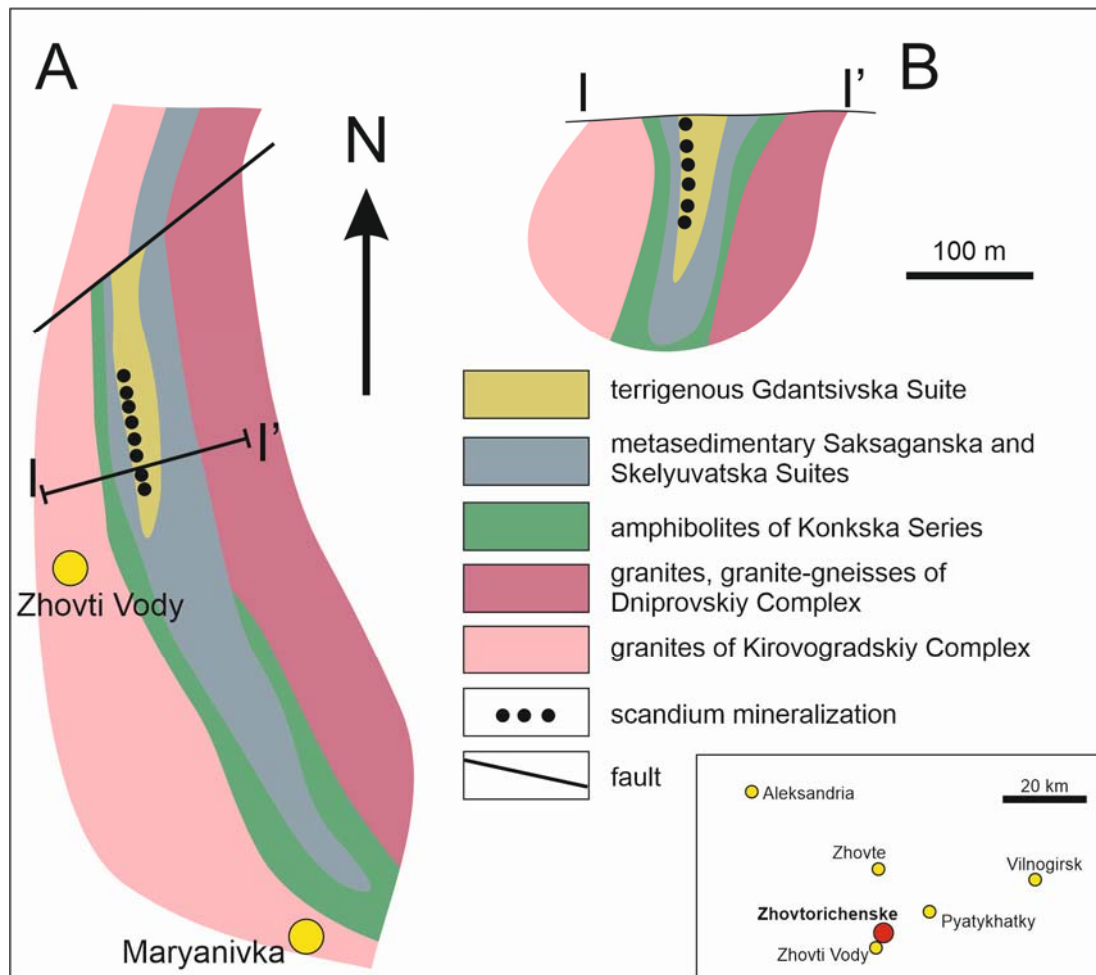


Fig. 4.17. The scandium mineralization zone within the western limb of the Zhovtorichenska syncline (A) and associated cross-section (B) (modified after Tarkhanov et al. 1991)

Rare-metallic vanadium-scandium ores occur in zones (up to tens of metres thick and up to 1 km long) of carbonate-aegirine metasomatites within the Paleoproterozoic Skelyuvatska Suite. Figure 4.17 illustrates, mineralisation is concentrated along the contact between the Skelyuvatska Suite and the Gdantsivska Suite (the latter comprising dolomites, actinolite and quartz-biotite schists, quartzites), and is represented by the vein and bunch-lens-like bodies of alkaline-amphibole-acmite metasomatites with albite, apatite, malacon, and tremolite. Ore bodies have a complex shape, discontinuous parameters (up to the first hundred meters), and composed of uranium-rare-earth and vanadium-scandium ores (Table 4.31).

Table 4.31. Content of scandium and related components in the ores of the Zhovtorichenske deposit, g/t (Tarkhanov et al. 1991)

Ore	Sc	V	P ₂ O ₅ %	TR ₂ O ₃	Y	V ₂ O ₅	Hf
Uranium-rare-earth	50-100	150-600	5.8	600-1,000	20-500	1,700	140
Vanadium-scandium	100-200	50-120	2.6	400-500	100-250	2,700	150
Mixed	100-150	100-200	3.4	500-600	150-250	2,500	150

Ore-bearing metasomatites consist of albite 6-15%, aegirine 9-21%, amphiboles (riebeckite, arfvedsonite, tremolite, actinolite) 11-21%, carbonates 21-46%, quartz 6-26%, talc 3-10% and apatite 3-20%. Ores are characterized by high malacon content (up to 1-2%), which forms individual accumulations (Zagnitko et al. 2017).

The average content of scandium in vanadium-scandium ores is 0.072% and 0.042% in mixed uranium-rare earth ores. Aegirine and alkaline amphiboles are the main concentrators of scandium. In addition to scandium, economic concentrations contain vanadium (0.036 – 0.54%), yttrium (0.022 – 0.019%), zirconium (1.1 – 1.2%), and rare earths (0.036%). Weathering of the hard rocks results in a clay-rich crust up to 40 m thick; analysis of this residual deposit indicates the presence of scandium 0.01 – 0.013%, zirconium 0.88 – 1.4%, yttrium up to 0.13%, and increased amounts of ytterbium (up to 0.013%). Lutetium and other lanthanides are also noted.

In 1993, a Ukrainian-Barbadian joint venture undertaken by Ashurst Technology Ltd., was established on the basis of complex scandium-vanadium and iron ores deposits. The technology for aluminium-scandium alloy production (ligature with 2% of scandium) was developed; however, in 1995 due to financial problems, the scandium program was stopped and not resumed. “Vostok-Ruda” LLC had a special permit № 3670 for iron ore mining, which carried it out in limited quantities, but this permit expired on December 5, 2015.

Information on scandium reserves is confidential, However, according to Western experts, the total Ukrainian reserve of the host ore is 7.4 Mt, potentially yielding 900 tons of scandium with average content of 105 g/t (Bernard 2001). Scandium resources in hard-rock ores reach a few kt, in weathering crusts – 100 t.

Scandium can also be extracted from bauxite found in the Vysokopilske, Pivdenonikopolske, Smilyanske deposits; for example, scandium the Vysokopilske deposit yielded on average 44.6 g/t. Bauxite is processed by the Mykolaiv alumina plant. In the tailings of aluminium production, scandium content reaches 50-100 g/t. Yttrium, lanthanum and neodymium are also present. At one time, research into the production of scandium oxide was launched at the plant, but that study has been terminated (Mykhailov 2010).

In the hard-rock ilmenite-apatite and titanium-magnetite ores of the Stremygorodske and Torchynske deposits, the main concentrator of scandium being ilmenite. The average scandium (Sc) content in the ores is 0.007-0.013%; whilst within the weathered crust it is up to 0.015%.

In placer ilmenite and rutile-zircon-ilmenite deposits (Malyshevske, Irshanske, Zlobytske), scandium is mainly contained in ilmenite where it averages between 0.001 – 0.01%. From placer concentrates, scandium is successfully extracted at the Ust-Kamenogorsk plant (Kazakhstan).

Scandium mineralization was also found in the Pervomaiske ferruginous quartzite deposit, where vanadium-scandium mineralization is confined to the zonal metasomatic halos of aegirinites in magnetite-cummingtonite ferruginous quartzites and cummingtonite ferruginous schists of the sixth iron-ore horizon. Here, aegirine is the main mineral concentrator of scandium. The average yield of scandium in the ores is 83 g/t, vanadium 742 g/t and iron 40.1%.

Scandium mineralization was also encountered in the Gannivske deposit of ferruginous quartzites, where the average content of scandium in the ores is 79 g/t, vanadium 701 g/t and iron 37.8%. In the Pervomaiske deposit, scandium ores are associated with the zoned bodies of sodium metasomatites.

In the ash of coal fields of the Lugansk region, the average content of scandium is 74-90 g/t, and its reserves are estimated at 18.7 kt (besides other elements – Bi, Cu, Sb, Zn, Co, Mo, V, Ti, Ag, Li, Be, Y, Yb, Zr, Ga, Cd, Nb, Ge, Sr).

Scandium is found in hydrogoethite-ferrymontmorillonite oolite iron ores of the Kerchenske deposit (yielding between 7-11 g/t), and in martite and goethite-hydrogoethite ferruginous quartzites of the Kryvyj Rig ore camp (yielding between 1-3 g/t).

In Ukraine, special permits for scandium extraction as a concomitant component of titanium ores were granted to JSC “United Mining and Chemical Company” (zircon-rutile-ilmenite placers of the Malyshevske deposit), “Demurinskiy MBP” LLC (zircon-rutile-ilmenite deposits)), "Valky-Ilmenite" LLC (ilmenite-zircon placers of Valky-Gatskivske deposit) and "Zhytomyrburozvidka" LLC (ilmenite-zircon placers of the Trostyanetske deposit).

4.2.6. Germanium

It has unique semiconductor properties and is widely used in radio-electronics, fibre and infrared optics, as a catalyst in the production of polymers, in solar panels, in mechanical engineering and in metallurgy.

World production of germanium in recent years has been about 100 tons per year. It is mined in China (which produces about 90% of world production), as well as in Russia, the United States, Japan, Ukraine and Finland (Table 4.32).

Table 4.32. World germanium mining production (World Mining Data 2021)

Country	Mining, t				
	2015	2016	2017	2018	2019
China	114	110	87	95	85
Russia	6	6	6	6	5
USA	3	3	2	2	2
Japan	2	2	2	2	2
Ukraine	1	1	1	1	1
Finland	13	0	0	0	0
Total	139	122	98	106	95

Germanium in Ukraine is associated mainly with the coal sequences of the Donetsk and Lvivsko-Volynskiy coal basins, where it occurs as concomitant component. The SIMR records 220 localities with reserves of germanium estimated to be up to 81.7 kt and included in categories A+B+C₁+C₂ (Mineral Resources of Ukraine 2021). Germanium production in 2020 amounted to 92.2 tons. Germanium production was established at 13 coking plants (namely, Avdiivskiy, Alchevskiy, Bagleyskiy, Donetsk, Enakiivskiy, Zaporizkiy, Kryvorizkiy, Makeivskiy and Yasynuvatskiy). These plants have the chemical facility to extract germanium from the tar waters from the coal coking process.

Germanium content in the Donbas coal ranges from 0.3-1.3 g/t in anthracites to 3.8-9.2 g/t in low-grade, metamorphosed coal; however, only coking coal with an average germanium content of 4.5 g/t is of industrial importance.

In the **Donetsk Basin**, the average content of germanium in coking coal is 3.8-6.8 g/t. Germanium occurs in all Lower, Middle and Upper Carboniferous coal beds, but the best yielding beds are those of the Middle Carboniferous coals. The distribution of germanium depends on the grade of coal. In the semi-anthracite (SA) and anthracite (A) grades, the germanium (Ge) content doesn't exceed 2-5 g/t of ash, whereas in coals which have been subjected to medium to low grade metamorphism i.e. categories L, G, C, G (long-flame, gas, coke, greasy), the germanium content reaches 50-70 g/t of ash, possibly more. Along with germanium, coal contains a number of other elements (in g/t of ash) namely gallium 20-100, lithium 50-400 and beryllium 20-50.

The germanium content of brown coals of the **Dniprovskiy Coal Basin** is relatively low (1-2 g/t of ash).

In the **Trans-Carpathian Brown Coal Basin**, the bulk of small deposits are confined to the Ilnytska Suite sediments of the Chop-Mukachivska and Solotvynska depressions. Brown coal is a typical lignite, which consists entirely of wood and weakly coalified residues. The content of germanium in lignites of the Novoselytske deposit is up to 280 g/t, in the Malobiganske deposit it's up to 1000 g/t. At the Malobiganske deposit, the reserves of germanium with 4.9 g/t as the cutoff reference parameter are estimated at 672 tons. This particular deposit warrants further research as there is the possibility of germanium enrichment of deeper sequences due to leaching processes.

Table 4.33. Distribution of germanium grade by ferruginous quartzite ore types

Ferruginous quartzite ore types	Germanium grade, g/t	
	Range	Average
Magnetite	2.4-8.0	5.2
Magnetite-martite	3.0-8.5	5.5
Martite	1.5-14.4	5.7
Jaspilite	2.0-6.0	4.0
Hematite-martite	1.8-14.5	6.3
Goethite-hematite-martite	4.0-14.5	5.4
Hematite	1.8-11.0	3.6

Significant resources of germanium are concentrated in ferruginous quartzites of the **Kryvorizkiy Basin**, where its average content is 6-8 g/t, and breakdown of grades by ores types is given in Table 4.33. The germanium extraction process in Ukraine was developed during the production of metallized pellets and technical combustion of

fuel together with iron ore concentrate in zinc furnaces. Pellets of the Poltavskiy MBP with germanium content of 11-38 g/t are exported.

4.3. Promising Types of Raw Materials

Promising metallic minerals of strategic economic importance to Ukraine include: nickel, cobalt, chromium, aluminium, copper, tantalum and niobium, beryllium and gold.

4.3.1. Nickel

Nickel is widely used in metallurgy to produce stainless and alloy steel, in the chemical and aerospace industries, in shipbuilding and instrumentation, in the automotive industry, in electrical engineering, in the manufacture of alkaline iron-nickel, nickel-cadmium, nickel-zinc, nickel-hydrogen batteries and the manufacture of electromagnet cores.

The main world reserves of nickel estimated at 89 Mt and are associated with two mineralogical suites namely, oxide-silicate (laterite) and sulphide copper-nickel. The largest of the global reserves of nickel are concentrated in Indonesia, New Caledonia, Australia, Brazil, Russia and Cuba. Nickel production is growing slowly, most is produced by Indonesia, which in recent years has sharply increased its production (38% of world production). The Philippines, Russia, New Caledonia and Canada are also significant producers (Table 4.34).

Table 4.34. World nickel mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
Indonesia	129.6	198.9	363.0	651.6	1,036.2	21.0
Philippines	415.0	300.5	339.4	345.0	323.3	4.8
Russia	261.0	223.0	223.0	238.8	233.9	6.9
New Caledonia	193.2	204.2	215.4	216.2	209.5	n.a
Canada	234.5	235.0	214.3	186.0	180.9	2.6
Australia	225.2	203.1	185.5	160.0	158.8	20.0
China	101.4	100.2	102.3	99.0	104.7	2.8
Brazil	89.3	78.6	68.8	65.2	55.7	11.0
Cuba	50.0	48.0	49.3	49.0	48.9	5.5
South Africa	56.7	49.0	48.5	43.2	43.4	n.a
Other countries	406.2	298.0	332.3	331.7	313.6	14.4
Total	2,162.1	1,938.5	2,141.8	2,385.7	2,708.9	89.0

In Ukraine, supergene deposits of silicate nickel occur in weathered crusts concentrated in two areas – Middle Pobuzhia (the Pobuzka Group) and Middle Dniprean (the Devladvivska Group). The ores from these deposits are of low quality (with nickel content between 0.38 – 1.24%) and may be suitable only for ferronickel smelting. The Pobuzkiy Nickel Plant operation relied on the Middle Pobuzhia deposits with a processing capacity of 1.5 Mt of ore and a production of 9.3 kt of

ferronickel. However, the Plant never reached its full capacity and in 1997, production stopped. Since 2004, the facility has smelted ferronickel from foreign imported raw materials.

The SIMR records 12 ore localities, comprising an estimated 43.9 Mt of nickel ore reserves that contain 271.8 kt of nickel, (Mineral Resources of Ukraine 2021).

Special permits for nickel ore mining have been granted for the development of ores of the Kapitanivske deposit (Cr+Ni) ("Mine Extraction" LLC) (described in the section "Chromium"), the Zakhidno-Lashchivska site (Co+Ni) ("VIP Trader" LLC) (described in the section "Cobalt"), and for the exploration of the Prutivske occurrence (Cu+Ni) ("Colormet of Ukraine" LLC) (described in the section "Copper") and the Karnaukhivska site (Co+Ni+Fe) ("Metals Exploration Ukraine" LLC) (described in the section "Cobalt").

Proposals have been submitted for licensing production in the Lipovenkivske deposit (Cr+Ni+Co) in the Kirovograd region (described in the section "Chromium"), for exploration of the Zheleznyaki site (Cu+Ni+Co) in the Zhytomyr region (described in the section "Copper"), and the Sukhokhutorska site (talc-magnesite+Ni+Co) in the Dnipropetrovsk region (described in the section "Magnesium").

Nickel and iron-nickel ore deposits are associated with the weathered crust of Precambrian ultramafic rocks; the weathered zone is usually between 25-35 m thick, but can be up to 100 m in thickness. The age of weathered crust, according to most researchers, is Jurassic-Early Cretaceous. Within this weathered layer, ocher-nontronite, ocher and ocher-siliceous profiles are developed. In the Pobuzkiy and Devladiivskiy Complexes, most ore-bearing deposits are associated with the ocher-nontronite profile.

The Pobuzka group of deposits occur at six localities namely Derenyukhynske, Kapitanivske, Lypovenkivske, Skhidno-Lypovenkivske, Pushkivske, Grushkivske and Tarnuvatsk in the Kirovograd region. Ultramafic bodies up to several square kilometres in size are confined to the Pobuzka Fault Zone in the central part of the Golovanivskiy Block. The ore deposits are confined to the weathered crust of the Archean age rocks, with a thickness of between 50 – 80 m. The ore bodies occur as sheeted units, between 200 – 2000 m long, 40 – 500 m wide, and with an average thickness of between 2.9 – 8.7 m. The depth of ore bodies is from the surface down to around ten metres deep. The average nickel content is between 0.9 – 0.99%, although in some areas it can reach up to 5%. The most important accompanying element is cobalt. The iron content varies widely, sometimes reaching between 45 – 50%. The main rock-forming mineral of nickel ores is nontronite. Other notable minerals include beidellite, montmorillonite, chlorite (pennine and clinocllore), jeffersite and vermiculite. Relict minerals are also often found namely chrysotile, antigorite, magnetite and chromite.

The Tarnuvatske silicate nickel deposit lies in the central part of the Golovanivskiy Block, on the right bank of the South Boug River, the area underlain by a serpentinite massif, which has a north-western extension and an intermittent

structure. It is divided into three parts namely, northern, central and southern (Fig. 4.18).

In the northern part of the Tarnuvatskiy Massif, dunite-rich rocks predominate. The total thickness of serpentinites is 600 m. The upper sections are composed of pyroxenites and amphibolites with a total thickness of up to 300 m. In the middle part of the Massif (drill-hole 15014 – see Fig 4.18) at a depth of 535 m, serpentinites are replaced by weakly-serpentinized dunites. The host rocks are represented by Archean sillimanite gneisses, amphibolites and plagiomigmatites, as well as Paleoproterozoic aplite-pegmatoid granites. Faults of east-west extension with amplitude up to 200 m separate the northern part of the massif from the central one. A series of low-amplitude faults determines the block structure of the Massif. The central and southern parts of Massif comprise monoclines with the sequences dipping to the southeast at angles of 70-75°. The section of serpentinites is characterized by intercalation of dunite and peridotite with the layers of pyroxenites; a combined thickness of up to 300 m.

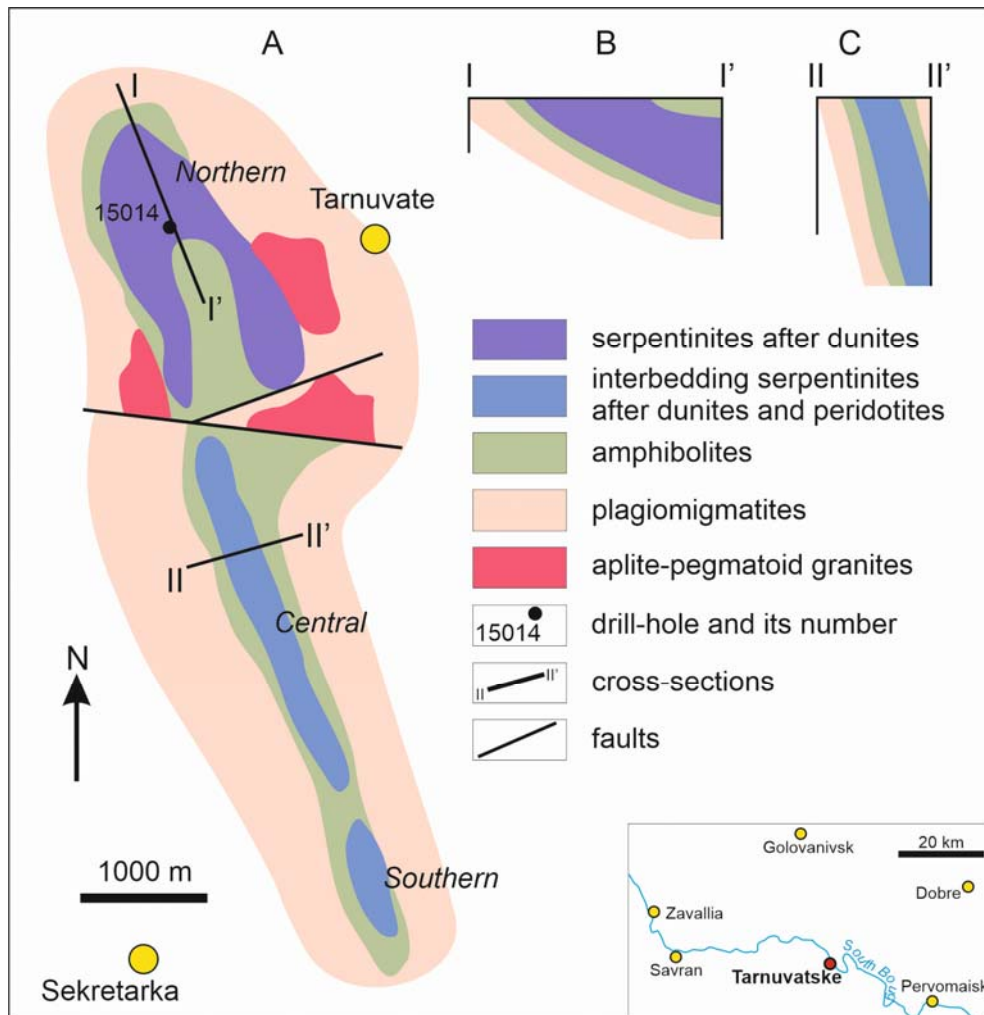


Fig. 4.18. Geological map (A) and cross-sections (B and C) of the Tarnuvatske deposit (Modified after Mykhailov et al. 2007)

The weathered crust of serpentinites up to 15 m thick, is predominantly nontronite in composition. It is covered by Neogene sands and clays and Quaternary loams with

a thickness of between 10-25 m. The average content of nickel is 0.91% and cobalt 0.046%. In terms of reserves, deposit is classed as medium scale.

The Devladvivska group of deposits is represented by four deposits namely Devladvivske, Nove, Ternivske and Chervonyj Yar in the Dnipropetrovsk region in the Middle Dniprean megablock of the Ukrainian Shield. Primary ultramafic rocks are of Archean age and belong either to the main stage of formation of greenstone belts (3.2-2.8 billion years) or to post greenstone (2.8-2.6 billion years) stage. Ultramafic rocks are widely developed in the Belozerska greenstone structure, much less so in the Konkska greenstone structure. The Devladvivsko-Ternivskyj area of ultramafic rocks is confined to the east-west trending Devladvivska Fault Zone some 4-7 km wide and up to 50 km long. The upper part of these ultramafic deposits commonly includes a weathered crust.

Devladvivske ultramafic body (9.0×0.35 -0.4 km) is elongated in the sublatitudinal direction, composed of intensively serpentinized dunites, dunite-harzburgites, lherzolites, and aluminous olivine harzburgites with a subordinate role (up to 10%) of actinolite rocks. Ultramafic rocks with high Ni content (0.15-0.35%) and low Cr_2O_3 (0.1-0.3%), as well as ultramafic rocks with low Ni content (0.25-0.05%) and increased Cr_2O_3 content (0.3-0.5%) are distinguished.

In the south-western limb of Ternivska syncline the batch of ultramafic rocks (4.5×0.3 km in size) of the same sublatitudinal extension is distinguished, composed of serpentinites and serpentinized dunites with a subordinate role of actinolites and chlorite schists, Serpentine contains 0.22-0.25% Ni, 0.48-0.56% Cr_2O_3 , 0.014-0.024% CoO.

The Devladvivske deposit is a complex deposit of nickel, iron ores and refractory clays. The ore field of the deposit is composed of peridotites and gabbro-peridotites, porphyry-like granites of Kirovogradskiy type, plagioclase granites and their migmatites, as well as polymigmatites of Proterozoic Dniprovski granites. The nickel deposit is confined to the weathering crust of peridotites and gabbro-peridotites, which make up the steeply-dipping dyke-like body.

The weathering crust is represented by zones (upward): a) destroyed serpentinized peridotites of variable thickness; b) nontronites (8-10 m) with nickel mineralization, c) ochre (15-20 m), which comprise economic iron ore. Nickel ores form 7 spatially separated ore bodies, consisting of 2-4 horizontally lying ore beds, more often confined to the upper parts of the nontronite zone. The average nickel content is 1.06-1.24%, in some areas it reaches 1.5-2.0%; cobalt content – 0.04-0.05%.

A number of other areas with intrusions of mafic-ultramafic composition are known at the Ukrainian Shield, where economic deposits of copper-nickel ores can be detected. All these massifs are confined, first of all, to the areas of Paleoproterozoic tectonic-magmatic activation in the Volyn, Ingulets and Azovian megablocks of Ukrainian Shield.

In addition to these objects, there are prospects for sulphide copper-nickel ores in Prutivskiy, Varvarivskiy, Volodymyrivskiy, Sukhoturivskiy and other occurrences.

4.3.2. Cobalt

The main uses of cobalt are metallurgy (for the production of high quality alloys), chemical and glass industries, but cobalt and its compounds are also widely used in nickel-cadmium and some lithium-ion batteries. Cobalt silicide is an excellent thermoelectric material, it is used in producing thermoelectric generators with high efficiency. Cobalt is also used in the manufacture of catalysts, aircraft engines, permanent magnets.

World reserves of cobalt are estimated at 7 Mt, the largest reserves are concentrated in the DRC (51.4% of the world), Australia (17.1%), Cuba (7.1%); Most cobalt is mined in the DRC (62.9% of world production), as well as in Russia, Australia, Cuba, Canada and others. (Table 4.35). In recent years, there has been a decrease in cobalt production from 158 kt in 2018 to 125 kt in 2019, which is due to a significant decrease in production of the DRC.

Table 4.35. World cobalt mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Mining, t					Reserves, kt
	2015	2016	2017	2018	2019	
DR Congo	84,400	69,038	82,461	111,713	78,664	3,600
Russia	8,600	8,600	8,900	8,700	8,700	250
Australia	5,930	5,183	5,034	4,878	5,746	1,200
Cuba	4,793	5,514	5,407	5,300	5,200	500
Canada	7,489	7,148	6,058	5,608	5,132	230
Philippines	3,900	3,500	3,700	3,600	3,750	260
China	10,093	9,293	8,300	3,100	3,000	80
Madagascar	3,920	3,654	2,967	2,887	2,947	120
Papua-New Guinea	2,505	2,187	3,307	3,275	2,915	56
Morocco	1,722	2,081	1,924	1,806	2,397	18
Other countries	13,680	14,541	10,414	13,099	6,707	686
Total	147,032	130,739	138,472	163,966	125,158	7,000

In Ukraine, cobalt reserves have been estimated in the nickel silicate ores from weathering crusts of ultramafic rocks in Middle Pobuzhia in the Kirovograd region and the Middle Dniprean area in the Dnipropetrovsk region described above. The SIMR records cobalt reserves in 11 silicate cobalt-nickel deposits and one sulphide copper-nickel deposit for the total amount of 49.3 Mt of ore and 12.1 kt of cobalt with an average cobalt content of 0.04% (that is low-grade).

In addition, there are a number of occurrences of hard-rock nickel-cobalt mineralization associated with intrusions of mafic composition: Prutivskiy (described in the section "Copper") and Kamyanskiy in the Zhytomyr region; Varvarivskiy, Alferivskiy, Vilnokhutorskiy, Granivskiy, Adamivskiy, Pototskiy – in the Middle Dniprean region; Demovyarivskiy – in Pobuzhia; Mykolaivskiy and Novotroitskiy – in the Azov region. They are weakly studied.

Special permits for the extraction of cobalt ores have been granted for the development of ores from Zakhidno-Lashchivska site (Co+Ni) ("VIP Trader" LLC) and Karnaukhivska site (Co+Ni+Fe) ("Metals Exploration Ukraine" LLC).

Proposals for mining licenses are opened at complex sites: Lipovenkivske deposit (Cr+Ni+Co) in the Kirovograd region (described in the section "Chromium"), and for exploration of Zheleznyaky site (Cu+Ni+Co) in the Zhytomyr region (described in section (Copper)), and Sukhokhutirska site (talc-magnesite+Ni+Co) in the Dnipropetrovsk region (described in the section "Magnesium").

The Kamenskiy Massif is located in the northern part of the Volyn megablock, represented by the zone of pentlandite-chalcopyrite-pyrrhotite bunch-disseminated mineralization over 60 m thick, where the content of cobalt is 0.145%, copper – up to 0.55%, nickel – from 0.1 to 0.46 %. According to geophysical data, the length of the deposit is predicted for 6.3 km (to a depth of 2.4 km), and in the northern part of the Massif – sulphide bodies up to 100 m thick are found.

Several promising ore occurrences with cobalt-copper-nickel mineralization were found in the Middle Dniprean area: Varvarivskiy, Alferivskiy, Vlnokhutirskiy, Granivskiy, Adamivskiy, Pototskiy and others. They are confined to Varvarivskiy ultramafic massif; the content of nickel is 0.5-1.5%, cobalt – up to 0.1%.

In the Middle Pobuzhia, in Golovanivska zone, the Demovyarivskiy occurrence is located, and in the Azov region, in Volnovaska Fault Zone, Mykolaivskiy and Novotroitskiy occurrences are located.

The Zakhidno-Lashchivska site of silicate cobalt-nickel ores in the Mykolaiv region with an area of 36.4 hectares is located in Pobuzkiy ore area, confined to Golovanivska suture zone. The site is composed of granitoids of Pobuzkiy Complex with blocks of mafic gneisses and plagiogranites of Dnistersko-Buzka Series, covered with weathering crust 50-80 m thick and Neogene sedimentary rocks. The mafic-ultramafic massif composed of serpentinized peridotites is located in the central part of the site.

The ore object is represented by the weathering crust of serpentinized peridotites composed of nontronite clays with an average thickness of 21.9 m. It is composed (downward): brown iron ores and ocher; nontronites and ferruginous nontronites; nontronite carbonatized serpentinites. The main productive horizon is the zone of nontronite crust and ferruginous nontronites. The main minerals are nontronite, kuramite, montmorillonite and jefferisite. Two subhorizontal layered ore bodies with a thickness of 5-16 m are distinguished.

Ukraine's prospects for hard-rock copper-nickel mineralization with cobalt of this type may be related to retrograde-metamorphosed and layered mafic-ultramafic intrusions, confined to the areas of Paleoproterozoic tectono-magmatic activation occurred in Volyn, Ingulets and Azovian megablocks of Ukrainian Shield.

4.3.3. Chromium

It is used in ferroalloy production, refractory, glass and chemical industries, transport, construction, electricity.

World chromium reserves are 569 Mt, the largest reserves are owned by South Africa, Kazakhstan and India (93% of world reserves); World chromium production is slowly growing from 13 Mt in 2015 to 16 Mt in 2019. The largest production is carried out by South Africa, Kazakhstan, India and Turkey (82.9% of world production), as well as Zimbabwe, Finland, Albania and other countries (Table 4.36).

Table 4.36. World chromium mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production of Cr ₂ O ₃ , kt					Reserves, Mt
	2015	2016	2017	2018	2019	
South Africa	6,660.5	6,254.6	7,073.4	7,524.7	7,384.0	200
Kazakhstan	1,992.4	1,989.5	2,193.5	2,378.2	2,458.8	230
India	1,335.6	1,728.3	1,609.0	1,864.1	1,819.2	100
Turkey	1,464.3	1,070.0	1,384.7	1,146.6	1,528.7	26
Zimbabwe	93.8	128.2	310.0	402.6	720.3	n.a.
Finland	457.1	469.1	411.1	466.8	502.1	13
Albania	284.1	317.5	351.5	497.1	488.7	n.a.
Oman	179.7	232.8	181.1	353.6	243.1	n.a.
Russia	226.4	186.0	195.2	202.8	237.6	n.a.
Brazil	204.3	166.3	212.5	219.7	199.3	n.a.
Iran	142.8	162.1	92.9	113.4	104.4	n.a.
Other countries	205.3	142.3	230.6	217.2	228.1	n.a.
Total	13,246.3	12,846.7	14,245.5	15,386.8	15,914.3	569

Usually chromium ores are associated with ultramafic rock massifs, the largest of which is known in South Africa (Bushveld Complex). In Ukraine, similar massifs are known, but much smaller in size. Deposits and occurrences of chromite ores are confined to these massifs in Middle Pobuzhia. About 60 small ultramafic massifs have been encountered there, 11 of which have an economic chromium content. According to the SIMR, chromium ore reserves are recorded in Kapitanivske (Central site) and Lypovenkivske deposits in the amount of 3,488.6 kt, including Cr₂O₃ – 679.9 kt (Mineral Resources of Ukraine 2021). Resources of chromium ores are estimated at 50 Mt (Gurskiy 2008).

Special permits for the extraction of chromium ores were granted for the development of ores of Kapitanivske deposit (Cr+Ni) ("Mine Extraction" LLC). Proposals for licensing are opened for production at complex Lipovenkivske deposit (Cr+Ni+Co) in Kirovograd region.

The Kapitanivske deposit (Cr+Ni) is located in the same-named ultramafic massif, composed of metamorphosed dunites, harzburgites, and pyroxenites. Ore mineralization is represented by nine contiguous steeply-dipping ore bodies of

lenticular and columnar shape, which have a relatively small thickness (0.5-12.0 m) and are traced by drilling at 50-160 m by strike and at 75-300 m by dip (Fig. 4.19).

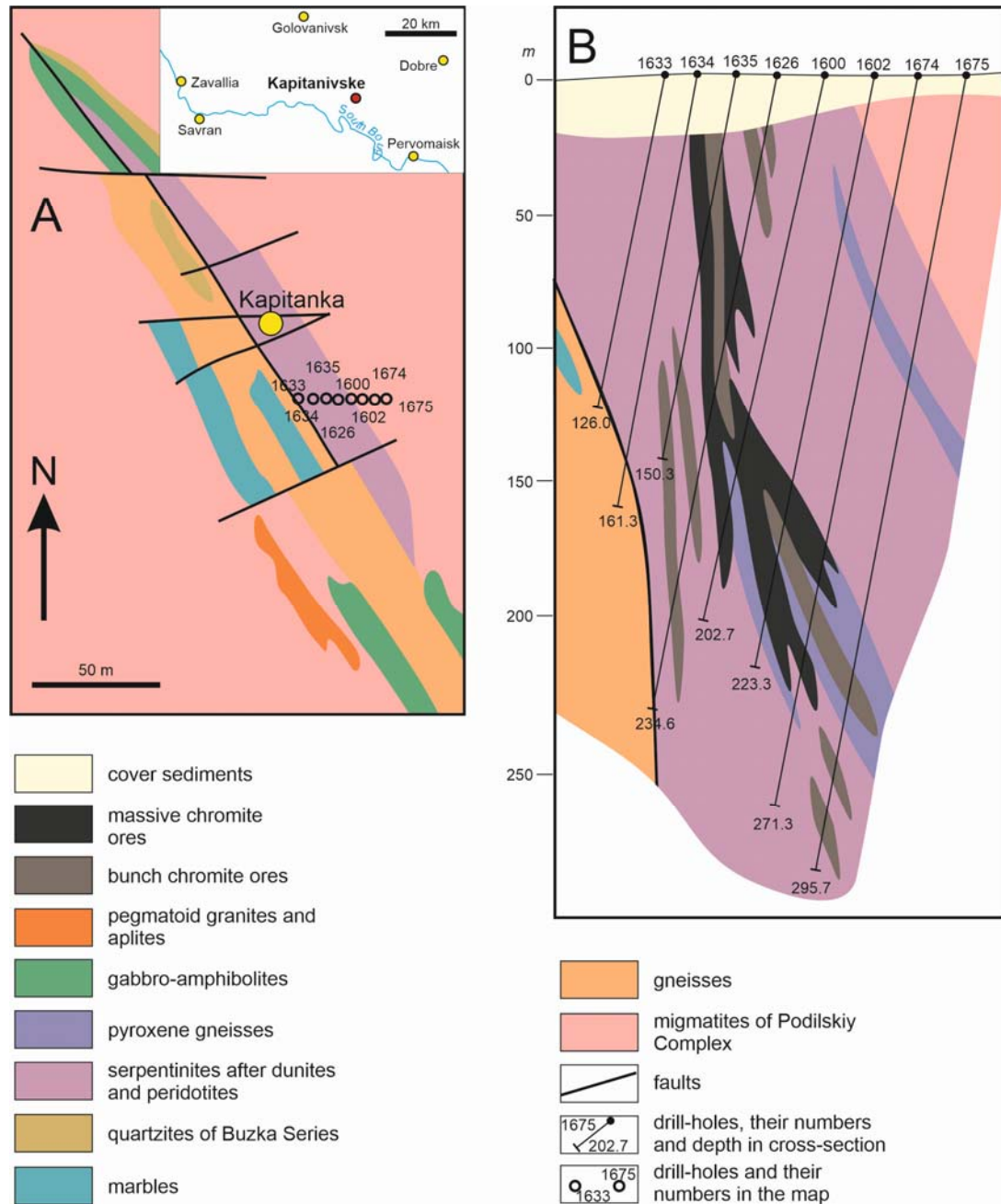


Fig. 4.19. Geological map (A) and cross-section (B) of the Kapitanivske chromite deposit (modified after Mykhailov et al. 2007)

The content of Cr_2O_3 varies from 6 to 45% (average 29%). According to textural and structural features and the content of Cr_2O_3 (%), the low-grade (6-15), disseminated (15-29), densely disseminated (28-30), and massive (40-45) ores are distinguished. Their mineral composition: chrompicotite (up to 90% of ore mass), ferrochrompicotite and manganochromite, there are also chromium diopside, magnetite and carbonates.

In the upper parts of chromium ore bodies (up to the depths of 100-300 m) the linear weathering crusts composed of conditioned chromium-nickel ores often are developed.

Prognostic resources of Kapitanivske deposit up to a depth of 600 m are 6.5-7.0 Mt of ore with an average Cr_2O_3 content of 28%.

The Lypovenkivske deposit (Cr+Ni+Co) in the Kirovograd region is represented by two parts – Zakhidna and Shkidna, confined to the serpentinite massif with areas of amphibolites and biotite gneisses cut by granite veins. Chromite ores are represented by the bodies of massive densely disseminated lenticular ores up to 15 m thick, which are traced at 40-80 m by strike and 50-75 m by dip. Ore bodies steeply dip to the northeast (70-80°). By the amount chromium spinels and the content of Cr_2O_3 chromite ores are divided into massive, dense- and scarce-disseminated. The content of chromium trioxide in ores is 35% and more, 15-35%, and 6-15%, respectively. The most common are dense-disseminated ores. The main ore minerals are chromium spinels. The content of harmful impurities is: S – 0.02-0.026% and P – 0.04%, which does not exceed the allowable limit for ferrous metallurgy.

Massive varieties of chromite ores are suitable for the manufacture of magnesite refractories, as well as for the smelting of ferrochrome. Dense-disseminated ores are easily beneficiated by the gravitational method with the extraction of 73.8% concentrate, which contains 42% Cr_2O_3 . Dense-disseminated ores in the deposits of Middle Pobuzhie make up 80% of the total chromite reserves to be beneficiated. Massive ores that do not require beneficiation account for 20% of reserves.

A significant part of chromium ores is confined to the weathering crust of ultramafic rocks and contains economic concentrations of nickel (0.86-1.09%) and cobalt (0.044-0.064%).

The total prognostic amount of chromite ores in the area is 30 Mt of ore with an average chromium content of 26-28% (Mykhailov et al. 2007).

Prospects for the growth of chromite ore reserves in Middle Pobuzhie area through discovery of new deposits are extremely limited, but it is possible to explore deeper horizons and flanks of known deposits. In addition, significant reserves can be found in the study of previously identified chromite occurrences (Pershotravneve, Lypovenkivska and Lypnyagivska groups of occurrences).

Thus, chromite deposits of the Middle Pobuzhia are of interest due to the need to secure Ukrainian industry with refractory raw materials and raw materials for the production of ferrochrome. Host rocks – serpentinites – can be considered as concomitant raw materials for plumbing products, mineral wool, magnesium fertilizers for agriculture and tiles with a pleasant green colour scheme.

4.3.4. Aluminium

Aluminium is widely used in automotive, aerospace, alloy production, electrical industry for the manufacture of high-voltage power lines, engine windings and transformers, cable, capacitors and many other products, as well as in transport, construction, electricity, and as packaging materials. Aluminoenergy uses aluminium

as a universal secondary energy source. Its use in this capacity includes: 1) oxidation of aluminium in water for the production of hydrogen and thermal energy; 2) oxidation of aluminium by air oxygen for electricity in air-aluminium electrochemical generators.

World aluminium production has been growing slowly in recent years from 57.9 Mt in 2015 to 64.5 Mt in 2018, while China produces the most (52.6% of world production), as well as Russia, India, Canada, UAE and other countries (Table 4.37).

Table 4.37. World aluminium mining production and reserves (World Mining Data 2021)

Country	Production, kt				
	2015	2016	2017	2018	2019
China	31,518.0	31,775.4	33,289.6	36,831.0	35,043.6
Russia	3,529.0	3,561.0	3,583.0	3,631.0	3,637.0
India	2,355.0	2,896.6	3,400.6	3,696.2	3,635.1
Canada	2,880.0	3,208.9	3,212.1	2,924.4	2,853.8
UAE	2,397.0	2,471.0	2,600.0	2,640.0	2,579.0
Australia	1,646.0	1,633.9	1,487.6	1,574.2	1,569.6
Bahrain	960.6	971.4	981.0	1,011.1	1,365.0
Norway	1,227.8	1,247.0	1,253.0	1,295.0	1,337.5
USA	1,586.5	818.4	740.9	896.7	1,126.0
Saudi Arabia	839.0	871.0	916.0	932.2	967.0
Other countries	8,918.8	9,173.0	9,235.1	9,025.0	8,742.2
Total	57,857.7	58,627.6	60,698.9	64,456.8	62,855.8

Bauxites are the main industrial type of aluminium raw materials. More than 90% of total and proven bauxite reserves are concentrated in 18 countries with tropical and subtropical climate. These are Australia, Guinea, Brazil, Jamaica, as well as India, Vietnam, China, Guyana and others. In the northern territories, bauxites are limited. In Europe, the largest reserves are found in Greece and Russia. Bauxite production is constantly growing from 294 Mt in 2015 to 363 Mt in 2019, it is carried out by Australia, China, Guinea, Brazil, India and other countries, and countries such as Australia, Guinea and Indonesia are constantly increasing production (Table 4.38).

Table 4.38. World bauxite mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, Mt					Reserves, Mt
	2015	2016	2017	2018	2019	
Australia	80.9	83.5	89.4	95.9	105.5	6,000
China	60.8	66.2	68.4	79.0	75.0	1,000
Guinea	20.7	32.4	51.7	59.6	70.2	7,400
Brazil	37.1	39.2	38.1	32.4	31.9	2,600
India	28.1	24.7	22.8	23.7	21.8	660
Indonesia	0.5	0.5	1.7	11.0	16.6	1,200
Jamaica	9.6	8.5	8.2	10.1	9.0	2,000
Russia	5.7	6.1	5.8	7.1	6.6	500
Saudi Arabia	3.0	4.8	4.1	4.9	5.1	200
Vietnam	1.4	1.6	2.6	3.6	3.7	3,700

Country	Production, Mt					Reserves, Mt
	2015	2016	2017	2018	2019	
Other countries	46.6	21.8	19.0	18.3	18.0	4,740
Total	294.4	289.3	311.8	345.6	363.4	30,000

Ukraine has powerful alumina and aluminium plants, such as the Mykolaiv Alumina Plant and the Zaporizhia Aluminium Plant, but Ukraine's aluminium industry is not supplied with domestic raw materials, so alumina and primary aluminium plants operate on imported raw materials from Guinea and Guinea. and other countries. Thus, the problem of securing the industry with its own aluminium raw materials is very hard in Ukraine, despite the available resources, which are represented by bauxite, alunite rocks, nepheline syenites, disthene-andalusite-sillimanite quartzites, gneisses and schists.

The main area of bauxite development is Ukrainian Shield and its margins, where they are associated with Mesozoic weathering crust of Archean greenstone rocks. Alunite ores are confined to the Trans-Carpathian province, where they are associated with polymetallic ores of Neogene deposits. Nepheline ores are known in the Azov region in Proterozoic syenites of Ukrainian Shield. Deposits of andalusite-disthene-sillimanite schists and quartzites were found in metamorphic sequences of Ukrainian Shield.

The most important in Ukraine is the bauxite formation of primary laterite weathering crusts, represented by bauxite bodies, which form several deposits and a number of occurrences in the Middle Dniprean region. The SIMR records reserves of Vysokopilske deposit, which contains 18,885 kt by categories A+B+C₁+C₂, and resources are estimated at 290 Mt (Gurskiy 2008; Mineral Resources of Ukraine 2020).

The Vysokopilske deposit is located on the southern margin of Ukrainian Shield in the junction zone with Fore-Black-Sea Depression, in the middle course of Ingulets River (Dnipropetrovsk region). The deposit comprises an ancient weathering crust, cut by a network of small paleo-valleys (Fig. 4.20). Bauxites form the upper zone of the laterite section of weathering crust of Archean gabbro-amphibolites and quartz-chlorite-amphibole schists. Bauxite bodies are overlain by Middle Eocene and younger friable cover sediments with a total thickness of 15 to 100 m. The age of bauxite is defined to be Aptian-Albian.

Bauxite bodies are irregular in shape, their contours in the plan have a wavy configuration. The ore layer consists of individual flattened boulders up to 4-5 m in diameter. Its upper part forms a strong shell of stony reddish-brown cavernous bauxite (armour), which turns into loose clay varieties. The total thickness of the ore body is 10-12 m, the weathering crust is 30-40 m thick.

The mineral type of bauxites is hydrogoethite-boehmite-gibbsite. Their average chemical composition is as follows: Al₂O₃ – 38%, Fe₂O₃ – 28%, SiO₂ – 8.5%. The explored reserves by categories A+B+C₁ are 18.9 Mt, total resources – 72 Mt. Deposit is not developed.

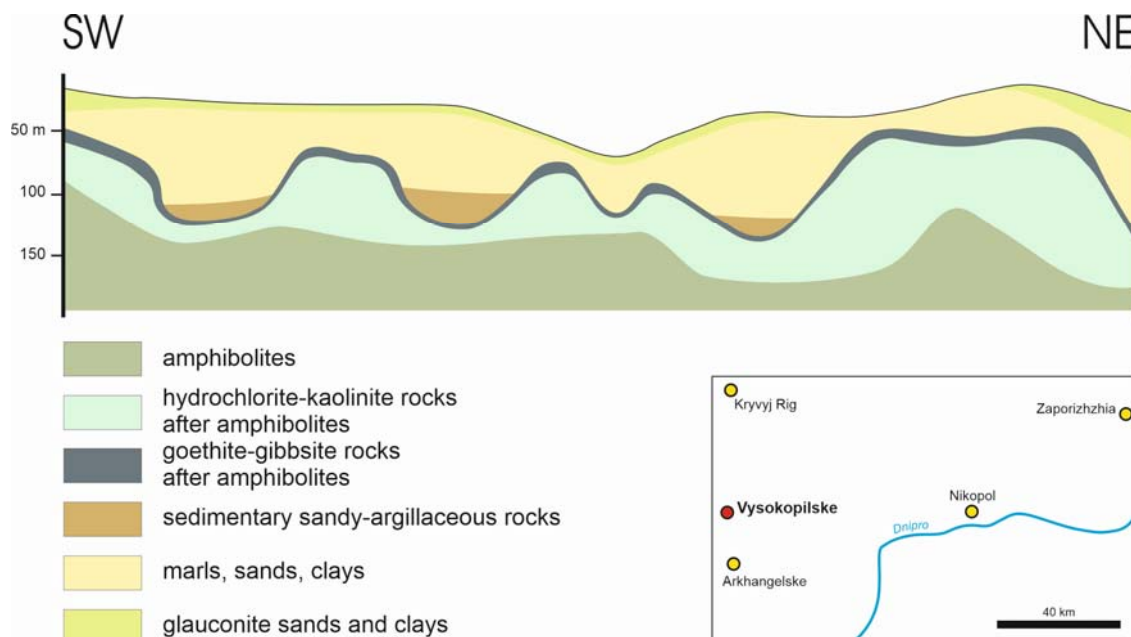


Fig. 4.20. Cross-section of the Vysokopilske bauxite deposit (modified after Mykhailov et al. 2007)

In the *Pivdennonikopolske deposit* bauxite bodies are confined to the upper part of the weathering crust of amphibolites, serpentinites and other rocks. There are 4 bodies (0.5 to 5.0 m thick) of high-iron bauxite of bean texture and hydrargillite-kaolinite composition. Reserves are estimated by categories B+C₁+C₂ to 535 kt.

In addition, small bauxite bodies of redeposited lateritic weathering crusts are known, exemplified by Smilyanske deposit in Cherkasy region, and bauxite occurrences in Vinnytsia region, but they have no practical significance.

Alunite formation is developed in the secondary quartzites of Trans-Carpathians, where several deposits are known with reserves of alunite ores over 400 Mt. These ores have a low content of alunite (30-40%), but they are suitable for complex use with production of alumina, sulfuric acid, alkaline salts etc. The largest bodies of alunite ores are associated with polymetallic deposits – Biganske and Beregivske.

The Biganske deposit in Trans-Carpathians was formed during the hydrothermal metamorphism of Miocene volcanic-sedimentary rocks. Alunite bodies are confined to the facies of secondary quartzites 70-120 m thick. With depth, quartz-alunite ores turn into barite-alunite and then into barite-polymetallic and polymetallic ores. The explored reserves of alunite ores comprise 290 Mt with an average content of alunite – 33.4%, alumina – 15%.

The Beregivske deposit has explored reserves of 50 Mt of alunite ores and mineralization parameters close to Biganske deposit. Alunite bodies over there occur in the simplest mining and geological conditions.

The formation of nepheline high-alumina rocks of metamorphogenic-magmatic genesis is developed in Proterozoic alkaline crystalline complexes, where nepheline syenites, foyaïtes, and alkaline pegmatites may be of interest (Donskoy et al. 2004). These rocks have an alumina content of 19-20%, silica – 53-56%, alkalies – 10-14%, iron oxides – 3-5%. They can be of interest only as the complex alumina-rare metal objects, exemplified by Mazurivske mariupolite deposit (Al₂O₃ – 22.45%, silicon

module ($\text{Al}_2\text{O}_3/\text{SiO}_2$) of 4.25, reserves over 1 billion tons) and Kalynino-Shevchenkivske deposit of mariupolites and foyaïtes (reserves of nepheline ores 330 Mt), which are confined to Oktyabrskiy Massif.

The formation of high-alumina quartzites is developed in Sushchano-Perzhanska Zone, where Sushchanske disthene (kyanite) deposit is known. Mineralization is associated with secondary quartzites, which form sheeted and lenticular bodies up to 37 m thick with an average disthene content of 20%. Precambrian metamorphic piles of Pryazovia are associated with garnet-sillimanite ores, their prognostic resources are amounted at 60-70 Mt. The SIMR records two deposits of high-alumina raw materials – Vovchanske and Malyshevskye in Dnipropetrovsk region. Their total reserves of disthene and sillimanite comprise almost 3 Mt.

Thus, Ukraine has good prospects for expanding the mineral resource base of aluminium raw materials, provided the development of new high-performance technologies for processing alunite ores of Trans-Carpathians and nepheline in Priazovye, but perspectives for industrial development of these facilities are unclear.

4.3.5. Copper

This is one of the non-ferrous metals, which is widely used in electrical engineering, machine-building, construction, military affairs, for the manufacture of various devices and equipment, works of art, coins and more. Much of copper is used in the electrical industry and communications, in particular, for the manufacture of electric batteries, due to its high electrical conductivity. High thermal conductivity and corrosion resistance make it possible to make copper parts of heat exchangers, refrigerators, vacuum devices, etc. (Copper 2015; The World Copper Factbook 2019). Thus, the modern industrial complex of any developed country cannot operate without the use of copper and its alloys. Therefore, in recent years there has been a steady increase in the price of copper (Fig. 4.21).

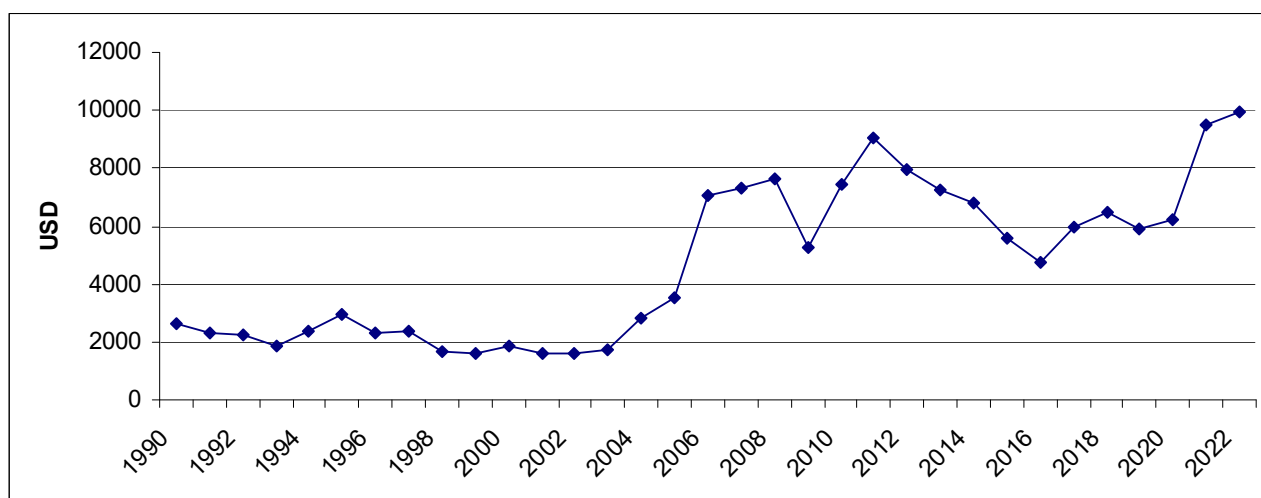


Fig. 4.21. Dynamics of copper prices in 1990-2022
(data source: <https://bhom.ru/commodities/med>)

World copper resources are estimated at 1,600 Mt, reserves – about 900 Mt, confirmed reserves – more than 600 Mt, which are concentrated mainly in Chile, Peru, Australia, USA, China, Zambia, Russia and other countries. They are the leading extractive countries, and in recent years Peru and the DRC have significantly increased production of copper raw materials (Table 4.39). Unfortunately, Ukraine is not one of them, there is no own MRB of copper, which we are obliged to import in the amount of about 90-100 kt per year. Therefore, the issue of creating its own MRB of copper is relevant and timely for Ukraine (Law 2011a; Mykhailov et al. 2007; Mineral Resources of Ukraine 2018; Orynychak 2021).

Table 4.39. World copper mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
Chile	5,772.1	5,552.6	5,503.5	5,831.6	5,787.4	200
Peru	1,700.8	2,353.9	2,445.6	2,437.0	2,455.4	87
China	1,706.4	1,851.0	1,706.4	1,618.5	1,683.5	26
DR Congo	1,039.0	1,023.7	1,094.6	1,239.1	1,461.1	19
USA	1,380.0	1,430.0	1,260.0	1,220.0	1,260.0	51
Australia	995.9	947.6	849.1	910.9	934.1	87
Russia	711.4	702.3	761.1	870.5	812.4	61
Zambia	711.5	774.3	799.3	857.8	789.9	19
Mexico	594.5	794.0	742.3	696.6	713.7	53
Kazakhstan	467.5	471.5	540.7	632.6	604.5	20
Canada	714.7	695.8	597.2	548.0	560.8	n.a.
Other countries	3,560.1	3,931.5	4,873	3,845	3,606.6	247
Total	19,353.9	20,528.2	21,178.2	20,707.6	20,669.4	870

In Ukraine, more than 150 copper occurrences of different geological and genetic types are known: native copper in sedimentary-volcanic piles (Volyno-Podilska Plate), stratiform mineralization in cupriferous sandstones and shales (Dniprovsko-Donetska Depression, Southern Donbas, Volyno-Podilska Plate, Folded Carpathians, Fore-Carpathian Trough), sulphide copper-nickel, massive copper, and iron-copper (Ukrainian Shield, Rakhivskiy Massif) (Gurskiy et al. 2006). The most interesting of them are occurrences of native copper formation in Riphean flood basalts of Volyn copper ore area (Fig. 4.22). The problem is the lack of objective geological and economic assessment of these occurrences, which makes it difficult to attract investment for their possible industrial use.

Special permits for copper ore mining have been issued for Zhyrychi (Cu) (SE “Volynpryrodrures”), Pivdennorafalivske (Cu) (“North-Western Mining” LLC) deposits, and for exploration of Prutivske occurrence (Cu+Ni) (“Colormet of Ukraine” LLC). Proposals on licensing are opened for exploration of Zheleznyaky site (Cu+Ni+Co) in the Zhytomyr region and Zalisys-Shmenky site (Cu) in the Volyn region (High copper test 2021).

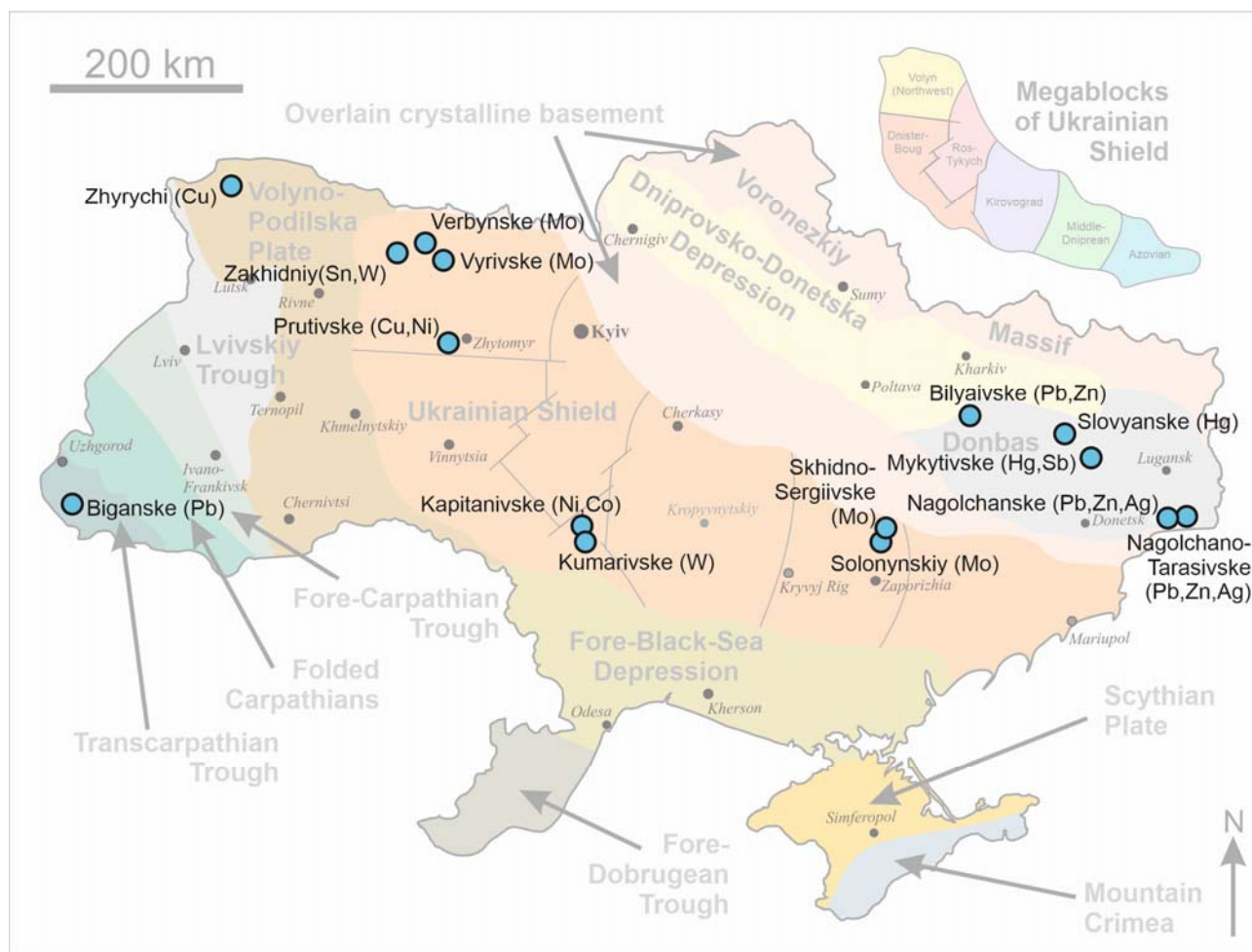


Fig. 4.22. Distribution of some non-ferrous metals deposits and occurrences

There is a significant interest of potential investors in the development of copper ore potential of Volyn ore district, which is widely described in the geological literature (Batsevych et al. 2016; Derevskaya, Shumlyanskiy 2009; Yemets 2008; Kvasnytsya et al. 2009; Melnychuk 2010; Melnychuk et al. 2011; Naumko et al. 2013; Prykhodko 2005; Prykhodko et al. 2010; Emetz et al. 2005; Sazonets, Malanchuk 2015).

In 1991-2008, the Rivne Geological Expedition of SE “Pivnichgeologia” was carrying out works to assess the ore potential of the ore area at the following sites: Zhyrychi, Zalyssy-Shmenky, Pivnichno-Ratnivska, Ratnivska, Teklya, Rafalivska, Telcha, Velyko-Midska (Prospecting for copper deposits 2008). Prediction factors and criteria have been established for the Volyn copper ore area, reserves of copper were estimated by category C_2 in the amount of 161.17 kt, as well as prognostic resources by categories: P_1 – 1,371.72 kt; P_2 – 2,109.09 kt; P_3 – 12,193.9 kt, a total of 15,835.88 kt of copper.

However, analysis of available exploration materials shows that during their implementation there was a significant overestimation of resources for these occurrences, which puts under question the overall assessment of copper resources of the Volyn ore area and perspectives for its industrial development (Mykhailov et al. 2022c, 2023). Three metallogenic areas have been identified in the Volynskiy ore camp, where occurrences, sites and ore fields with copper mineralization are located:

Volynska in the west, Kukhotsko-Volska in the northeast, and Manevytska in the southeast. Native copper mineralization there is associated with extrusive-pyroclastic and sedimentary rocks of the Vendian (Ediacaran) Volynska Series, where a number of copper-bearing horizons are distinguished (Fig. 4.23).

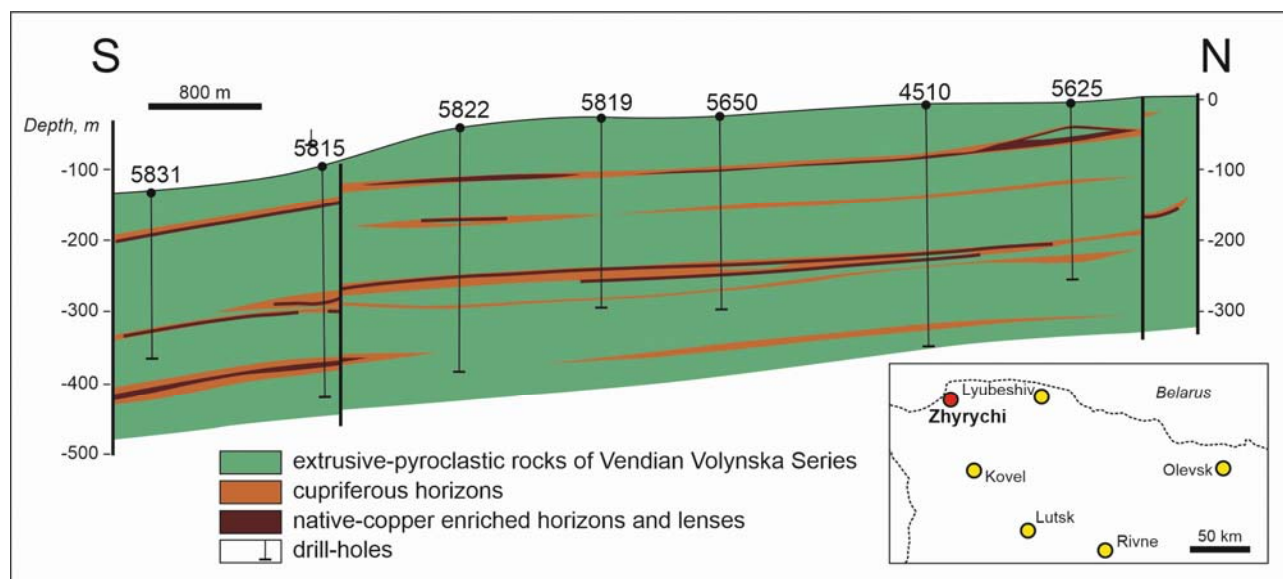


Fig. 4.23. A cross-section segment along the line of wells at the Zhyrychi native copper ore occurrence (modified after Mykhailov et al. 2022c)

The Volynska metallogenic area includes a number of native copper occurrences: Zhyrychi, Zalisyy-Shmenky, Pivnichno-Ratnivskiy, Ratnivskiy, Teklya.

At the **Zhyrychi copper ore occurrence**, 53 wells were drilled, that provided the basis for detailed analysis of materials which questions the notions of a considerable horizontal length (up to 4-5 km) of ore bodies. These actually are lenticular in shape and extend for a maximum of the hundreds of metres. It is shown that during evaluation of resources, in addition to artificial overestimating of ore body parameters, there was a systematic violation of the calculation conditions, namely copper cutoff grade (0.2%), minimum ore body thickness (1.0 m) and maximum thickness of barren rocks and ores below cutoff grade (1.0 m). All this led to a significant exaggeration of ore resources, which in the exploration materials by category P_1 were estimated at 858.93 kt, and by category P_2 – at 133.39 kt of copper, with a total of 992.32 kt of copper (Prospecting for copper deposits 2008). According to our assessment, for the Zhyrychi occurrence prognostic resources of copper by category P_1 are 220.4 kt, which is 4.5 times less than that given in the previous estimates. The rest of 125 kt prognostic resources, obviously, should be transferred to the category P_2 , the total resources of which will be 905.31 kt of copper (Mykhailov et al. 2022c).

The Zalisyy-Shmenky occurrence is a continuation of Zhyrychi occurrence to the southeast. Here, 31 wells were drilled, 504 samples were taken, but the copper content of 0.2% and more was established only in 47 samples (9.3%). According to the exploration materials, 6 ore-bearing horizons (1A, 2A, 2B, 2B, 3A, 3B) were identified, but this is not confirmed by a detailed analysis of primary exploration

materials: the persistent ore bodies were not determined in the "ore-bearing" horizons, as mineralization comprises discontinuous strike and dip localized ore bodies with limited resources that are unlikely to be of commercial interest.

The Pivnichno-Ratnivskiy occurrence is located to the north-east of the Zhyrychi ore occurrence and comprises continuation of the latter on the north-western border of the Girnytskiy Horst. Here, 26 wells (8,071.9 m) were drilled, 835 samples were taken, of which the copper content of 0.2% and more was recorded in 41 samples (4.9%). According to the exploration materials, 6 ore-bearing horizons (1A, 2A, 2B, 2B, 3A, 3B) have been identified, but according to the analysis of primary exploration materials, only one of these may be of economic interest, namely horizon 2A. According to our estimates, the total prognostic resources of ore by category P_1 are 6,408 kt of ore and 20.66 kt of copper, which is clearly insufficient to prove to be economically viable.

The Ratnivske occurrence is located to the north-east of the Zalisz-Shmenky occurrence, as a continuation; it has a similar structure and is also located on the southern border of the Girnytskiy Horst. Over a number of years, 15 wells were drilled there, in seven of which the samples with a copper content of 0.2% or more (only 15 samples) were identified, but, as the analysis of primary exploration results shows, the copper mineralization does not form more or less continuous ore bodies, they comprise small lenses scattered laterally and by dip, and have no practical interest.

The Teklya occurrence is located to the south of previous localities in the Teklinske uplift at the intersection of the Minsko-Vyzhivska and Zabolotivsko-Buzka fault zones. The geological structure of the site affects the rocks of the Kanylivska, Ratnivska, Babynska, Zabolotiska, and Gorbashivska Suites of the Poliska Series, as well as Jurassic, Cretaceous, and Quaternary sediments. The known findings of copper mineralization are associated with ore horizons 3A and 3B, confined to the sediments of the Ratnivska Suite. During the exploration, 5 wells (1985.0 m) were drilled, 242 core samples were taken, of which only in 5 samples (2.1%) the copper content exceeded 0.2%. Economic copper mineralization was only found in drill-hole № 5659, where two ore intervals were recorded in horizon 3A with a copper content of 0.27% for a thickness of 3.0 m (interval 323.0-326.0 m) and 0.25% for a thickness of 2.4 m (349.0-351.4 m). No potentially productive intervals were found in adjacent drill-holes (№№ 5568, 4540, 5519, 4511). Given these facts, the Teklya occurrence prospects for copper mining are minimal.

In the **Kukhotsko-Volska metallogenic area**, no deposits of copper mineralization that could be of practical interest have been identified.

The Manevytska metallogenic field includes the Rafalivska site (Pivdenno-Rafalivskiy occurrence, Komarivske, Chudlynske and Lyshnivske ore sections), and the Telcha and Velyko-Midska sites.

The Pivdenno-Rafalivskiy occurrence is practically interesting, hosted by the rocks of the Babynska and Ratnivska Suites of Lower Vendian (Ediacaran) Volynska Series, and the Chartoriyska Suite of Upper Vendian Mogyliv-Podilska Series, which are partially overlain by Upper Cretaceous, Paleogene and Quaternary sediments. The

ore-bearing horizons $3A_1$, $3A_2$, $3A_3$, $2B$, $V_2 cr_2$, $V_1 br$ are distinguished. According to the exploration results, reserves by category C_2 of this occurrence amount to 161.17 kt of copper, and resources by category P_1 – 512.79 kt of copper (Prospecting for copper deposits 2008).

However, these calculations cannot be substantiated. The results of drilling 286 wells (23,012 m) and sampling (10,842 samples), indicates that a copper content of 0.2% or more was found in only 70 samples only (0.6%). An additional 561 samples were taken from the quarries at the Rafalivska site, where copper content of 0.2% or more was detected in 21 samples only (3.7%). Significant copper contents are only sporadically found in various wells scattered over the site that do not form continuous groups, and are usually surrounded by the "barren" wells. Where did these reserves and resources come from, approved by the State Committee on Mineral Reserves nonetheless?

The fact is that calculation of the resource base of these deposits were carried out exclusively on the basis of neutron activation logging (NAL) data, which in most cases do not coincide with the sampling results. Thus, the authors of the report rejected a huge amount of analytical data, which exceeds 10,000 chemical analyses for copper, and replaced this data with hypothetical calculations, that we are unable to verify or support. Therefore, assessment of the resource base of the Pivdenno-Rafalivskiy occurrence during exploration seems to be unreliable. According to our estimates, prognostic resources of the occurrence can be estimated at 3.8 kt of copper by category P_1 . It is evident that such small ore bodies scattered over a large area have no economic potential.

Other deposits of the Manevytska metallogenic field are of no practical interest.

Thus, of all the numerous deposits of this ore province, only the Zhyrychi deposit may have some potential, where, unlike other areas, more or less extended ore bodies have been encountered. But they are small-scale, the contours of individual ore horizons are often not correlated between the wells and ore bodies, they occur at considerable depth (164.0-537.2 m), which makes open cast mining impracticable, and the profitability of the development of ores will be limited (Mykhailov et al. 2022c).

The total prognostic resources of the ore fields by category P_1 are estimated at 241.06 kt of copper, and P_2 – 905.31 kt of copper (Mykhailov et al. 2023). In our opinion, this makes it impossible to assess positively the investment attractiveness of the ore deposits.

Stratiform copper occurrences are known in the Lower Permian Kartamyshska Suite in the Bakhmutska Depression (Berestyanskiy, Gladosivskiy, Ivangradskiy, Pokrovskiy, Gurtynskiy, etc.), in Lower Devonian Dnisterska series of the Transnistrian region, in the Cretaceous-Eocene sediments of folded Carpathians, and in Miocene rocks of the Fore-Carpathian Trough, but they do not have economic value (Mykhailov et al. 2007).

For example, the **Berestyanskiy occurrence** in the Golubivsko-Maryivska Syncline is confined to the Kartamyshska Suite, where several ore-bearing horizons from 0.3 to 2.0 m thick (average 0.6 m) are distinguished at a depth of 855 m. The ore beds are

lenticular and sheeted in shape. They are confined to calcareous siltstones, dark-grey aleuritic clays, fine-grained sandstones, and dolomite limestones. Ore mineralization is represented by chalcocite, bornite, chalcopyrite, with less common covellite, cuprite, and native copper. Related minerals include galena, sphalerite, greenockite, pyrite, acanthite, malachite, azurite, and limonite. Chalcocite predominates and occurs finely disseminated (0.1-0.2 mm). Ores are usually finely disseminated, bunch-disseminated, and occasionally vein-disseminated. Substitution textures are characteristic, with lattice intergrowths, banded, cemented, concretionary and veinlet structures. The Cu content in the ores is 0.5-1.7%, Pb (0.1-1.2%), Zn (0.1-1.2%) with Ni, Ga, Ag, Re, Au, Au, Pb. Estimated copper resources are 1.7 Mt. Ore mining is possible by open-cast and underground methods using leaching and biotechnological methods.

Copper sulphide and polymetallic deposits have been encountered in metamorphic rocks of the Ukrainian Shield and in the Carpathians (Rakhivskiy Massif), but their small scale and low copper content do not warrant consideration of them as promising resources.

For instance, copper sulphide mineralization of *the Krutobalkinskiy occurrence* in the Verkhivtsivska greenstone structure is confined to a steeply-dipping zone 200-250 m wide, where several subparallel ore bodies with a thickness of 0.2 to 9 m and a length of 200-800 m are located. Copper content varies from 0.5 to 3.3%. The main ore body with an average thickness of 3.4 m and copper content of 0.86%, was traced by strike for 800 m and by dip to 250 m. Prognostic copper resources (category P₁) are estimated there at 23 kt.

Table 4.40. Metal grades of massive copper sulphide ore bodies in the Dilovetskiy area

Element	Grade
Cu, %	up to 3.2 (usually 0.6-0.82)
Pb, %	0.42
Zn, %	0.33
Mo, %	up to 0.12
Ag, g/t	up to 138
Au, g/t	1.0

traced for tens of metres, with thickness up to 38 m. The thickness of ore bodies is 3 m, and their metal grades are given in Table 4.40.

The Prutivske occurrence of copper-nickel sulphide ores is located in the Volyn megablock of the Ukrainian Shield, in the Krasnogirsko-Zhytomyrska Zone. It is associated with the Paleoproterozoic Prutivska Intrusion – a sill-like body 1000-1500 m wide and 130-160 m thick, which occurs in the core of an anticline fold composed of shadow biotite migmatites and gneisses of the Teterivska Series. The body plunges to northeast at an angle of 25-35°, and is traced in the north-western direction for 3 km. The intrusion is dominated by gabbroids. Gabbronorites, troctolites, and gabbro-pegmatites are found in the form of schlieren bodies in relatively thin layers.

Copper deposits of chalcopyrite-pyrite type of massive copper sulphide formation were found in the *Dilovetskiy area* of the Rakhivskiy Massif (Polonske, Pip Ivan, Gavryshchuk, etc.), where they are confined to quartzites (metarolites) in quartz-chlorite-sericite schists of the Dilovetska Suite. Mineralized zones are

Ore zones with sulphide mineralization are mainly confined to the endo- and exocontacts of the intrusion. Their thickness varies from metres to 15.1 m. The content of sulphide dissemination varies from 3 to 20%, reaching in places 50-70%. Veinlet ores up to the several centimetres thick are often found. The average metal contents and ratios are given in Table 4.41. Typical ore mineral assemblages are: chalcopyrite-pentlandite-pyrrhotite, pentlandite-cubanite-chalcopyrite-pyrrhotite, pyrite-violarite-mackinawite; the latter is secondary, developing in the process of epigenetic alteration of minerals of the first two assemblages.

Table 4.41. Average metal contents in ore zones of the Prutivske occurrence and Zheleznyaki site

Element	Prutivske occurrence	Zheleznyaki site
Ni, %	0.58	0.66
Cu, %	0.26	0.063
Co, %	0.022	0.013
Ni:Co	10-15 to 35-37	n.a.

The Zheleznyaki site in the Zhytomyr region with an area of 290 hectares is a complex occurrence of copper, nickel, and cobalt ores, which is considered to be of the copper-nickel sulphide type. It is confined to a small oval-shaped intrusion of the same name, 1.0×1.8 km in size, funnel-shaped in cross-section, which cuts migmatites of the Kirovogradsko-Zhytomyrskiy Complex. The intrusion is composed of peridotites, pyroxenites and gabbro-norites of the Bukinskiy Complex, where two ore intervals with a thickness of 3.5 and 2.0 m are encountered, with average metal content for a total thickness of 5.5 m is shown above in Table 4.41. The deposit was studied by a single well. Prognostic resources by category P₃ are as follows: nickel – 150.9 kt, copper – 14.4 kt, cobalt – 3.0 kt.

Table 4.42. Metal grades and resources in waste of Konstyantinivskiy plant

Element	Resources, kt	Avg, grade, %
Cu	8	1.2
Zn	24	3.8
Pb	10	1.5

In addition to the copper deposits of various genetic types, an important potential source of copper production may be industrial waste from mining activities. One of the technogenic copper accumulations is the waste of the

Konstyantinivskiy plant "Ukrzinc" in the Donetsk region. Increased content of copper, lead, zinc and precious metals was found in the waste of this plant. The waste is essentially a complex technogenic deposit (Table 4.42). It is possible to extract them by means of heap leaching with a high level of profitability (50-70%), which will contribute to the elimination of dumps and an improvement of the environment in Kostyantynivka town and around.

4.3.6. Tantalum and Niobium

The main area of application of tantalum is the production of miniature capacitors, which are used in radio engineering, radio electronics, aerospace equipment and military applications. Other uses of this metal are electrovacuum technology (anodes, parts of high-temperature vacuum furnaces), aerospace technology (parts of jet engines), defence industry (hulls of deep-sea submarines). An alloy of tantalum

(80%), tungsten (8%) and hafnium (2%) is used as a structural material in nuclear reactors.

Niobium is used in ferrous metallurgy for the production of stainless heat-resistant and corrosion-resistant alloys and steel, for the production of oil and gas pipelines, in the construction of bridges, and offshore oil rigs. Heat-resistant alloys containing up to 50% of niobium are used in the manufacture of jet engines. Niobium carbide in a mixture with tantalum carbide is used in super hard alloys instead of the more expensive pure tantalum carbide. Niobium alloys with titanium, tin, aluminium and germanium are used in superconducting technology. Niobium is used in particle accelerators, nuclear tomographs, and magnetic separators.

World reserves of tantalum exceed 90 kt, world production is 1.5-2.2 kt, the leading extractive countries are the DRC, Rwanda, Brazil, Nigeria, China and other countries, and while the countries such as Nigeria and Australia have increased production, the DR Congo has decreased (Table 4.43).

Table 4.43. World tantalum mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Extraction of Ta ₂ O ₅ , t					Reserves, kt
	2015	2016	2017	2018	2019	
DR Congo	736	845	761	644	440	n.a.
Rwanda	380	290	395	380	310	n.a.
Brazil	268	234	270	150	250	34
Nigeria	72	66	480	230	200	n.a.
China	110	120	110	100	135	n.a.
Australia	20	10	20	40	80	55
Mozambique	28	41	57	66	59	n.a.
Ethiopia	75	101	90	104	50	n.a.
Russia	32	49	45	44	32	n.a.
Malaysia	9	8	6	27	10	n.a.
Bolivia	1	0	3	18	10	n.a.
Burundi	19	11	26	8	8	n.a.
Total	1,750	1,775	2,263	1,811	1,584	>90

World niobium reserves exceed 13 Mt, world production is constantly increasing from 87 kt in 2015 to 135 kt in 2019. The leading mining countries are Brazil (94% of world production), Canada, Russia, DR Congo, Rwanda, Nigeria, China, and other countries, and Brazil has significantly increased production in recent years (Table 4.44).

Table 4.44. World niobium mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Extraction of Nb ₂ O ₅ , t					Reserves, kt
	2015	2016	2017	2018	2019	
Brazil	80,465	80,669	83,166	99,554	127,220	11,000
Canada	5,385	6,099	6,981	7,700	6,800	1,600
Russia	628	628	648	669	659	n.a.
DR Congo	694	797	717	607	415	n.a.

Country	Extraction of Nb ₂ O ₅ , t					Reserves, kt
	2015	2016	2017	2018	2019	
Rwanda	248	190	260	245	200	n.a.
Nigeria	29	104	122	181	150	n.a.
China	30	30	30	20	20	n.a.
Ethiopia	20	28	25	28	14	n.a.
Mozambique	5	7	10	12	11	n.a.
Burundi	13	8	18	5	5	n.a.
Uganda	n.a.	4	3	2	2	n.a.
Total	87,517	88,564	91,980	109,023	135,496	>13,000

In Ukraine, the resource potential of tantalum and niobium is thought to be the highest in Europe. There are two main rare-metal areas, where occurrences of promising genetic types of tantalum-niobium mineralization are known: the Azovian megablock and the north-western part of the Ukrainian Shield. Two complex deposits of rare metals were discovered and estimated in the Azovian region – ore-bearing carbonates of the Novopoltavske deposit and rare metal syenites and metasomatites of the Mazurivske deposit, where the main reserves of Ta and Nb of Ukraine are concentrated.

In the north-west of the Ukrainian Shield, tantalum and niobium are associated with granitoids and metasomatites of the Sushchano-Perzhanska Zone; in the central part of the Ukrainian Shield there is the rare-metal Shpolyansko-Tashlytskiy area with deposits of lithium pegmatites and concomitant tantalum-niobium mineralization.

The SIMR records reserves of tantalum and niobium in 5 deposits: zircon-rutile-ilmenite placer Malyshevske and Vovchanske (Dnipropetrovsk region), hard-rock apatite-rare metal Novopoltavske (Zaporizhia region), wastes from beneficiation of weathered ores of the Eastern section of Mazurivske deposit (Donetsk region), and the Mostove tantalum ore site (Kirovograd region) (Mineral Resources of Ukraine 2021). Mining is carried out on small scales at the Malyshevske and Vovchanske deposits.

The Mazurivske deposit is described above. Regarding tantalum-niobium mineralization, the nepheline rocks, their pegmatites and metasomatites (albitized nepheline syenites, albitites, mica rocks) are of practical interest. The highest-grade mineralization is associated with mariupolites and microcline-nepheline pegmatites. Extended thick ore zones are distinguished, where the ore bodies are located. The length of ore bodies reaches 1.5 km. The ores are complex, pyrochlore-zircon in composition. Along with pyrochlore and zircons, fersmite, columbite, and ilmenorutile are abundant. The content of the main useful components in the ores is as follows: Nb₂O₅ – 0.1-3.0%, and Ta₂O₅ – 0.005-0.12%, ZrO₂ – 0.01-6.17%. Ores are easily beneficiated to obtain rough tantalum-niobium (pyrochlore) and zirconium saleable concentrates with concomitant extraction of saleable feldspar product.

The weathered crust of the deposit reaches a thickness of 40-60 m, belongs to the areal type, divided into three zones: disintegration, dense clays and final products (friable and unstructured clays). In the crust there are significant increases in the

content of tantalum and niobium compared to the primary rocks. Pyrochlore is very altered, characterized by a metamictic state, and becomes unstable and crushed during beneficiation.

The total prognostic resources of the deposits are quite significant (Nb_2O_5 – 1-8 Mt, and Ta_2O_5 – 30 kt within the depths for opencast mining (Mykhailov et al. 2007). The MBP can operate on the basis of the deposit, which will process up to 15 Mt of ore per year. Industrial development of the Mazurivske deposit, by processing the rough concentrates of the Donetsk Chemical and Metallurgical Plant, and high-quality tantalum and niobium products at the Prydniprovskiy plant, can significantly meet Ukraine's tantalum needs in the near future. Areas where estimated resources are promising for the development of reserves in the deposit are East, West, Kalyno-Shevchenkivska, South, Vyanivska.

The Novopoltavske rare-metal-apatite deposit is described above. It belongs to the phosphorus-rare-earth-rare-metal ore formation in carbonatites. The following assemblages of rare-metal minerals are distinguished:

- 1) getchelite with baddeleyite in calcite carbonatites;
- 2) monazite-cerite-fergusonite in calcite and dolomite-calcite carbonatites;
- 3) pyrochlore-columbite with zircon in carbonatite phenites;
- 4) pyrochlore-zircon in syenite alkaline rocks.

Weathered crust with a high content of niobium, rare earths and phosphorus is widespread at the deposit. Along with apatite, fergusonite, getchelite, florenceite, columbite, pyrochlore, and fersmite are noted.

Resources of hard-rock complex ores (phosphorus, tantalum, niobium, fluorine) amount to 384.7 Mt (Mykhailov et al. 2007). The deposit has been thoroughly explored and prepared for operation. It is planned to develop a deposit up to a depth of 600 m with a pillar of 100 m height to support the unstable rocks of the crust. Development is planned to be carried out from below by chambers with produced space filling.

4.3.7. Beryllium

It is widely used in electronic, aerospace, metallurgical, military and other fields for the manufacture of electronic and communication equipment, automotive, aerospace and defence components, automotive and consumer electronics, and security systems.

Beryllium reserves in the world exceed 100 kt, production is about 6 kt, and the major share of production falls on the United States (68% of world production) and China (29.4%), much less is produced by Brazil, Madagascar, Nigeria, Rwanda, Zambia (Table 4.45).

Table 4.45. World beryllium mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Mining, t					Reserves, kt
	2015	2016	2017	2018	2019	
USA	5,100	3,870	3,760	4,170	4,050	n.a.

Country	Mining, t					Reserves, kt
	2015	2016	2017	2018	2019	
China	1,200	1,250	1,250	1,250	1,750	n.a.
Brazil	100	125	75	70	70	n.a.
Madagascar	140	140	140	140	30	n.a.
Nigeria	56	0	0	35	25	n.a.
Rwanda	23	30	30	30	20	n.a.
Zambia	7	5	4	7	7	n.a.
Mozambique	312	181	53	416	0	n.a.
Total	6,938	5,601	5,312	6,118	5,952	>100

In Ukraine, in the Zhytomyr region, a unique **Perzhanske deposit** of genthelvite beryllium ores was discovered (Metalidi, Nechaev 1983; Mitskevich et al. 1986). Mineralization is associated with quartz-feldspar, quartz-biotite-feldspar, alkaline metasomatites and perthosites, which occur in the Perzhanski granites (Zagnitko et al. 2017). Beryllium-bearing alkaline metasomatites form a series of ore bodies with high-grade genthelvite mineralization up to 5 km long and 35-100 m wide (Voinovsky et al. 2000). The zones include en-echelon ore bodies with a thickness from metres to 20-30 m (Fig. 4.24). The content of Be_2O_3 in ore bodies reaches 0.55%, ores are characterized by relatively simple beneficiation. In addition to genthelvite, beryllium is contained in phenakite, developed in granite porphyries and fine-grained granites of the western endocontact of the Perzhanski granites. Secondary accessory minerals include martite, cirtolite, galena, sphalerite, occasionally cassiterite with micro inclusions of columbite, etc.

The reserves of the deposit are estimated by category A+B+C₁ at 2,065.9 kt of ore and 11,441.2 tons of beryllium oxide, and by category C₂ – 769.8 kt of ore and 3,866.6 tons of beryllium oxide (Mineral Resources of Ukraine 2021). The deposit is not being developed, although “Perzhanska Rudna Kompaniya” LLC has a license (special permit) for beryllium ore mining.

In addition, promising beryllium resources have been identified at Novostankuvatske, Lypnyazke and Talytske, and reserves have been assessed at the Shevchenkivske lithium deposit. Proposals for licensing are open at the Lypnyazke, Tashlytske and Novostankuvatske deposits in Kirovograd region.

4.3.8. Gold

The value of gold is determined primarily by its role as the world's monetary equivalent, although due to its unique physicochemical properties (plasticity, malleability, chemical inertness, low oxidation, etc.) it is widely used in jewellery, electronics, space and aviation, medicine, etc.

World gold reserves are estimated at 50 kt, which are concentrated in Australia, Russia, United States, South Africa, Indonesia, Peru, Canada and other countries. Gold production in recent years ranges from 3.1 to 3.4 kt. The largest gold-producing countries are China, Australia, Russia, USA, Canada, Ghana, etc., with the countries such as Australia, Russia, Ghana, Indonesia, Kazakhstan is constantly increasing gold

production, while China, Peru, and South Africa are declining (Table 4.46).

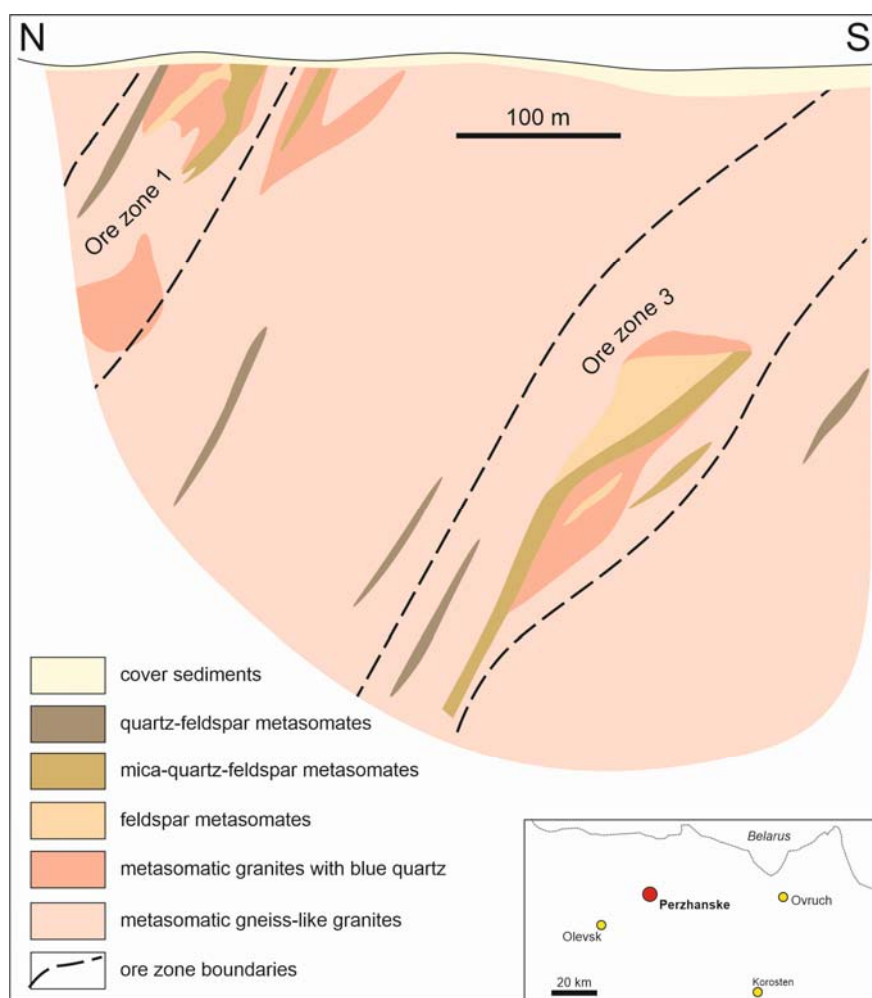


Fig. 4.24. Geological cross-section of the Perzhanske deposit (modified after Mykhailov et al. 2007)

Table 4.46. World gold mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Mining, t					Reserves, kt
	2015	2016	2017	2018	2019	
China	450.1	453.5	426.1	401.1	380.2	2.0
Australia	277.4	290.8	292.0	313.0	325.7	10.0
Russia	255.2	253.6	270.3	279.9	305.1	5.3
USA	213.8	228.3	236.8	226.0	200.0	3.0
Canada	162.5	163.9	178.6	194.2	182.8	1.9
Ghana	96.9	128.0	143.4	149.1	142.4	1.0
Mexico	134.8	133.6	126.8	141.1	133.9	1.4
Peru	146.8	153.0	152.0	140.2	128.4	2.1
Indonesia	92.2	91.1	101.5	135.3	108.9	2.6
Kazakhstan	63.6	74.7	85.3	100.3	106.6	1.0
South Africa	144.5	142.2	137.3	117.1	105.2	3.2
Other countries	1,082.5	1,145.3	1,186.3	1,179.6	1,173.1	16.5
Total	3,120.3	3,258.0	3,336.4	3,376.9	3,292.3	50.0

In Ukraine, there are three important gold ore provinces with different types of mineralization (Fig. 4.25): 1) Ukrainian Shield province, where gold deposits are associated either with the Mesoarchean greenstone belts (Sergiivske, Balka Zolota, Balka Shyroka, Surozke deposits) or with Paleoproterozoic activation structures (Maiske, Klyntsivske, Yuriivske deposits); 2) Carpathian province, where two types of gold deposits are distinguished: i) associated with Neogene volcanism of the Beregovy Hills (Muzhyivske, Beregovske), and ii) associated with Proterozoic – early Paleozoic structures of the Rakhivskiy Massif (Saulyak deposit); 3) Donetsk province, where gold deposits are associated with Paleozoic Carboniferous piles (Bobrykivske, Gostriy Bugor deposits, Mykhailivske occurrence).



Fig. 4.25. Distribution of precious metals deposits of Ukraine (modified after Mykhailov et al. 2007)

The SIMR records gold reserves in 7 deposits – Sergiivske, Balka Zolota (Dnipropetrovsk region), Klyntsivske (Kirovograd region), Muzhyivske, Saulyak, Dilovetska field (Bilopotikhska and Tukalo-Yasenivska sections (Trans-Carpathians), Bobrykivske deposit (Lugansk region).

Special permits for gold ore mining have been granted to the following enterprises: PJSC “Carpathian Ore Company” (Muzhyivske deposit); “Saulyak” LLC (Saulyak); “Stone Processing Company of Ukraine” LLC (Sergiivske); “Donetsk Ridge” LLC (Bobrykivske); “Lira Main Minerals” LLC (Klyntsivske). Extraction in 2020 was

carried out only at the Muzhyivske deposit (Mineral Resources of Ukraine 2021).

Exploration licenses were granted to the following companies: PJSC “Carpathian Ore Company” (Beregivske deposit), “Western Geological Exploration Company” LLC (Kvasivske ore field), “Spys Ukraina” LLC (Zhovtovodska site).

At the same time, proposals for licensing are open for mining at the Balka Zolota deposit in the Dnipropetrovsk region, for exploration – Balka Shyroka in the Dnipropetrovsk region, Maiske and Kvitkivske sites in the Odesa region, Yuriivske site in the Kirovograd region (Investment Atlas of Subsurface User 2021).

Exploration and evaluation works have been carried out in recent years in the following sites: Novoselivska (flanks of Balka Zolota deposit); Andriivska (western part of the Solonyanske ore field in Surska greenstone structure); Northern, Central and Zhovtianska (Zhovtovodske field of Kryvorizko-Kremenchutska Zone); Gubivska (Klyntsivske deposit); Chemerpilska, Kvitkivska (Savranska metallogenic zone); Bobrykivska Zakhidna, Bobrykivska Pivnichno-Skhidna and Bobrykivska Pivnichno-Zakhidna (Bobrykivske deposit); Grabivska (Vilkhovatsko-Volyntsiivska anticline) (Mineral Resources of Ukraine 2020).

Characteristics of Ukraine's gold deposits are provided by (Gurskiy et al. 2006a; Gurskiy 2008; Mykhailov et al. 2007; Mykhailov, Fedchuk 2008).

In *the Ukrainian Shield province*, a number of tectonic-metallogenic zones (TMZ) with Mesoarchean deposits are associated with greenstone structures (Sergiivske, Balka Zolota, Balka Shyroka, Surozske), and Paleoproterozoic deposits are associated with the zones of tectonic-magmatic activation) (Maiske, Klitsivske, Yuriivske).

The Sergiivske deposit (Dyshchuk 2000; Koval et al. 1997; Yatsenko et al. 2000) is located in the Surska greenstone structure (Fig. 4.26) and is controlled by the zone of Pivnichno-Sergiivskiy Fault, where a subvolcanic body of granodiorite-porphyrries is located, plunging to the north at an angle of 50-70°. The gold mineralization is located in the schistosity zone in the hanging-wall and foot-wall of subvolcanic body, the highest-grade part is confined to the extensively dislocated areas at the intersection of longitudinal and transverse-diagonal schistosity and crushing zones. Host rocks are represented by metabasalts, metagabbro-dolerites, metadacites and metagranodiorite-porphyrries, transformed into schists.

Three ore-controlling sublatitudinal zones of quartz-carbonate-amphibole metasomatites with a width of 80-160 m and a length of up to 1.5 km are distinguished, commonly associated with exocontacts of stocks and dykes of felsic composition. Gold mineralization is represented by:

- 1) quartz-carbonate veinlets in shearing zones of metabasalts with low-grade sulphide mineralization;
- 2) east-west-trending banded and lenticular zones of silicification of metavolcanic rocks with abundant (up to 30%) sulphide inclusions (pyrite, pyrrhotite, chalcopyrite);
- 3) east-west-trending quartz-carbonate-tremolite veins in the zones of amphibolite metasomatites;

- 4) north- to north-north-west-trending ankerite-sulphide-quartz veins. Ore bodies (about 20) are accompanied by carbonisation, silicification and amphibole metasomatism.

The average gold content in ores is 7-8 g/t, Au:Ag ratio is 1: 2.

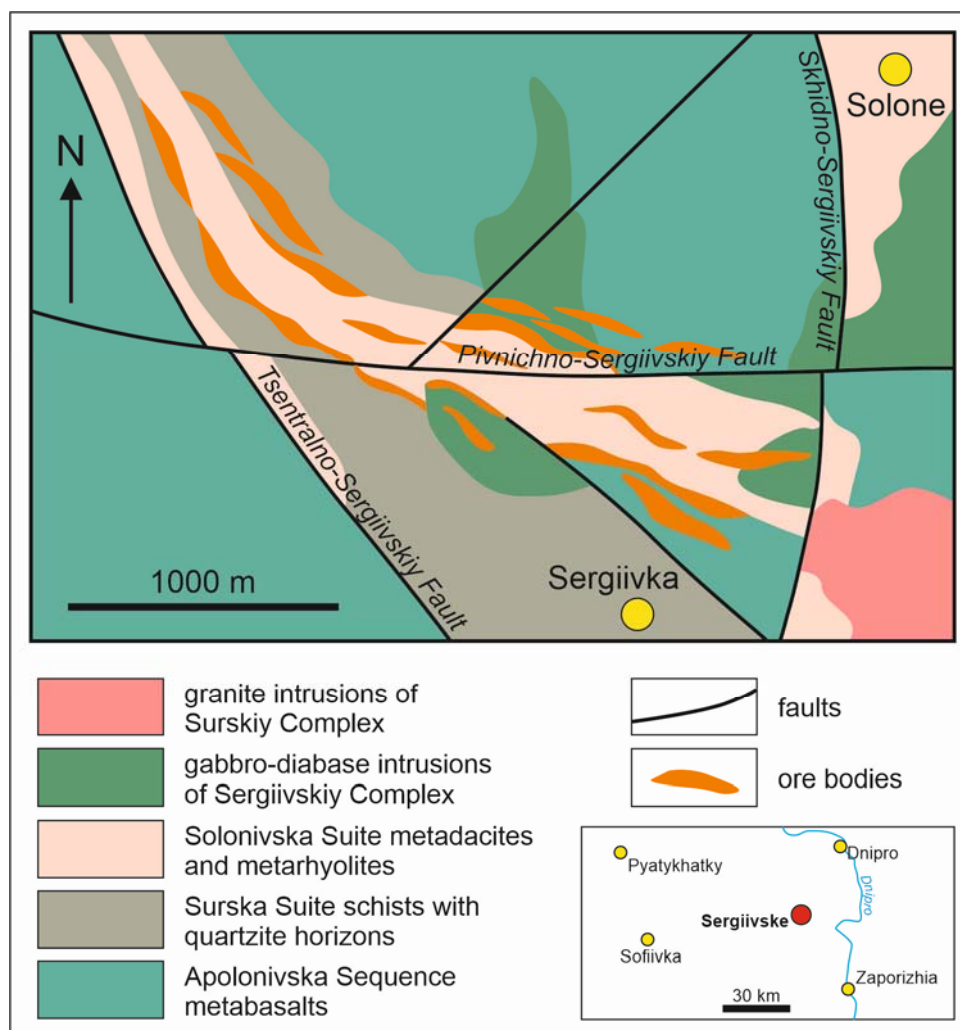


Fig. 4.26. Geological map of the Sergiivske deposit (modified after Mykhailov et al. 2007)

The most important mineralogical types of ores are as follows:

- 1) *gold-silver-bismuth-tellurium* (Au from 0.5 to 100 g/t): native gold, pilsenite (Au up to 4.01%), sylvanite (Au 23.5-24.15 %), petzite (Au 23.6-24.9%), pyrite (Au up to 14 g/t);
- 2) *gold-copper-molybdenum*;
- 3) *gold-sulphide* stratiform in quartzite horizons (Au 1-3 g/t), gold is represented by a fine dissemination in pyrite.

Gold fineness varies from 810 to 950, gold is native, with a small proportion of gold tellurides and gold dispersed in sulphides and rock-forming minerals. Commonly gold is associated with chalcedony-like grey quartz, rarely it is found in carbonates and chlorite, and forms dust-like accumulations in thin quartz veinlets. The dimension of gold is 0.05-0.1 mm, sometimes up to 1.5 mm. Sulfosalts Pb, Bi, Ag, tellurides Au, Ag, Bi (sylvanite, petzite, Cu-cosalite, pilsenite, tellurobismuthite), as well as native Bi are found in the form of single grains or bunches (1-2 mm) in

quartz. Relic magnetite, ilmenite, titanomagnetite (up to 10%), occasionally (in areas of amphibole metasomatism) – scheelite occur in places.

The Balka Zolota deposit is located in the southern part of the Surska greenstone structure and belongs to the gold-quartz vein type, confined to the stock of quartz porphyries (3.15-3.07 billion years). Ore bodies are represented by zones of vein-disseminated sulphide mineralization in sublatitudinal zones of silicification. By morphology of ore bodies, two types are distinguished:

- 1) linear stockworks (1-10 m) in shearing zones with quartz-carbonate veinlets, insignificant role of sulphides (pyrite, pyrrhotite) (1-3%), tellurides and sulfosalts;
- 2) quartz and carbonate veins from tens of centimetres up to 5-6 m thick, pipe-like and columnar vein bodies.

Ore minerals include pyrite, chalcopyrite, pyrrhotite, sphalerite, and others. The gold content varies from 0.7 to 30.2 g/t (average content 6.2 g/t). The age of galena from quartz veins corresponds to 3.0-2.9 and 2.7-2.5 billion years.

The Balka Shyroka deposit (Koval et al. 1998; Romanyuk et al. 1997; Fomin et al. 1994) is located in the Dnipropetrovsk region, in the Chortomlytska greenstone structure in the zone of intersection of submeridional Skhidno-Chortomlytska Zone of shearing, cataclase, mylonitization, brecciation, and north-eastern Derezhovatskiy Fault, in the vicinity of subvolcanic bodies of plagiogranite-porphyries of the Chkalovskiy Massif (Fig. 4.27).

In total, 285 prospecting and exploration wells with a total length of 92,480 m were drilled at the deposit, and a mine shaft was built to a depth of 168.4 m.

Gold mineralization is located in a series of subparallel north-western zones of listvenitization and propylitization up to 280 m wide, traced along the Skhidno-Chortomlytskiy Fault for 3 km and for 800 m by dip. Mineralization is concentrated in zones (2-80 m) of brecciated, cataclased, mylonitized rocks, turned into steep folds, mainly at the contacts with ferruginous quartzites. Ore bodies are represented by lenses, horizons, ore columns, veins, thin stockworks (0.4-6.4 m, on average 1.45 m), located in metasomatites of berisite-listvenite formation.

Five mineral types of ores are distinguished (Investment Atlas of Subsurface User 2021):

- 1) *gold-quartz* (76% of ores) – characterized by the presence of free gold and low sulphide content (up to 5%), gold content from 0.5-6.9 g/t to 1,023 g/t, silver – from 0.5 to 19 g/t;
- 2) *gold-sulphide-quartz* (19% of ores) – is characterized by the presence of both free and bound gold, the content of sulphides 5-25%, gold – 0.5-32 g/t, silver – 0.5-13 g/t;
- 3) *gold-pyrite* (2.5% of ores) – native gold occurs in the form of dissemination in pyrite, occasionally in quartz, sulphide content over 25%;
- 4) *gold-silver-polymetallic* (2.5% ores) – the content of sulphides is from 8-10 to 50-60%, ores are complex, gold content – up to 20 g/t, silver – up to 434 g/t, lead – up to 5%, zinc – up to 1%, copper – up to 0.1%, cadmium – up to 300 g/t;
- 5) *gold-quartz-pyrite-arsenopyrite* – very scarce, usually combined with gold-sulphide-quartz and gold-silver-polymetallic types, low gold content.

Ore minerals include: magnetite, pyrrhotite, chalcopyrite, sphalerite, pyrite, marcasite, arsenopyrite, tetrahedrite, native gold. The most important ore bodies are conformable to host rocks, they are controlled by transverse faults, flexures, and structures such as "horsetail". The average gold content in ores is 4-7 g/t. The age of

mineralization of vein gold-quartz type – 3.0-2.9 billion years, mineralization in ferruginous quartzites – 2.55-2.50 billion years for gold-pyrite-pyrrhotite and 2.60-2.55 billion years for gold-polymetallic ores.

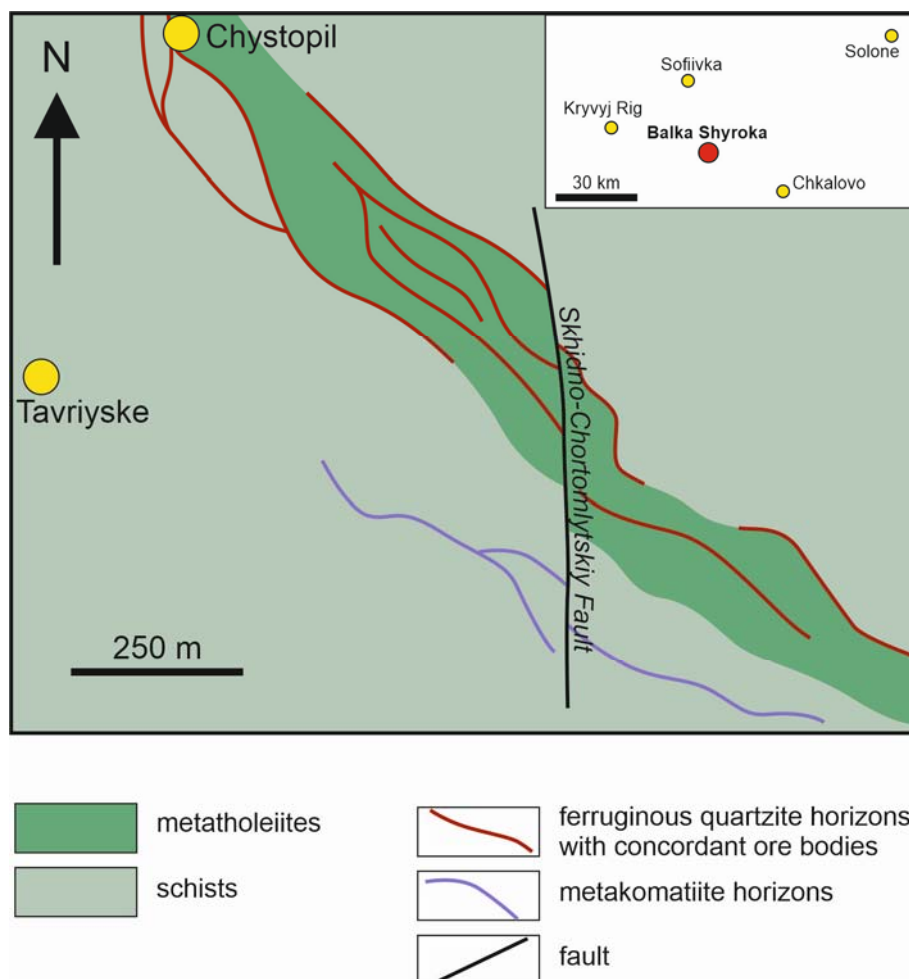


Fig. 4.27. Geological map of the Balka Shyroka deposit (modified after Mykhailov et al. 2007)

Prognostic gold resources at 3.9 g/t cutoff grade are estimated by category P_1 to 12,549.65 kg, P_2 – 15,133.05 kg, the average content in blocks – 7.1 g/t (Investment Atlas of Subsurface User 2021).

The Surozke deposit (Bobrov et al. 2000a; Kravchenko 1999) is located in the Sorokynska greenstone structure at the intersection of the ancient NW-trending Skifskiy Fault and the younger NEE-trending Sichniy Fault (Fig. 4.28). Ore zones are represented by sheeted and strip-like bodies (0.2-3.1 m) of silicified and sulphidized metasomatites in cataclased, brecciated amphibolites and magnetite quartzites, which form an ore column. They occur conformably to the host rocks, often confined to the contacts of various rocks (e.g., amphibolites and schists), controlled by an en-echelon detachment fracture system. Ore bodies are sheeted and lenticular in shape, less often vein-shaped, 0.2-3.1 m thick, on average 1.9 m. Low-grade mineralization (up to 4 g/t Au) is more common for hanging-wall portions of ore bodies, and the high-grade (up to 66 g/t Au) is more often associated with the footwall ones.

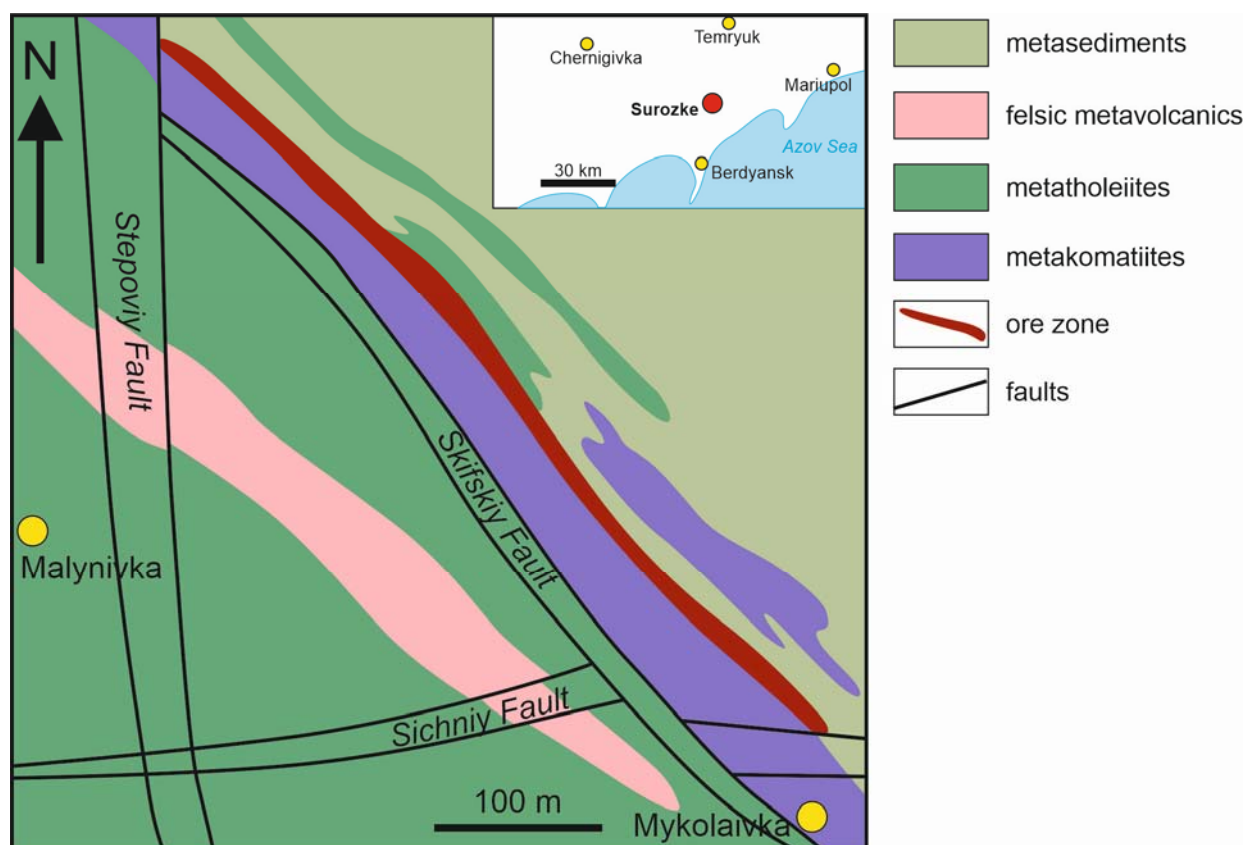


Fig. 4.28. Geological map of the Surozke deposit (modified after Mykhailov et al. 2007)

Ore minerals include magnetite, ilmenite, pyrrhotite, pyrite, pentlandite, sphalerite, tellurobismuthite, nickelite, arsenopyrite, gersdorffite, cobaltite, native gold, and others. Gold is associated with quartz (up to 114 g/t), to a lesser extent – with pyrrhotite and pyrite (up to 41 g/t). Visible gold is dominated by grains 0.01-0.02 mm in size, gold up to 0.1-0.5 mm in diameter is less common, and even less up to 1-2 mm. Gold fineness is 869-983, increased content (%) of Ag (7.72-12.78), Cu (0.05-0.24), Bi (0.4-1.0), Fe (up to 2) is noted.

Several stages of mineralization are distinguished: 1) early oxide (magnetite-1, ilmenite), 2) early and middle sulphide with associated early gold ore (pyrrhotite-2, chalcopyrite-2, sphalerite, galena, pyrite-2, molybdenite, bismuthite, native bismuth, gold-1); 3) middle oxide (magnetite-2); 4) late gold-ore (native gold-2, tellurobismuthite); 5) late sulphide (pyrite-3, marcasite); 6) late hydroxide (goethite, hydrogoethite).

The Maiske deposit (Bobrov et al. 1999; Bobrov et al. 2000b; Bochay et al. 1998; Koval et al. 1998) in Odesa region, site area 253.05 ha, is located in the Savranske ore field, at the intersection of the Odeskiy submeridional, Khmilnytskiy and Talnivskiy diagonal faults, and is hosted by biotite gneisses, plagiogneisses, amphibolites, migmatites of the Pobuzkiy Complex, at a flexure-like feature of the Savranska syncline limb, located in the east-west-trending fault zone (Fig. 4.29).

In total, 177 exploration wells of total length 64,510 m, and 40 hydrogeological wells (of total length 7,726 m) were drilled at the deposit, and a mine shaft was built to a depth of 204 m.

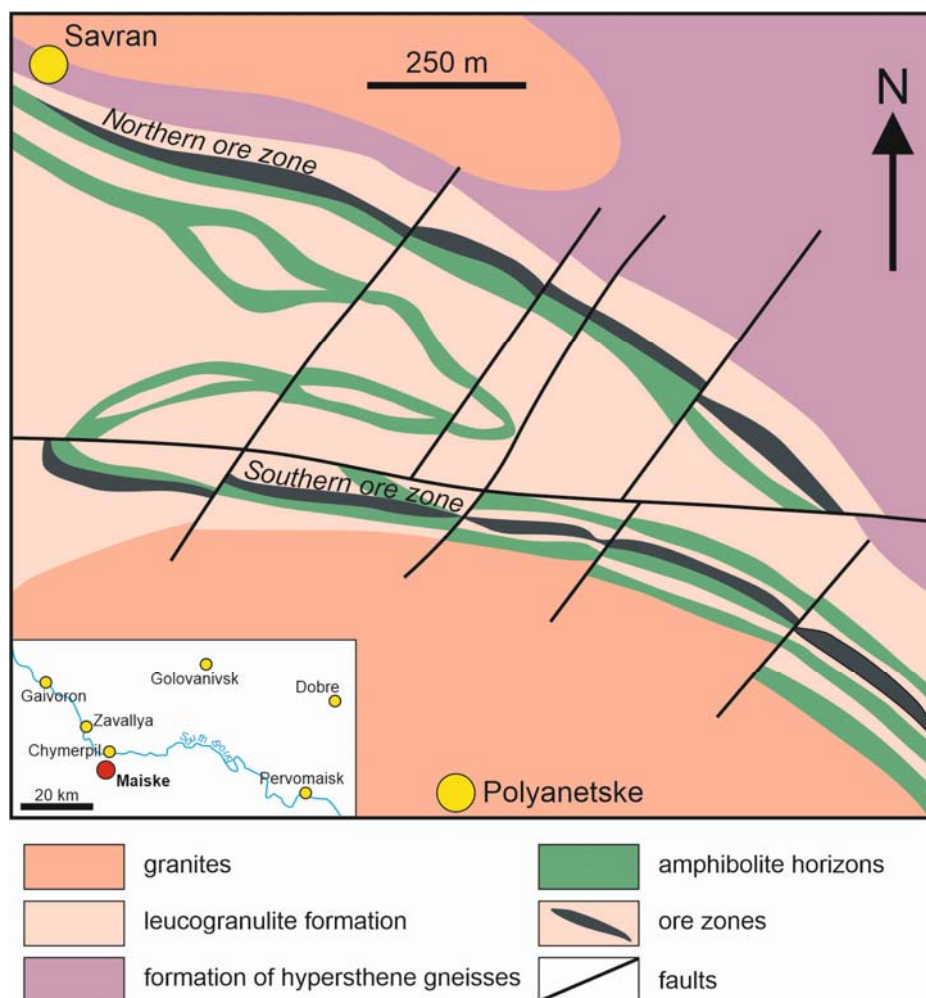


Fig. 4.29. Geological map of the Maiske deposit (modified after Mykhailov et al. 2007)

The Northern and Southern ore zones of north-western extension ($290-300^\circ$), with subvertical dip, 100-250 m thick, can be traced for up to 1.8 km and up to 350 m by dip. They are associated with biotite-quartz-oligoclase metasomatites after amphibolites and pyroxene-cummingtonite rocks.

With 0.5 g/t cutoff grade, the ore bodies of 1-18 m thickness with an Au content from 1 to 70 g/t are distinguished in these zones. They are represented by steeply-dipping ore pillars of vein-disseminated mineralization, 0.5-5.5 m thick, where gold is associated with pyrite and marcasite and are confined to the fractures of the northwestern extension.

The ores of the deposit are of gold-quartz low-sulphide type, mineralization is represented by oxide, sulphide and precious metal forms. The oxide form is represented by magnetite, chrome-magnetite, ilmenite, scheelite, rutile, anatase, sulphide – pyrrhotite, pyrite (three phases), pentlandite, marcasite, chalcopyrite (two phases), sphalerite, galena, as well as arsenopyrite, loellingite, cobaltite. Precious metal mineralization is represented by two types: the first is dominated by high-grade native gold and gold tellurides with a subordinate amount of bismuth tellurides and native bismuth; in the second the bismuth-silver-telluride association is developed with the main part of native bismuth and subordinate – native silver, electrum, hessite and galena.

The main ore minerals are: pyrite, pyrrhotite, chalcopyrite, and nickel sulphides, galena, sphalerite, molybdenite, scheelite, native gold, tellurium, silver and electrum. Native gold is relatively large (0.001-2.0 mm, sometimes up to 4 mm), and sulphide content is within the lower percent. Gold is represented by lumpy, lamellar, dendritic, hooked, film varieties. The gold content varies from 1 to 70 g/t, in some samples – up to 1570 g/t, an average grade is 7.1 g/t. Gold fineness is high (900-992), Au/Ag ratio is 7: 1.

The following ore mineral assemblages are distinguished:

- 1) magnetite, gahnite;
- 2) hexagonal pyrrhotite, ilmenite (loellingite, graphite);
- 3) pyrrhotite-1, chalcopyrite-1, pentlandite, molybdenite (arsenopyrite, nickel, gersdorffite, glaucodot, cubanite, scheelite);
- 4) pyrrhotite desulphidization products, pyrite-II, marcasite, sphalerite (rutile, galena, smithite, bravoite, mylerite, violarite);
- 5) productive assemblages:
 - a. monoclinic pyrrhotite, pyrite-III, siderite, hematite, gold;
 - b. chalcopyrite, gold, bismuth, bismuthite;
 - c. tellurides, silver, copper;
- 6) pyrite-IV, phlogopite.

The gold resources are estimated by category P_1 to be 21.98 tons, P_2 18.75 tons, the weighted average gold content by blocks – 3.4 g/t (Investment Atlas of Subsurface User 2021). The location of the Maiske deposit is in the same ore field with Kvitka occurrence (Savranske ore field) and allows them to be considered as a single investment project.

The Klyntsivske deposit (Bochai et al. 1998; Zagnitko et al. 1999; Gold deposits 1998) is located in the submeridional Kirovogradskiy deep-seated fault zone, in the eastern exocontact of the Novoukrainskiy Granitoid Massif, hosted by Archean gneisses and amphibolites (3195 ± 200 million years), which contain sub-conformable bodies of pegmatoid granites and zones of potassium feldsparization (Fig. 4.30).

Ore bodies (0.1-3.7 m thick) of vein-disseminated low-sulphide and gold-quartz mineralization are located in two strip-like submeridional mineralized zones 2.3 and 5.7 km long, 70-100 m wide, and are traced to a depth of 530 m. They are rimmed by zones of local metasomatites (sulphidized berisites, propylites, quartz rocks). Local ore bodies with a thickness of 0.1 m to a few meters with a gold content of more than 1 g/t are found in the zones which are characterized by cataclase and development of sulphides associated with native gold: pyrite, pyrrhotite, arsenopyrite, loellingite and chalcopyrite (up to 5%). Two phases of gold are determined – fine-dispersed in arsenopyrite and free, paragenetically associated with native bismuth. High gold content (up to 200 g/t) is associated with the gold-bismuth association. The particle size of native gold varies from 0.01 to 0.8 mm, occasionally up to 4-6 mm, with a fineness of 820-970.

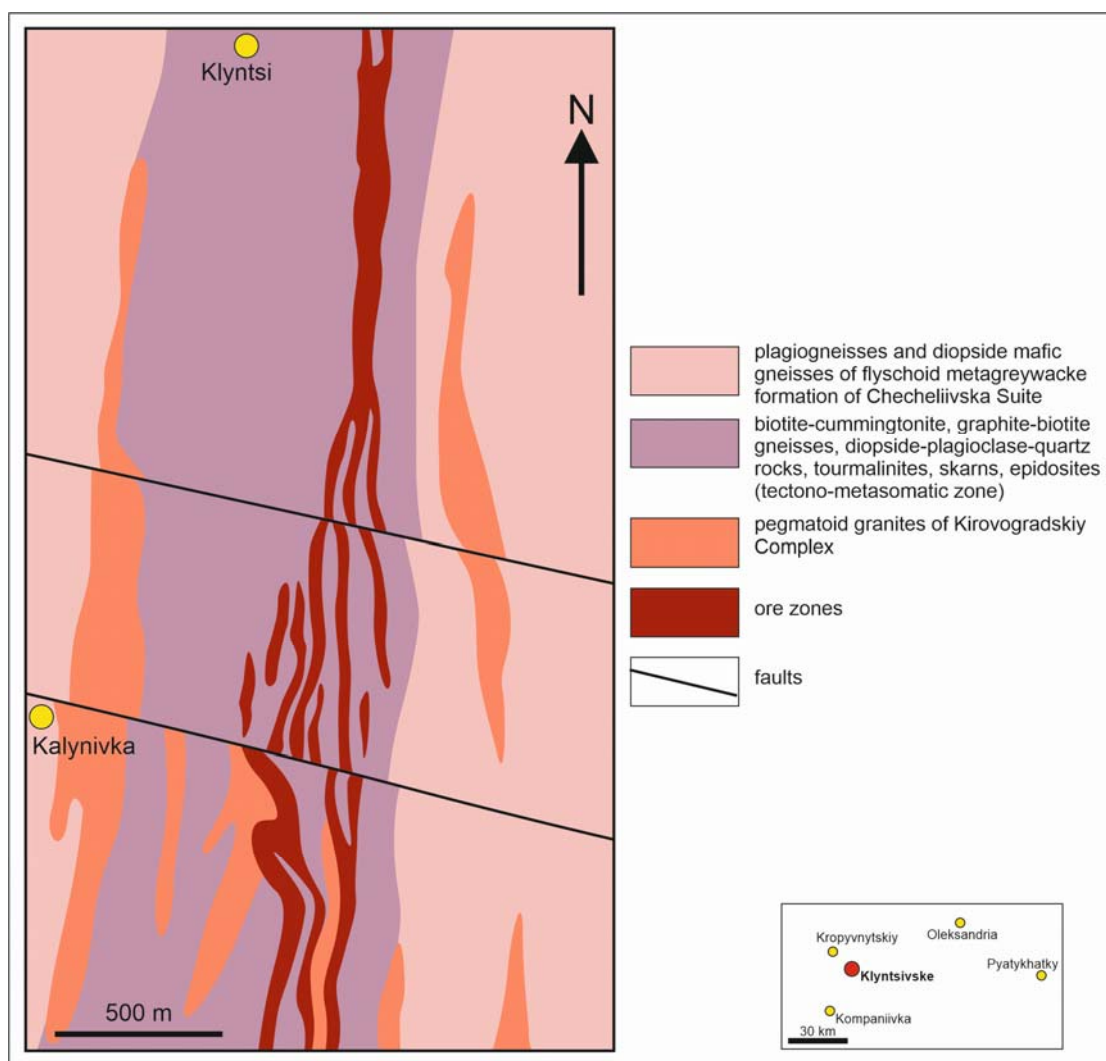


Fig. 4.30. Geological map of the Klyntsi deposit (modified after Mykhailov et al. 2007)

Ore minerals include loellingite, arsenopyrite, pyrite, pyrrhotite, chalcopyrite, gersdorffite, sphalerite, galena, yttrialite, magnetite, ilmenite, native bismuth, arsenic and gold with high (970-990) and medium (880-930) fineness having an average content of 5.27 g/t. Gold-quartz type of mineralization prevails, while gold-sulphide-quartz is less developed. Types of ores include: pyrite-arsenopyrite (up to 30% of sulphides) and low-sulphide (2-3%).

The Yuriivske deposit (Belous et al. 2001; Bochay et al. 1998; Fomin et al. 2001) is located in the Kirovograd region, the area of 163.2 hectares, in the eastern exocontact of Novoukrainskiy Massif with steeply-dipping ($50-70^{\circ}$) towards the eastern Paleoproterozoic graphite gneisses of Checheliivska Suite of Ingulo-Inguletska Series (2.5-2.39 billion years), in the zone of submeridional Kirovogradskiy Fault and its intersection with northeastern Mariivska zone of silicification and crushing (Fig. 4.31). Aplite-pegmatoid veins are widely developed.

In total, 88,841.5 m of exploration wells were drilled at the deposit. Based on these results, 21 mineralization zones are distinguished with a gold content of more than 0.1 g/t. Mineralization zones are represented by columnar, lenticular, vein and stockwork like bodies of metasomatic ores, vein-dissemination zones, veins and strip-

like bodies located in extensively silicified rocks in en-echelon fractures in zones of sublongitudinal faults, often conformable with host graphite-biotite gneisses. Gold mineralization is confined to linear silicification zones 5-17 m thick, 400-1600 m long traced over 980 m by dip, and in cross-section they form a fan of 17 ore zones that diverge upwards. The ore bodies which are 50-400 m long and 0.2-4 m thick (average 1.2 m) are identified in the zones.

Ores belong to the gold-quartz low-sulphide type, the main ore minerals include gold, pyrite, pyrrhotite, arsenopyrite, chalcopyrite, sphalerite, galena, complex sulfosalts, loellingite, native bismuth, maldonite. The amount of sulphides in mineralized zones reaches 5-7%. The gold content varies from 0.1 g/t to 77.1 g/t, in some samples it is up to 153.8 g/t. It is most often associated with quartz, sometimes with biotite, occasionally with pyrite and pyrrhotite, in some cases – with arsenopyrite and loellingite. Gold is closely associated with sphalerite, chalcocite, arsenopyrite, galena. According to the ratio of lead isotopes, the age of galena is 2.0 ± 0.15 billion years. Gold ores belong to the gold-quartz low-sulphide type.

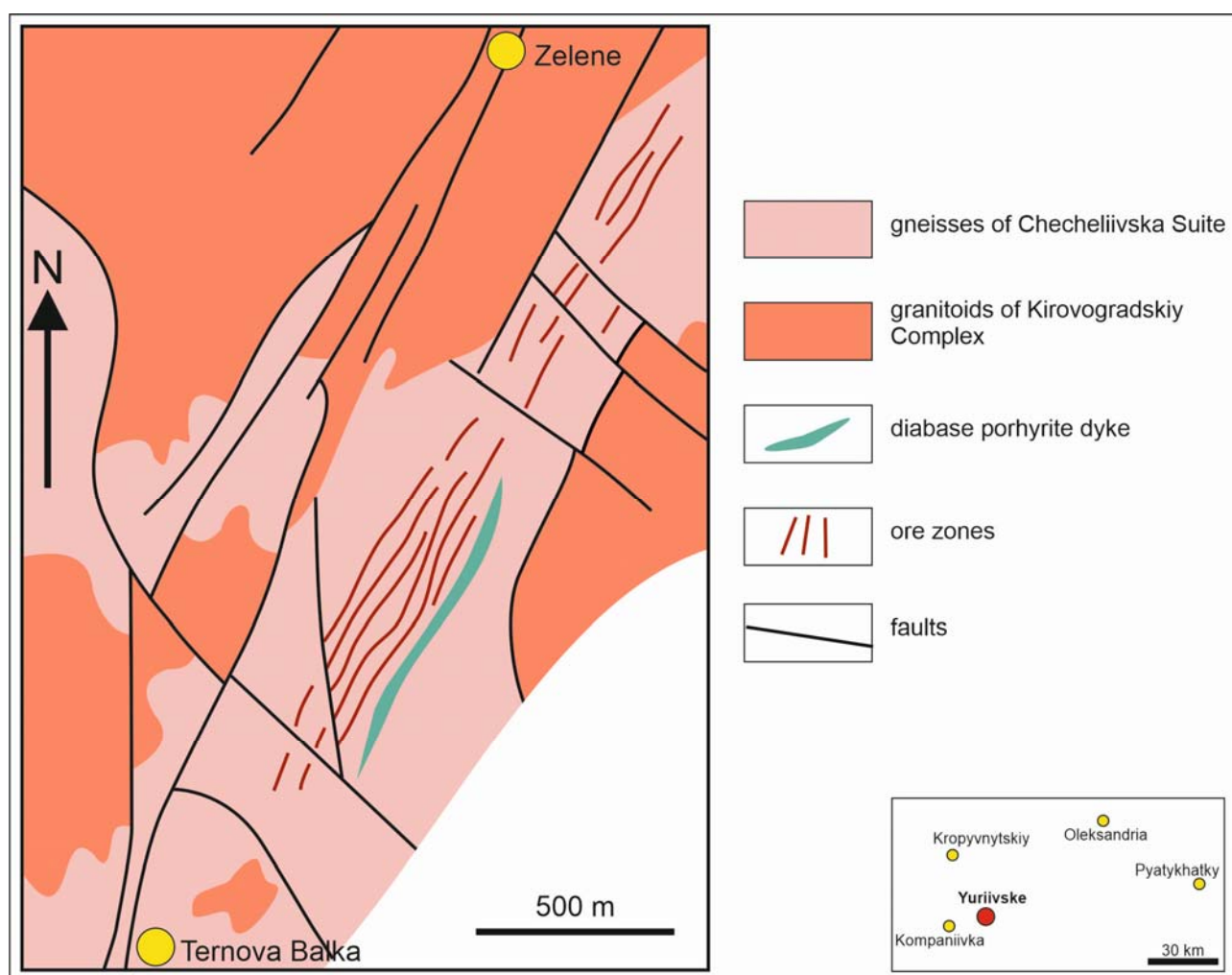


Fig. 4.31. Geological map of the Yuriivske deposit (modified after Mykhailov et al. 2007)

The ore assemblage is represented by native gold, pyrrhotite (up to 3-5%), chalcopyrite (up to 0.5%), pyrite (3-10% of the amount of ore minerals), arsenopyrite (up to 0.5%), loellingite, sphalerite (up to 0.5%), galena (0.2-0.5%), marcasite (up to

0.5%), native bismuth, bismuthite, complex sulphosalts (tennantite, tetrahedrite), bornite, chalcocite. Native gold is characterized by uneven distribution, it occurs in the form of separate grains, mainly associated with quartz (size 0.001-0.07 mm, sometimes up to 0.1-1.0 mm), and in the form of intergrowths with complex sulphosalts, sphalerite, native bismuth, maldonite, galena. The shape of gold is isometric, irregular, lamellar, drop-like or hooked. Gold fineness is 930-990, impurities are represented by Ag, Bi, Fe, Hg, Te, As. Ores are easily concentrated by a gravity-flotation scheme; As content does not exceed 0.021%.

Gold resources are estimated by category P_1 at 1,693 kg, P_2 at 10,608 kg, the average gold content in blocks is 9.2 g / t (Investment Atlas of Subsurface User 2021).

The Kvitkivska site is in the Odesa region with an area of 670.73 hectares. The Maiske deposit is located in the Savranske ore field in the submeridional mineralization zone traced for 6 km, within which two ore-bearing zones are defined: the Central and Eastern. It was studied with 25 prospecting and evaluation wells (8,859 m), and 234 exploration and mapping wells drilled at the site.

The Central Zone is confined to submeridional fault, traced for 5 km, 75-100 m wide in the north and 300-500 m in the central part of the zone. It steeply ($65-85^\circ$) plunges to the east. The zone is composed of intercalating migmatized biotite and amphibole-biotite gneisses and migmatites with small bodies of leucocratic and pegmatoid granites and biotite-quartz-oligoclase metasomatites 2-6 m thick.

The Eastern Zone is confined to the submeridional Eastern fault, traced for 5 km by strike with width from 450-500 m to 100-150 on the northern flank. It plunges steeply ($60-85^\circ$) to the east and has a structure similar to the Central Zone.

Gold mineralization is confined to the bodies of biotite-quartz-oligoclase metasomatites formed after amphibole-containing gneisses and schists. Quartz veins are often found in the central parts of the bodies. The mineral assemblage chalcopyrite-pyrite-pyrrhotite (0.5-12%) is formed in the wall-rocks of the latter, The gold content in ore bodies ranges from the 1 g/t to 14.7 g/t. Sulphides include pyrite, pyrrhotite, chalcopyrite, pentlandite, marcasite, sphalerite. A number of mineral assemblages are distinguished : spinel-magnetite, ilmenite-hexapyrrhotite, chalcopyrite-I-pyrite-I, pyrite-II-chalcopyrite-II-clinopyrrhotite, marcasite-pyrite-III with hematite; sphalerite (0.9-30%) and gahnite (up to 5%) is widespread, and molybdenite (up to 30% of ore minerals) is sometimes noted.

Native gold is associated with an assemblage pyrite-II-chalcopyrite-II-clinopyrrhotite, which also contains silver, bismuth and tellurides. The grain size of gold is up to 0.5 mm, it is most often found in areas of silicification with high sulphide content and is developed in association with pyrrhotite, pyrite, chalcopyrite by cracks in quartz. The form of gold is isometric, often flattened, sometimes amoebic and lumpy.

Prognostic gold resources by category P_2 are estimated at 40,992 kg (Investment Atlas of Subsurface User 2021). The location of Kvitka occurrence in the same ore field as the Maiske deposit (Savranske ore field) allows them to be considered within a single investment project.

There are two types of gold deposits in **the Carpathian province**: those related to the Neogene volcanism of Beregivski Hills (Muzhyivske, Beregivske) and to Proterozoic – Early Paleozoic structures of Rakhivskiy Massif (Saulyak).

The Muzhyivske deposit is characterized by a two-fold structure. The lower level is composed of a series of steeply-dipping quartz-sulphide veins 1-5 m thick with polymetallic and concomitant silver and gold mineralization. The upper level (at a depth of 60-150 m) is represented by an amoeba-like stockwork (50×50 m) of finely disseminated gold mineralization in metasomatites of secondary quartzite and argillite formations after tuffs and breccias of Neogene rhyolites (Fig. 4.32).

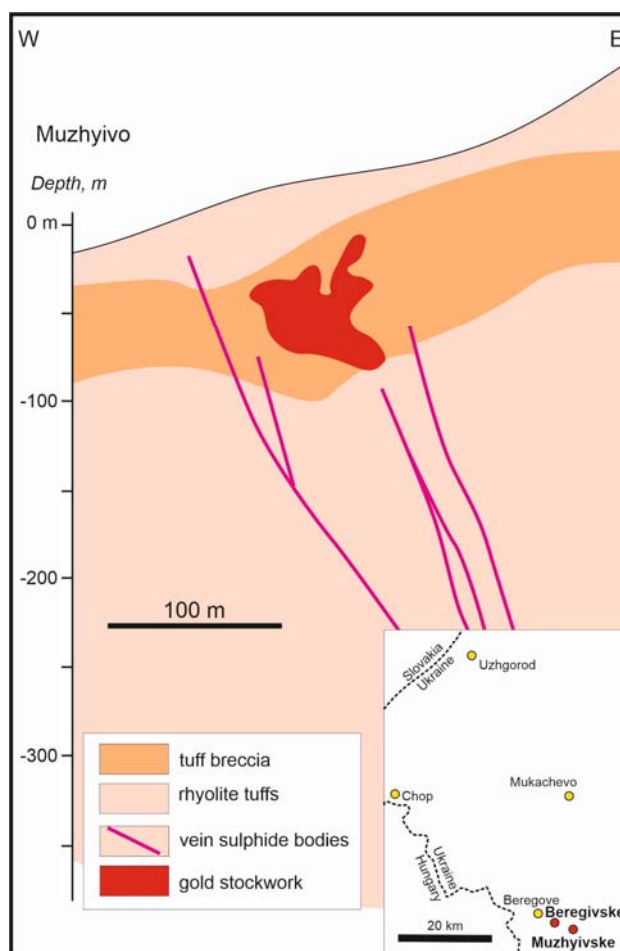


Fig. 4.32. Crossection of the Muzhyivske deposit (modified after Mykhailov, Fedchuk 2008)

Ore minerals include sphalerite, galena, pyrite, pyrrhotite, gold, electrum; proustite, polybasite, argentite and native silver are also noted; gangue minerals include quartz, adularia, rarely chalcedony, kaolinite and hydromica. Gold is abundant, from fine to large, fineness is 500-900 (predominantly 720-760), grade is 4.5-15 g/t, Au/Ag ratio is 1: 3.

The deposit is being developed by PJSC “Carpathian Ore Company”, but the patterns of gold distribution with the gold grade decreasing downward, changing mineral assemblages and other characteristics may in the near future cause problems with increasing reserves of this metal and its extraction technology.

The Berehivske deposit is located in ignimbrites and rhyolite tuffs of volcanic neck, where sulphide, quartz-sulphide, quartz-barite, quartz-carbonate and quartz veins 600-1300 m long and vein-disseminated zones are developed. The average thickness of ore bodies is 3.6 m. The reserves are amounted to 18 tons of gold, the average content of gold is 5 g/t, silver – 15 g/t, with lead and zinc at – 5%.

The Saulyak deposit is located in the zone of nappe-thrust dislocations at the margin of the nappe structures of Riphean Bilopototska and Dilovetska Suites, composed of various schists, and in the Dilovetska Suite the latter include limestone and marble lenticular and sheeted bodies that probably comprise typical olistostrome confined to the zone of con-sedimentation thrust (Mykhailov et al. 2003). Gold mineralization is encountered in both “over-” and “under-carbonate” locations, and also is found in quartz-carbonate bodies that occur conformably in the sequence of coaliferous quartz-sericite-chlorite schists (Fig. 4.33).

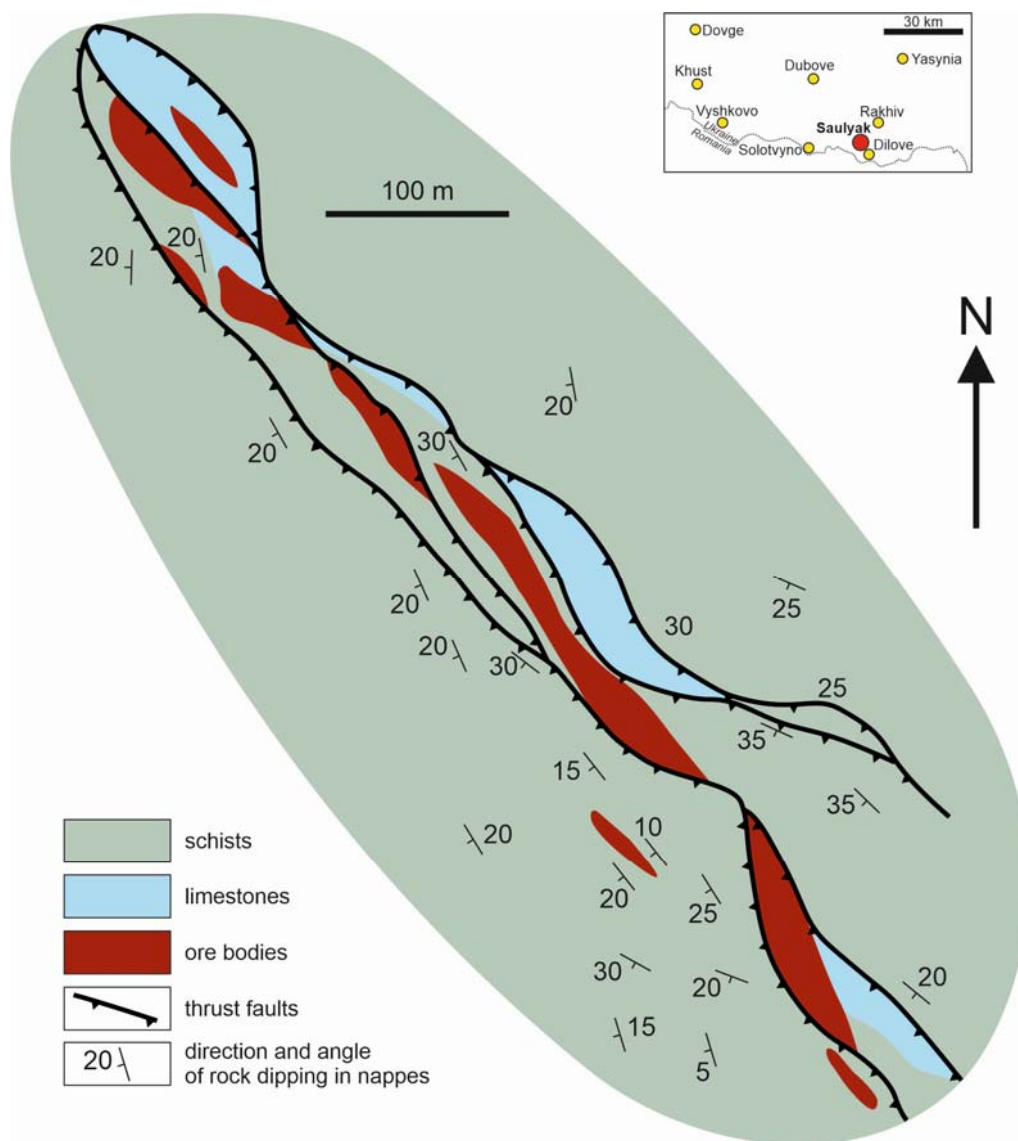


Fig. 4.33. Geological map of the Saulyak deposit (modified after Mykhailov, Fedchuk 2008)

The thickness of mineralization zone reaches 18-30 m, with the thickness of ore bodies of 0.5-8.0 m and more in places. They have no clear boundaries, and are outlined in the sampling data, having an irregular shape, sharply pinched out by strike, often confined to the boundaries of quartz-carbonate rocks and schists. The gold content changes sharply, the average content is 2-8 g/t. In the ore, the quartz gold content varies from 20-30 to 200-300 g/t and more; in thin-banded schists of inhomogeneous composition with ore quartz micro-veins it is from 5.0 to 15-20 g/t; in homogeneous sericite and chlorite schists from 0.1 to 2.0-3.0 g/t, and usually up to 0.5 g/t. The content of sulphides (pyrrhotite, marcasite, pyrite, galena, sphalerite, arsenopyrite) does not exceed 0.2-0.4%.

Gold is present in the native form, mostly free, of particle size 0.01-0.1 mm, sometimes up to 2-4 mm. Bright-yellow high-fineness gold (830-930) forms hooked, jagged or curved plates at the grain boundaries of gangue minerals or in interstitials, caverns and microcracks in quartz; drop-shaped micro inclusions in pyrrhotite or sphalerite; flat very thin cleavage films in galena; irregular particles in the intergrowths of various sulphides. Relatively low-grade tellurium gold is found in chalcopyrite aggregates with complex sulphosalts. Ag, Fe, As, Hg and Cu are detected in the native gold. Silver is not typical for these ores, the average ratio Au/Ag is 3:1. The ores are processed by gravity-flotation and gravity-cyanide schemes with the extraction of 90-92% of gold and 80-82% of silver into refined concentrate.

According to various estimates, reserves of the deposit range from 3-4 to 10-11 tons of gold. Geological evidence suggests that gold mineralization is not limited to the Saulyak ore field, but may spread over a larger area, including the basins of Bredetzel, Biliy Potik and Dovgorun streams. The Rakhivskiy ore field has significant prospects for discovery of gold mineralization of a nationally significant geological-industrial type large-scale asset, which in a number of factors resembles Carlin-type mineralization (Mykhailov et al. 2003). This assumption is confirmed by the location of known occurrences in the zone of nappe-thrust dislocations in carbonate-bearing coaliferous piles, scattered stratiform patterns of mineralization, development of silicification and pyritization zones, texture and mineralogical features of ores and a relatively high Au/Ag ratio (3:1). This indicates good prospects of the area for gold mineralization.

The special permit for development of deposit is granted to "Saulyak" LLC.

In the **Donetsk province** deposits of vein-disseminated ores are known in folded coaliferous terrigenous piles, which belong to two mineral types: gold-polymetallic (Bobrykivske and Gostriy Bugor) and gold-pyrite (Mikhailivskiy ore occurrence).

The Bobrykivske deposit is confined to the uplifted part of the crest and southwestern limb of the Bobrykivska Anticline, composed of Carboniferous mudstones with scarce layers of quartzite-like sandstones of flysch formation, controlled by submeridional faults of the Elanchyk-Rovenkivska Zone and with Bobrykivskiy reverse strike-slip fault. Ore bodies are represented by veins of submeridional, north-western and north-eastern extensions; the conformable veinlets are of subordinate importance. Mineralization is spread over an area of 17,500 m² and traced to a depth

of more than 3 km. Hydrothermal-metasomatic rocks are represented by listvenites, beresites and argillites. The gold content in the ore bodies is extremely uneven. Disseminated ores contain little gold. There are higher concentration found in quartz-carbonate-galena-sphalerite veins and veinlets, and the highest – for quartz-carbonate-galena-sulfosalt veinlets, is mainly in the stockwork of the upper ore level, as well as near the Bobrykivskiy Fault. The content of gold in ores is 2-9 g/t (in some samples 40-106 g/t), silver up to 320 g/t. The Au/Ag ratio varies from 1:7 to 1:10.

In beresites, gold is concentrated in pyrite and arsenopyrite (0.8-60 g/t) in the form of fine-scattered disseminations, and is observed in quartz, siderite, and arsenopyrite. Gold fineness ranges from 551 to 962. The main concomitant elements of gold include As in beresites; Pb, Zn, Ag, Cu – in polymetallic ores; Pb, Sb, Hg, Ag, Ni – in sulphide-sulphosalt ores.

The estimated age of galena (from lead isotopes) is 178 million years. Gold reserves by category C₁ in the upper ore level to a depth of 140 m amount to 8 tons (average Au content 6.9 g/t), silver – 21 tons (37 g/t). The estimated resources of gold in the lower ore level by category P₁ are 430 tons, the average Au content is 0.63 g/t. In deluvial-eluvial deposits near the ore body № 1 the gold content is up to 23.5 g/m³, which justified mining by open-cast methods.

A special permit for the industrial development of deposit was granted to “Donetsk Ridge” LLC. Mining at the deposit was carried out in 2010-2014.

The Mykhailivske ore occurrence is confined to beresitized or argillitized pyrite-bearing sandstones, siltstones and mudstones of the Olkhovatska Anticline. Ore bodies (thickness 0.1-8 m, average 2.3 m) have the form of layers and lenses traced for hundreds of metres in length and up to 150 m in width. Gold content is 1.5-2.0 g/t, gold is associated with fine-grained massive pyrite, where its average content is 27 g/t and As content is 2.6%. In addition, Co (up to 0.2%) and Te (up to 0.15) are detected. The probability of occurrence is the result of the significant length of the mineralization zone (4 km), multiple-level structure, stable, albeit low (1.5 g/t), Au content. Ores are gold-pyrite with an admixture of As (2.0-2.5% in pyrite concentrate).

In addition, other insignificant placers of gold are known in Ukraine, which have no industrial value. According to international experts, Ukraine's gold resources are estimated at 3,200 tons (Law 2011a).

4.4. Types of Raw Materials with Unclear Prospects

Various types of raw materials with undetermined prospectivity include the following metallic minerals that are of strategic importance to the economy of Ukraine: vanadium, lead and zinc, tungsten, molybdenum, PGM, strontium, magnesium, arsenic, rubidium and cesium.

4.4.1. Vanadium

It is used mainly in ferrous and non-ferrous metallurgy, for the production of high-strength alloys for aviation, space, nuclear reactors, etc., as well as in chemical, printing and other industries, and as a catalyst for oil cracking as well as other uses..

Known world reserves of vanadium are estimated at about 18 Mt, which are concentrated mainly in China, Russia and South Africa, which together hold almost 82% of discovered reserves. These countries are also the leading ones in terms of vanadium production; together they produce more than 90% of vanadium, and China accounts for more than 60% of world production (Table 4.47). Vanadium production has been growing slowly in recent years, from 83,000 tons in 2015 to 90,000 tons in 2019. China and Brazil have increased production in recent years, while South Africa, India and Kazakhstan have decreased outputs.

Table 4.47. World vanadium mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Mining, t					Reserves, kt
	2015	2016	2017	2018	2019	
China	42,000	45,000	48,500	53,200	56,000	9,500
Russia	16,196	16,886	18,636	17,052	18,380	5,000
South Africa	17,455	15,877	7,958	7,691	7,964	3,500
Brazil	4,988	6,544	6,798	6,562	7,045	120
USA	-	-	-	-	460	45
India	1,124	1,125	-	442	450	n.a.
Kazakhstan	1,000	-	-	-	-	n.a.
Total	82,763	85,432	81,892	84,947	90,299	18,165

In Ukraine, vanadium as a concomitant component was found in apatite-ilmenite deposits (Stremygorodske, Torchynske, Fedorivske), where its average content is 0.22-0.25%; ilmenite placers of the Irshanska Group (0.23-0.26%); hard-rock uranium-vanadium-scandium ores (Zhovtorichenske deposit, where content of V_2O_3 is 0.36%). The SIMR records vanadium reserves for 13 complex deposits to be 6.5 Mt of ore and 332 kt V_2O_5 (Mineral Resources of Ukraine 2021). Vanadium is mined in Ukraine in small quantities (190 tons in 2020), the prospects for increasing industrial production are associated with the development of hard-rock complex apatite-ilmenite deposits.

4.4.2. Lead and Zinc

Lead bismuthate, lead sulphide PbS and lead iodide are used as cathode material in lithium batteries, lead chloride $PbCl_2$ – as cathode material in backup power sources; lead telluride $PbTe$ – as a thermoelectric material (thermo-emf $350 \mu V/^\circ C$), it being the most widely used material in the manufacture of thermoelectric generators and thermoelectric refrigerators; lead dioxide PbO_2 in lead batteries, as well as the basis for the production of chemical power sources (lead-chlorine element, lead-fluorine

element, etc.); and lead sulphate PbSO_4 in batteries. In addition, lead is considered as a heat-transfer agent in the design of next-generation nuclear reactors on fast neutrons. Lead alloys are widely used for example solder containing 67% Pb and 33% Sn is used in electrical engineering. Lead alloys with antimony are usually used for cable sheaths and plates of electric batteries. Lead-acid batteries are used as starter batteries in vehicles, emergency and backup power sources.

The main application of zinc is galvanizing the surface of steel and cast iron products, but it is also used to make alloys (brass, bronze, cupronickel, etc.), batteries, sheets, pipes, car tires, whitewash, typefaces, etc.

Known world reserves of lead amount to 90 Mt. The largest discovered reserves are in Australia, China, Russia, Peru, Mexico and the USA, which are the most important producers of this metal. China accounts for 42% of world production (Table 4.48). Lead production is growing in Russia, India, and Iran, while amounts in China and the United States are declining.

Table 4.48. World lead mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
China	2,339.0	2,227.5	2,080.0	2,033.0	2,097.0	18.0
Australia	653.5	441.3	395.2	446.6	509.2	36.0
Mexico	263.8	246.8	243.0	230.9	372.1	5.6
Peru	315.5	314.4	306.8	289.1	308.1	6.3
USA	370.0	346.0	310.0	280.0	274.0	5.0
Russia	156.0	204.3	204.7	206.1	207.9	6.4
India	143.7	150.9	172.3	207.1	203.0	2.5
Bolivia	75.3	89.9	113.3	112.1	88.0	1.6
Iran	32.5	36.9	44.9	49.6	72.5	n.a.
Turkey	75.9	64.3	75.0	76.0	71.5	0.86
Other countries	559.6	599.3	687.5	698.9	764.7	7.74
Total	4,984.8	4,721.6	4,632.7	4,629.4	4,968.0	90.0

Known world reserves of zinc amount to 250 Mt, the largest discovered reserves being in Australia, China, Mexico, Russia, Peru, Kazakhstan and the USA. World production in recent years has stabilized at 12-13 Mt per year, the leading producers are China, Peru, Australia and other countries (Table 4.49).

Table 4.49. World zinc mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
China	4,748.0	4,635.0	4,300.0	4,160.0	4,353.0	44.0
Peru	1,421.2	1,337.1	1,473.1	1,474.7	1,404.4	19.0
Australia	1,610.0	884.8	852.2	1,146.8	1,337.3	68.0
Mexico	786.8	666.9	671.4	662.4	859.2	22.0
USA	824.7	804.8	773.8	824.0	753.0	11.0
India	740.7	755.8	772.6	728.4	723.4	7.5

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
Bolivia	442.2	487.0	527.2	519.6	527.5	4.8
Canada	289.6	321.3	346.8	305.0	323.0	2.2
Russia	213.8	245.8	255.2	288.0	275.4	22.0
Sweden	247.0	258.3	251.2	237.7	247.7	3.6
Kazakhstan	342.5	324.8	315.9	304.4	244.7	12.0
Other countries	1,679.5	1,653.0	1,774.3	2,021.1	2,126.2	33.9
Total	13,346.0	12,374.6	12,313.7	12,672.1	13,174.8	250.0

A number of lead-zinc mineralization targets are known in Ukraine, but their small size does not meet the needs of Ukrainian industry, which are satisfied through supplies from Kazakhstan, Russia, Uzbekistan, Bulgaria, the Czech Republic and Poland.

The following polymetallic deposits are known in Ukraine:

- 1) vein and vein-disseminated deposits in extrusives (Beregivske, Biganske, Muzhyivske deposits in Trans-Carpathians);
- 2) salt domes (Bilyaivske in Dniprovsko-Donetska Depression);
- 3) veins in folded terrigenous piles (Nagolno-Tarasivske and Nagolchanske in Donbas);
- 4) stratiform in terrigenous and carbonate rocks (Markivske at the margin of the Voronezkiy Massif and Truskavetske in Carpathians).

The SIMR records the reserves of Beregivske, Biganske, Muzhyivske and Perzhanske deposits to be 41.8 Mt of ore, 670,000 tons of lead and 1,555,000 tons of zinc (by categories A+B+C₁+C₂), while Biganske, Muzhyivske and Perzhanske deposits are in development (Mineral Resources of Ukraine 2021).

The Beregivske gold-polymetallic deposit is located in the Neogene tuffogenic sequence, and the ore-bearing horizon is mainly comprised of rhyolite tuffs, cut by two fracture systems of north-western and north-eastern directions (Fig. 4.34). Gold-polymetallic mineralization is represented by three morphological groups of ore bodies: 1) complex ore veins in the faults of the north-western and north-eastern directions; 2) vein-disseminated mineralization in the areas of extensive fracturing; 3) sheeted bodies in volcanic-sedimentary rocks. The veins are up to 3-5 m thick and 350-450 m long extending to a depth of 350 m. The main ore minerals include sphalerite, pyrite, galena, marcasite and chalcopryrite; the secondary minerals are hematite, tetrahedrite, gold, silver, electrum, wurtzite and melnikovite.

The average lead content is 2.09%, zinc – 5.08%. A high content of cadmium and low – antimony and arsenic are noted. The following mineral types of ores are distinguished: gold-pyrite-galena-sphalerite, gold-quartz-hematite, gold-adularia-quartz, gold-silver-barite-hydromica. Lead and zinc reserves and resources are shown in Table 4.50.

Table 4.50. Breakdown of lead and zinc reserves and resources at Beregivske and Muzhyivske deposits (modified after Gursky 2007)

Commodity	Beregivske		Muzhyivske	
	Reserves	Resources	Reserves	Resources
	C_1	P_1+P_2	C_1+C_2	P_2
Lead, tons	5,410	342,800	295,000	480,000
Zinc, tons	14,400	832,800	621,600	960,000

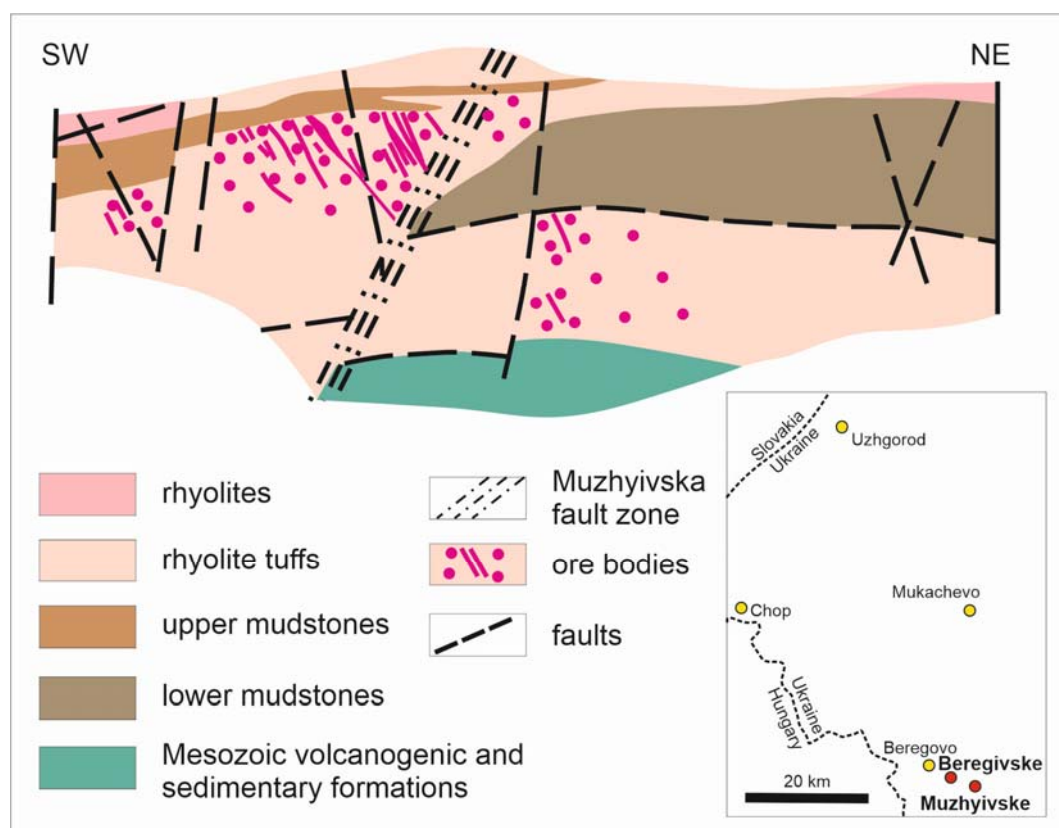


Fig. 4.34. Cross-section of the Beregivske deposit (modified after Mykhailov et al. 2007)

The Biganske deposit of complex alunite-barite-polymetallic ores has a similar structure. Alunite ores form the upper part of deposit, with reserves of 196 Mt. Barite ores with reserves of 4.2 Mt are formed below alunite ores. The lower level of deposit is composed of barite-polymetallic ores with associated mineralization of copper, cadmium, silver and gold. The main ore minerals include pyrite, marcasite, sphalerite, galena, chalcopryrite, complex sulphosalts, chalcocite, covellite, pyrargyrite, proustite, argentite. Lead reserves are of 120,200 tons (average Pb content is 1.22%), and Zn of 381,100 tons (3.83%) (Gursky 2007).

The Muzhyivske gold-polymetallic deposit has a zonal structure, the upper level is represented by stockwork zones with gold-ore bodies; the lower level by sulphide, quartz-sulphide, quartz-barite and quartz veins and veinlets with a thickness of 0.5 to 50 m, and length up to 600-1300 m, with vein-disseminated sulphide mineralization. The main ore minerals include sphalerite, galena, pyrite, chalcopryrite and sulphosalts.

The average content of lead is 1.62% and zinc of 2.01%. Lead and zinc reserves and resources are shown above in Table 4.50.

In general, the ore potential of the Beregovovo ore camp is as follows: lead resources – 822,800 tons, lead reserves – 420,600 tons; zinc resources – 1,792,800 tons, zinc reserves – 1,017,100 tons.

The Bilyaivske lead-zinc deposit is confined to the south-eastern part of the same-named salt dome structure in the north-western part of Donbas, in the Bakhmutska Depression, and is located in the rocks of two structural layers. The upper layer is composed of Lower Triassic sandstones, the lower one is located beneath salt tectonic breccia, represented by the fragments of Devonian – Lower Triassic sandstones, limestones, mudstones, siltstones, anhydrites, extrusive rocks of mafic composition, cemented with clay-carbonate material. Breccia is sometimes saturated with bitumen. Mineralization is vein-disseminated, disseminated, veinlet, sometimes massive. The thickness of ore bodies varies from 2.7 to 90.7 m. The depth of mineralization is 200-1000 m (Fig. 4.35).

Ore minerals include galena, sphalerite, pyrite, marcasite and millerite. Less common are chalcopyrite, pyrrhotite and pentlandite. There are gangue minerals of calcite, dolomite, manganese siderite, barite, anhydrite, kaolin, jarosite and bitumen. Massive pyrite-marcasite-galena-sphalerite ores are located in the upper part of the ore zone. The distribution of lead and zinc is extremely uneven. The average ratio of zinc to lead in deposits is 3:1. The average content of Pb in sandstones – 0.84%, Zn – 2.36%; in ore breccia: Zn – 3.04%, Pb – 1.1%. Accompanying components include Cd (95 g/t), Tl (7.4 g/t).

Reserves of deposits by category C₂ are as follows: lead – 265,000 tons, zinc – 618,000 tons; of the prognostic resources: zinc 556,000 tons and lead – 142,000 tons (Gursky 2007). Technological testing of ores with the production of saleable lead and zinc concentrates was carried out. Concomitant components include silver, gold and cadmium.

4.4.3. Tungsten

It is used for the production of special grades of steel and alloys, materials for the electronic, electrical, military industries, milling, cutting and mining tools, in construction, metalworking.

Known world tungsten reserves are 3.2 Mt, China has the largest reserves (54% of the world), world production in recent years has stabilized at 84-86 kt, China has the largest production (83.8% of world production), as well as Vietnam, Russia, North Korea, Rwanda, Bolivia and other countries (Table 4.51).

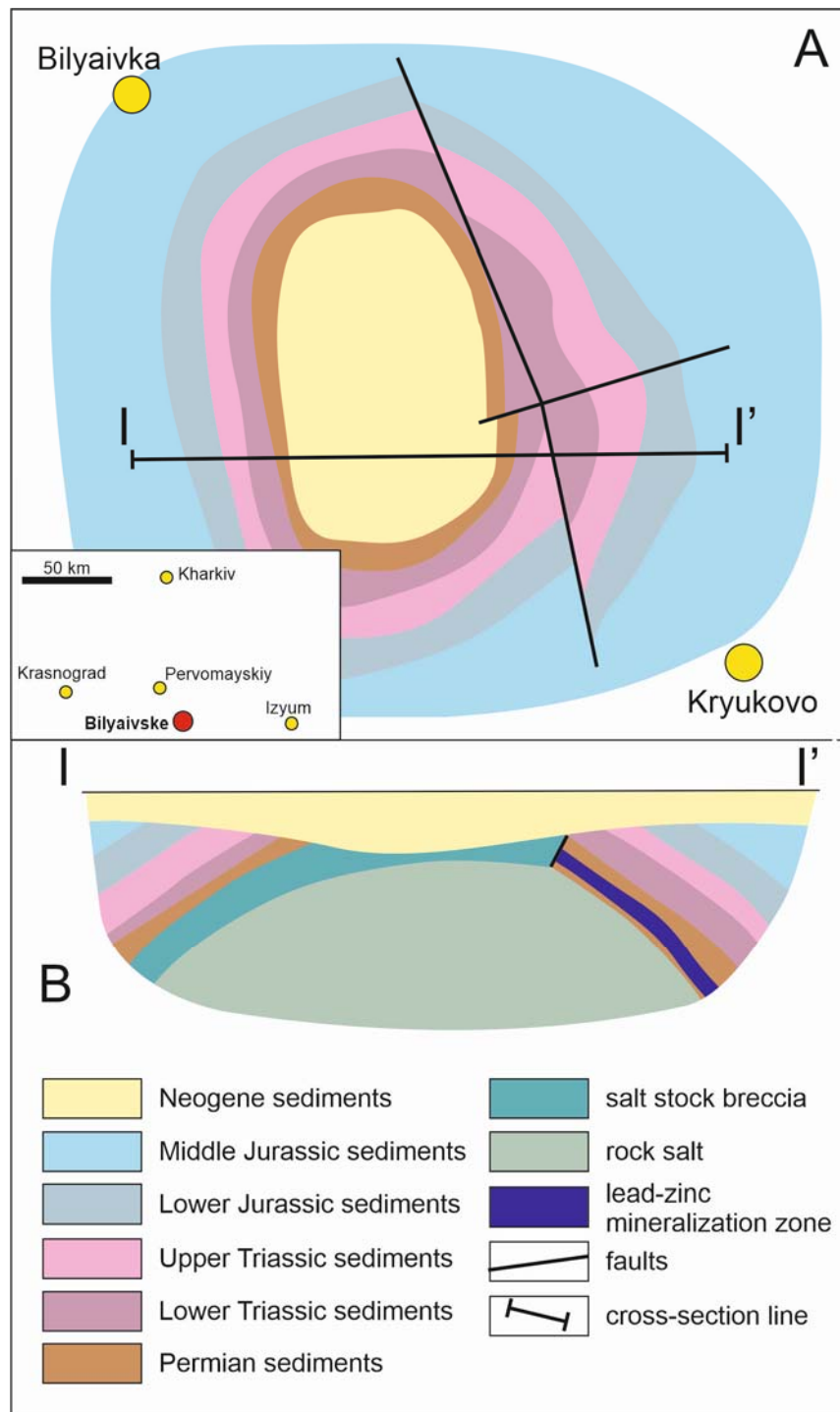


Fig. 4.35. Geological map (A) and cross-section (B) of the Bilyaivskiy salt dome (modified after Mykhailov et al. 2007)

Table 4.51. World tungsten mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Mining, t					Reserves, kt
	2015	2016	2017	2018	2019	
China	72,200	72,000	71,800	68,000	72,200	1,900.0
Vietnam	4,063	5,041	5,141	4,881	4,816	95.0
Russia	2,642	2,707	2,144	2,234	2,433	240.0
North Korea	72	50	310	1,410	1,130	29.0
Rwanda	1,060	1,020	905	1,155	1,120	n.a.
Bolivia	1,461	1,109	1,015	1,366	1,064	n.a.
Austria	861	954	975	936	892	10.0
Portugal	474	549	669	716	518	3.1
Brazil	432	323	411	300	431	n.a.
Mongolia	877	755	523	430	370	n.a.
Other countries	3,874	2,206	2,482	2,681	1,179	922.9
Total	88,016	86,714	86,375	84,109	86,153	3,200.0

No economic tungsten deposits have been identified in Ukraine, although a number of occurrences of tungsten mineralization are known, which are associated with Perzhanskiy, Korostenskiy, Korsun-Novomyrgorodskiy, Kamyanomogylskiy intrusive complexes, etc. (Mineral Resources of Ukraine 2020).

For example, the *Selyshchanskiy occurrence* of scheelite-bearing skarns is located in gneisses, amphibolites, marbles, and calciphyres on the western exocontact of the Korsun-Novomyrgorodskiy Pluton. It is represented by a skarn zone 50-125 m thick, up to 3 km long by strike and over 500 m by dip, where zones (1.2-1.5 m thick) with high tungsten content (from 0.015 to 0.055%) are encountered. The composition of skarns is magnesian (phlogopite-diopside) and calcareous (gedenbergite-diopside-andradite-grossular). The former variety forms bimetasomatic bodies along the contact of mafic schists and serpentine calciphyres, the latter forms infiltration bodies in amphibolites and replacement bodies in magnesium skarns. Tungsten mineralization is represented by single grains (from 1 mm to 2 cm) and granular aggregates of scheelite. In addition, native bismuth, galena, molybdenite and arsenopyrite are noted. Higher gold content (up to 1 g/t) was found in some samples.

Unfortunately, the types of geological structure of Ukraine do not allow us to expect significant prospects for tungsten mineralization.

4.4.4. Molybdenum

It is used in metallurgy for the manufacture of high-strength steel, super alloys, to a lesser extent, in the chemical industry.

Known world reserves of molybdenum are estimated at 18 Mt, the largest reserves are in China (46% of the world), as well as in Peru, USA, Chile, etc.; world production is 270,000 to 280,000 tons, most of which is extracted by China (38% of world production), as well as Chile, the United States, Peru, Mexico (Table 4.52).

Molybdenum production is growing steadily in Peru and Mexico, while that in China and Russia are declining.

Table 4.52. World molybdenum mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Mining, t					Reserves, kt
	2015	2016	2017	2018	2019	
China	135,150	112,590	117,090	98,420	104,440	8,300
Chile	52,579	55,647	62,746	60,705	54,759	1,400
USA	47,400	36,200	40,700	41,400	43,600	2,700
Peru	20,153	25,757	28,141	28,034	30,441	2,900
Mexico	11,327	11,896	13,985	20,265	21,694	130
Armenia	5,131	5,771	5,038	5,422	7,137	150
Iran	3,337	3,340	4,280	3,690	4,160	43
Canada	2,505	2,783	4,765	5,048	3,940	100
Mongolia	2,557	2,432	2,640	2,580	2,490	210
Russia	3,254	3,359	3,227	2,262	1,989	1,000
Other countries	3,833	3,481	2,766	2,274	1,855	1,067
Total	287,226	263,256	285,378	270,100	276,505	18,000

There are no molybdenum deposits in Ukraine, although several occurrences are known (Verbynskiy, Ustynivskiy, Richytskiy, Vysokiy in Perzhanskiy ore camp; Skhidno-Sergiivskiy and Gannivskiy in Middle Dniprean, etc.). Total potential molybdenum resources are estimated at 43,700 tons.

A special permit for exploration of molybdenum ores of Chervona site in Kryvyj Rig area of the Dnipropetrovsk region is granted to “Rud Investrium” LLC. At the same time, a proposal for licensing has been opened for the exploration of molybdenum ores at Verbynskiy occurrence in the Zhytomyr region and at Skhidno-Sergiivskiy occurrence in the Dnipropetrovsk region.

The Verbynskiy occurrence in the Zhytomyr region is located in the Ustynivske ore field in the northwestern margin of Korostenskiy Pluton, in the Central Korostenska fault zone in the eastern endocontact of the Ustynivskiy granitoid massif, in the area of its junction with the western limb of the Ovruchskiy Trough. Increased molybdenum content (from particles to 5-10%) was recorded in a small intrusion of granite-porphyrries, where the presence of molybdenite was detected.

Molybdenum mineralization is represented by a stockwork (0.3 km²) of quartz-muscovite greisens and sericitolites with a fine dissemination of molybdenite; topaz-zinnwaldite greisens with bunches of coarse-grained molybdenite; and quartz veins with molybdenum mineralization. The ore-bearing zone is traced to an extension of 800 m, and to a depth of 450 m. The mineralized zone is not delineated by dip on the western flank. Within its boundaries, 16 steeply-dipping vein- and lens-like ore bodies with length of 40 to 285 m (average 160 m) by dip, and thickness of 0.2 to 18.6 m (average 2.4 m), are identified.

Table 4.53. Content of impurities in molybdenite of the Verbynskiy occurrence

Element	Content. %
Fe, %	up to 0.34
Cu, %	up to 0.3
Zn, %	0.02-30
Pb, %	0.03-0.5
W, %	up to 0.03
Ag, g/t	1-250

molybdenite are listed in Table 4.53. Occasionally, small xenomorphic grains of bismuthite and native bismuth (up to 0.08 mm) are found in molybdenite. Accompanying components are bismuth, silver, tin, lead, zinc, copper, fluorite. K-Ar age of molybdenum mineralization by zinnwaldite is 1845 ± 45 million years

Occurrence belongs to the copper-molybdenum formation, and greisen type of linear-stockwork of a type suitable for industrial use. Reserves of molybdenum ore by category C_2 are 1,792,878 tons, molybdenum – 5,678 tons, prognostic resources by category P_1 – 90,204 tons of ore and 2,745 tons of molybdenum (Investment Atlas of Subsurface User 2021).

The Skhidno-Sergiivskiy occurrence in the Dnipropetrovsk region is located on the eastern flank of the Sergiivske gold deposit, at the intersection of the sublatitudinal Pivnichno-Sergiivskiy and submeridional Skhidno-Sergiivskiy faults. It is represented by a stockwork of thin quartz veins with molybdenum and molybdenum-tungsten mineralization in porphyry-like plagiogranites and plagiogranite-porphyrries of Surskiy Complex, where bunches and veins (up to 0.3 cm thick) of molybdenite are observed. Molybdenum mineralization is mainly found in quartz-epidote-carbonate zones away from contacts with plagiogranite massifs of the Surskiy Complex. Metavolcanics in such areas are epidotized and carbonatized. Molybdenite occurs in vein-like particles (1.5-2.0 mm).

Three separate ore-bearing linear-stockwork zones are distinguished: Northern, Central and Southern, located, respectively, in the northern hanging-wall of Sergiivske subvolcanic body, in its central part and in the southern footwall side. The northern and southern zones are composed of metabasalts, whilst the central zone is of metasomatically altered subvolcanic rocks of felsic composition. At their intersection, lenticular and striped areas of stockwork mineralization are observed, and tectonic breccias are developed, cemented with carbonate- and albite-quartz material with high-grade molybdenum mineralization, cataclase, shearing, blastomylonitization, alkaline-feldspar, listvenite-berezite and propilite metasomatites. The most productive are alkaline-feldspar metasomatites and listvenite-berezites.

Ore zones with a thickness of 20 to 120-200 m are dominated with veins and veinlets of quartz, carbonate-quartz, epidote-carbonate-quartz, albite-quartz composition with molybdenum mineralization, which is located at their margins in the form of lenticular-shaped thin-flake aggregates or solid rims 1-7 mm thick,

The main ore mineral is molybdenite, which forms separate monomineral bunches (1-10 mm), and molybdenite-fluorite-quartz, less often monomineral veinlets (0.1-3 cm). There are two phases of molybdenite: 1) medium- and coarse-grained grains (0.8-4 mm), nest-, rosette- and vein-like aggregates; 2) fine dissemination, accompanied by fluoritization. Impurities detected in

lenticular clusters and inclusions inside the veins, dusty particles in the vein quartz. The highest concentrations of ore mineral are confined to the bends of boudinaged veins. Molybdenite veinlets (1-2 mm thick) also occur.

Mineral compositions of ores are as follows: molybdenite, pyrite, chalcopyrite, pyrrhotite, magnetite, rarely bismuth and silver tellurides, sphalerite, scheelite, sometimes galena, fluorite. The ore structure is veinlet-disseminated and veinlet. The content of Mo in the ore zones is above 0.01% , the ore bodies are from 0.7 to 8.0 m thick with molybdenum cutoff grade of 0.05% or more. Prognostic Mo resources at metal cutoff grade 0.1% to a depth of 300 m reach 12,678.8 tons of metal with an average Mo content of 0.24%, and at Mo cutoff grade 0.05% – 17,071 tons of metal with an average Mo content of 0.15% (Gursky et al. 2006a).

The Dmytrivskiy occurrence. Molybdenum mineralization had also been found in the Azovian region in Oktyabrskiy Massif, in the Volnovaska Fault Zone, in Khibodariivskiy and Kalchytskiy quarries, and so on. Of these, the most interesting Dmytrivskiy occurrence was found near Dmytrivka village in the submeridional strike-slip zone, where an ore zone (3-5 m thick) was encountered in metasomatically altered Paleoproterozoic granites with bands and sections of green aegirine rocks with abundant molybdenite dissemination and veins (up to 1 cm thick). Molybdenite inclusions most often occur in the fibrous aegirine mass, often at the contacts of relic feldspar grains, and sometimes inside the latter. The content of Mo at an apparent thickness of 3m is 0.3%, Nb – 0.084% and Zr – 0.058% (Fig. 4.36).

The detailed data on molybdenum occurrences is insufficient to determine the investment attractiveness of these objects.

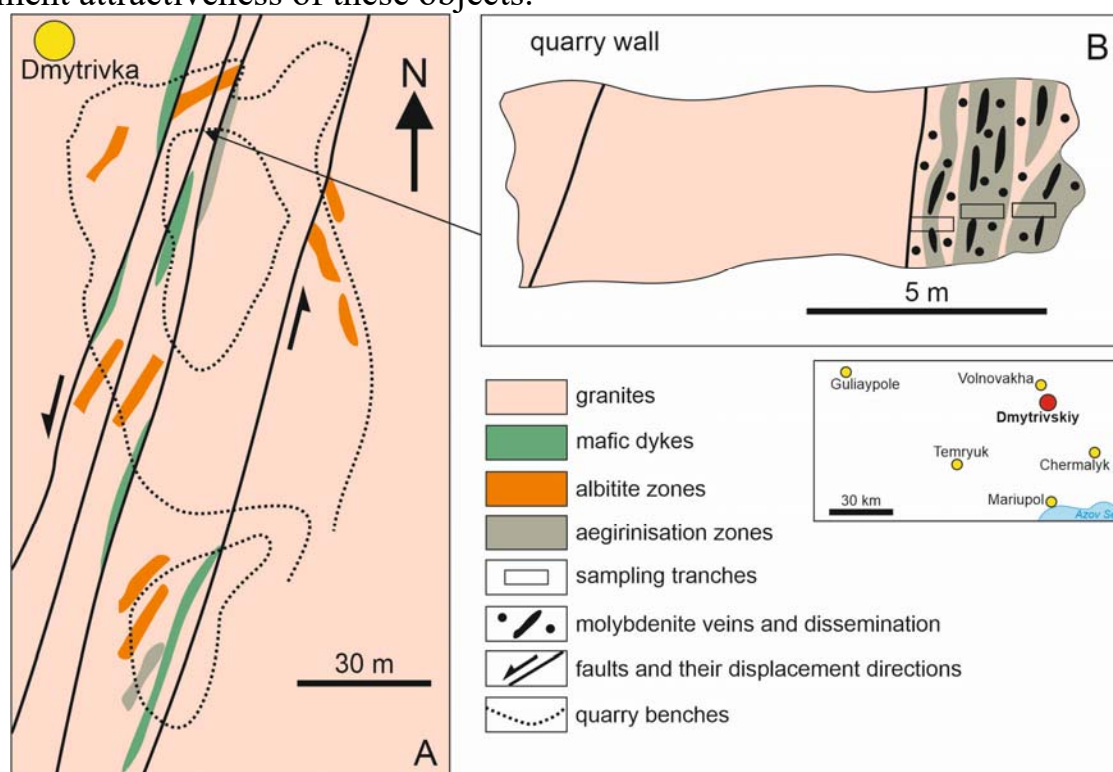


Fig. 4.36. Geological map (A) and cross-section (B) of the Dmytrivskiy occurrence (modified after Mykhailov et al. 2007)

4.4.5. Platinum Group Metals

These include platinum, palladium, osmium, iridium, ruthenium and rhodium. They are used in the chemical industry as catalysts for catalytic reforming in refineries, for coating electrodes, resistance thermometers, ferromagnetic alloys, gas filters, permanent magnets, in jewellery, and in computer technology.

Known world PGM reserves reach 69.3 kt, most of which belongs to South Africa (91%); Platinum production stabilized at 185-190 tons per year, the largest mining countries are South Africa (72% of world production), as well as Russia, Zimbabwe, Canada and other countries (Table 4.54).

Table 4.54. World platinum mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kg					PGM reserves, t
	2015	2016	2017	2018	2019	
South Africa	139,125	133,241	132,500	137,053	132,989	63,000
Russia	20,839	22,300	22,400	21,370	22,420	3,900
Zimbabwe	12,564	15,110	14,257	14,703	13,857	1,200
Canada	10,000	9,700	6,850	7,460	7,050	310
USA	3,667	3,891	3,980	4,165	4,152	900
China	2,300	3,000	2,500	2,500	2,500	n.a.
Finland	992	1,178	1,418	1,576	953	n.a.
Colombia	861	917	567	269	163	n.a.
Australia	108	152	155	110	95	n.a.
Serbia	2	3	3	6	10	n.a.
Poland	40	50	11	8	8	n.a.
Botswana	31	0	0	0	0	n.a.
Total	190,529	189,542	184,641	189,220	184,197	69,310

World palladium production is over 220 tons, most of which is extracted by Russia and South Africa, which together provide 78% of world production. Other sources include those from Canada, the United States and Zimbabwe. (Table 4.55).

Table 4.55. World palladium mining production (World Mining Data 2021; USGS 2020)

Country	Production, kg				
	2015	2016	2017	2018	2019
Russia	75,710	86,500	76,270	92,570	92,900
South Africa	82,691	76,273	80,713	80,629	80,684
Canada	22,600	21,200	19,140	20,880	19,750
USA	12,532	13,070	13,600	14,267	14,323
Zimbabwe	10,055	12,222	11,822	12,094	11,640
China	1,200	1,300	1,400	1,300	1,300
Finland	784	901	1,021	1,157	699
Australia	425	610	610	430	390
Serbia	22	23	50	55	100
Uzbekistan	-	-	-	0	28
Poland	20	30	7	5	5

Country	Production, kg				
	2015	2016	2017	2018	2019
Botswana	156	0	0	0	0
Total	206,195	212,129	204,633	223,387	221,819

World production of rhodium is more than 23 tons. South Africa produces the most (82% of world production), as well as Russia, Zimbabwe, Canada and the USA (Table 4.56).

Table 4.56. World rhodium Mining production (World Mining Data 2021; USGS 2020)

Country	Production, kg				
	2015	2016	2017	2018	2019
South Africa	18,722	19,237	18,665	18,608	19,545
Russia	2,488	2,644	2,426	2,146	2,115
Zimbabwe	1,128	1,322	1,283	1,334	1,224
Canada	530	650	600	750	700
USA	96	103	100	100	100
Total	22,964	23,956	23,074	22,938	23,684

In Ukraine, increased PGM content have been found in many intrusive ultramafic massifs and in some zircon-ilmenite placers, but there are still no industrial scale PGM assets in Ukraine, although mafic-ultramafic complexes with high platinum content are known in Precambrian rocks of Volyn (Prutivskiy, Zaliznyakivskiy, Kamenskiy, etc.), Dniester-Boug (Northern-Tarnovatskiy), Middle Dniprean (Varvarivskiy, Alferivskiy, Sukhokhutirskiy, etc.), and Azovian megablocks of the Ukrainian Shield. The content of platinum in some of them reaches (g/t) 0.1-4.9, Pd – 1.15, Ir – 0.46, Os – up to 0.03, Rh and Ru – up to 0.1. Particularly high content of platinoids was found in chromite ores of Kapitanivskiy and Lypovenkivskiy Massifs (Pt – 41.3-41.8 g/t; Rh – 2.5-2.6 g/t), where lazurite, irarsite, ferrous native platinum were found, as well as anduoite, ruarsite, sperrylite, stibiopaladinit, iridoosmin, PGM natural alloys, arsenides and bismuthides; in ultramafic rocks of the Zhdanivska intrusion, where sperrylite is located, an increased content of platinoids (Pt – up to 3.68 g/t) was detected. The platinum resources of some objects are estimated at 10 tons.

In addition, the increased content of platinum and platinoids was found in the Riphean flood-basalts of Volyn, iron-ore formations of Kryvyj Rig Basin, alpine-type ultramafics of the Carpathian Cliff Zone, beresite-listvenite gold-bearing metasomatites of Middle Dniprean greenstone structures, ore-bearing skarns of Middle Pobuzhie, red-colour sediments and metasomatites of Donbas, weathering crusts of mafic-ultramafic massifs of the Ukrainian Shield, alluvial gold-bearing placers of the Middle Transnistria and Pobuzhie.

At one time, the State Commission on Mineral Reserves had approved prognostic resources by category P₁ and reserves by category C₂ of platinum and palladium for the copper ores of Zhyrychi occurrence in Volyn, but, as it was shown above, this information is unreliable.

Therefore, there is little justification to support prospects of platinum

mineralization in Ukraine.

4.4.6. Strontium

It is used in the manufacture of special glass for televisions, computers, radars; ceramic magnets, medical devices, pigments, in pyrotechnics, as additives to alloys and drilling fluids.

Known world reserves of strontium are estimated at 6.8 Mt, production reaches 220,000 tons, the main mining countries are Spain (40.9% of world production), China (22.7%), Mexico (18.2%), Iran 16.8%), as well as other countries (Table 4.57).

Table 4.57. World strontium mining production and reserves (USGS 2020)

Country	Mining, t		Reserves*, kt
	2018	2019	
Spain	90,000	90,000	n.a.
China	50,000	50,000	n.a.
Mexico	40,000	40,000	n.a.
Iran	37,000	37,000	n.a.
Turkey	1,000	1,000	n.a.
Argentina	700	700	n.a.
Other countries	1,300	1,300	n.a.
Total	220,000	220,000	6,800

* Weight of celestine in tons (strontium content in celestine – 43.88%)

The SIMR records strontium reserves as concomitant component of Novopoltavske apatite-rare metal deposit in amounts of 955.5 Mt of ore and 952,000 tons of strontium (by categories A+B+C₁+C₂); these deposit are ready for development. The PJSC "Volyn Mining and Chemical Company" used to have a special permit for the extraction of rare metal-apatite ores (Mineral Resources of Ukraine 2020) but this license is now terminated.

4.4.7. Magnesium

It is used in metallurgy, chemical industries, pyrotechnics, military equipment, electronics, medicine, construction, agriculture, in the production of lightweight structural materials and alloys, in aircraft and rocketry and in the manufacture of some nuclear reactors and cars.

World magnesium resources and reserves are not known, the world production is about 400,000 tons per year. The main producers are the United States (over 100 kt), China (about 90 kt), Canada (65 kt), Russia and Norway (35-40 kt each), Israel (about 30 kt), as well as Brazil, France, Iceland and Australia.

Ukraine has significant reserves of magnesium (over 150 Mt of MgO) in the hard-rock deposits of potassium-magnesium salts of the Fore-Carpathian Trough (Kalush-Golynske, Stebnytske), Dniprovsko-Donetska Depression (Zaturynske, Novopodilske), magnesium salts dissolved in the brines of Crimean lakes and bays, Syvash, Stare, Donuzlav). The largest amount of magnesium metal is produced by

Kaluskiy Chemical and Metallurgical Plant and Zaporizhia Titanium and Magnesium Plant.

The Kalush-Golynske deposit is represented by two salt-bearing bodies ranging in size from 300×700 to 1000×2000 m, up to 50 m thick. Kaluska material is up to 600 m thick and is turned into gentle folds. At depths of 40-150 m the gypsum-clay caps are 30-100 m thick and are developed in the crestal parts of anticlines. Salt-bearing bodies are composed of intercalating kainite, langbeinite, kainite-halite layers with admixtures of kieserite, polyhalite and polyhalite-clay layers. The average content of MgO in ore bodies is 5.06%, K₂O – 11.25%; the content of insoluble residue is 5-25%.

The Stebnytske deposit is represented by potassium-magnesium salts bodies in the Lower Miocene Vorotyshchenska Suite, where five potassium-magnesium horizons ranging in size from 100×700 m to 2000×4000 m and up to 30-50 m thick are found. The main minerals are halite, kainite, langbeinite and sylvite, with kieserite and polyhalite also noted. Kainite occurs in the form of fine-grained, parallel-fibrous and radial-fibrous aggregates. The average MgO content in salts is 8.32%, K₂O – 10.64%. The total reserves of crude salts at Kalush-Golynske and Stebnytske deposits by categories A+B+C₁+C₂ are about 1.7 billion tons (including about 130 Mt of MgO).

The Deposits of magnesium salts in Dniprovsko-Donetska Depression are confined to the Permian Kramatorska Suite, where 5 potassium-magnesium horizons 15-30 m thick are encountered. Of these the lower layers consist of carnallite-kieserite and bischofite salts, the three middle layers are of salts of sylvinite composition, and carnallite-kieserite salts are developed in the upper horizon.

The Zaturynske deposit is represented by a horizon with bischofite 14.5-24.0 m thick on an area of about 200 km², at a depth of 2658-2678 m. Bischofite rock consists of 88.47% of bischofite, as well as halite (8.53%), kieserite (1.87%), gypsum (0.82%), and other salts (0.31%).

The Novopodilske deposit is represented by 3 layers of potassium-magnesium salts: the lower layer is composed of carnallite, the middle layer of bischofite, and the upper layer of carnallite and halite with a high content of clay impurities. The pile of halite-bischofite-carnallite salts lies at a depth of 2338-2387 m. The thickness of the bischofite horizon is 15-35 m, the bischofite content is up to 94%. Reserves are estimated at 1.68 billion tons.

Bischofite is extracted by well dissolution in Zaturynske and Novopodilske deposits. The total resources of bischofite brines are at least 50 km³.

The Brine deposits of Crimean bays and lakes are modern deposits of complex salts, which are formed as a result of constant evaporation of the waters of Azov Sea, entering the shallow, separated from the general water bay of Syvash, and neighbouring separate lakes (Stare, Sasyk, Donuzlav) also form the brine. The average MgO content in brine ranges from 0.38 to 1.15%.

In addition to the above, metamorphogenic deposits of magnesite and talc-magnesite (Pravdyske, Veselyanske), high-magnesium metatuffic rocks (Pryazovia), dolomite marbles and calciphyres (Zavallivske deposit), that are non-traditional for Ukraine types of magnesium raw materials, may be of interest in the

future. A license proposal has been opened for one of these at the Sukhokhutirska site of complex talc-magnesite ores, nickel, and cobalt.

The Pravdynske deposit of talc-magnesite is represented by a series of steeply-dipping layered bodies of submeridional extension 0.5-2.5 km long, 80-350 m thick, 150-350 m wide in the same-named ultramafic intrusion, composed of chrysotile, antigorite serpentinites and talc-magnesite rocks, talc-chlorite and chlorite-carbonate-talc schists.

Table 4.58. Major-element composition of altered ultramafic rocks at the Pravdynske deposit

Elements	Content, %	
	Talc-magnesites	Carbonatized serpentinites
SiO ₂	25-30	31-37
Al ₂ O ₃	up to 2	1
MgO	32-36	36-41
CaO	up to 20	20

Two types of ores are distinguished: talc-magnesites and carbonatized serpentinites. The first are composed of talc (35-50%) and magnesite (breunnerite) (40-60%), with minor serpentine (antigorite), dolomite, magnetite, chlorite, chromite and sulphides. Massive, occasionally sheared structures, and porphyroblastic

and lepidogranoblastic textures are characteristic. Carbonatized serpentinites are composed of (%) serpentine (60-80), magnesite (10-30) and other carbonates (10-20), talc, magnetite, chromite, olivine, bastite, and sulphides. Major elements content of talc-magnesites and carbonatized serpentinites is shown in Table 4.58.

The reserves of these deposits (by categories A+B+C₁) are 105 Mt of ore with 55% of talc-magnesite and 45% – carbonatized serpentinites, prognostic resources to a depth of 300 m are estimated at 300 Mt. Conditions of ores: MgO content – not less than 38.4%; Al₂O₃ – not more than 2%; CaO – not more than 2.5%; MgO/SiO₂ – not less than 1.1. Technological research has proved the possibility of using the raw materials of deposit as magnesite-breunnerite and talc grades A and B of multiple-purpose concentrates; forsterite refractories from talc-magnesites and serpentinites; fine talc-magnesite and carbonate-serpentine powder for the production of fertilizers, insecticides, slag, heat-resistant concrete, refractory bricks, etc.

The Veselyanske deposit of talc-magnesite is located in Precambrian schists (serpentinites, talc-carbonate, talc-chlorite, chlorite-amphibole rocks). It is represented by three steeply-dipping bodies with serpentinite lenses and interbeds. The length of bodies is 600-1280 m, thickness 50-180 m. They are composed of magnesite (20-60%), talc (15-45%), serpentine (3-30%), and magnetite (3-8%). The reserves of deposit by categories A+B+C₁ are estimated at 1,322 kt, with prognostic resources of 250 Mt.

The Sukhokhutirska site of complex talc-magnesite ores, nickel, and cobalt in the Dnipropetrovsk region with an area of 127.6 ha is represented by talc-magnesite ores with a thickness of 15-82 m (average 42.6 m) after Archean serpentinites, overlain by Meso-Cenozoic weathering crust 23.9 m thick in average, and Neogene-Quaternary clay rocks with an average thickness of 32.5 m. Increased content of nickel (0.2-2.0%), cobalt (average content 0.055%) and iron (average content 24.3%) is observed in the weathering crust. The chemical composition of talc-magnesite ores does not differ from the ores of Pravdynske deposit: the content of MgO is 37.59%, SiO₂ –

30.34% (MgO/SiO_2 – 1.26), CaO and Al_2O_3 – less than 2%. Reserves of talc-magnesite ores by category C_2 are amounted to 75,739.7 kt, resources (P_1) – 164,693.3 kt; reserves of associated nickel weathering crust by category C_2 are 72.96 kt (at nickel cutoff grade 0.5%), cobalt – 4,770 t, iron – 1,420.2 kt (Investment Atlas of Subsurface User 2021).

Thus, there are prospects for increasing the production of magnesium salts in Ukraine by identifying other deposits in Dniprovsko-Donetska Depression, with additional exploration of the flanks and deep horizons of Fore-Carpathian deposits, the study of talc-magnesite and carbonatized serpentinites (Pravdyske deposit).

4.4.8. Arsenic

It is used for strengthening lead alloys, the synthesis of a number of semiconductor materials, in the military, in medicine, in the manufacture of lead-acid batteries and in agriculture,

World arsenic production in recent years has fluctuated at 53,000 to 59,000 tons, the largest extractive countries are Peru and China, which together provide 86% of world production, as well as Morocco, Russia, Belgium and other countries (Table 4.59).

Table 4.59. World arsenic mining production (World Mining Data 2021)

Country	Mining, t				
	2015	2016	2017	2018	2019
Peru	-	23,252	22,403	20,376	24,915
China	25,000	25,000	25,000	24,000	24,000
Morocco	7,567	6,122	6,879	5,578	5,055
Russia	1,500	1,500	1,500	1,500	1,500
Belgium	1,000	1,000	1,000	1,000	1,000
Bolivia	38	38	20	238	126
Japan	45	45	45	45	45
Namibia	2,000	1,960	700	0	0
Iran	110	0	400	0	0
Total	37,260	58,917	57,947	52,737	56,641

No industrial scale arsenic ores were found in Ukraine. Arsenic occurs in complex ores. Increased arsenic content was found in the ores of some deposits in Ukraine, in particular, Mykytivske and Konstyantynivske mercury deposits, gold ore in Klyntsiyske deposit and Mykhailivskiy occurrence, and gold-polymetallic Berehivske deposit.

4.4.9. Rubidium and Cesium

They are used in the electron-optical industry, for the manufacture of vacuum radio lamps, thermistors, lasers, masers, fluorescent screens and tubes, cathodes for photovoltaic cells, special ceramics, glass, enamel; rubidium salts – as a catalyst in organic synthesis; isotope ^{133}Cs – in quantum frequency standards, in biomedical

research; cesium – in magnetohydrodynamic generators, plasma high-frequency amplifiers, automatic control systems, missile control and guidance, long-range communication and missile defence systems, for the manufacture of photovoltaic cells, and in energy production.

Significant reserves of rubidium are found in Namibia (50 kt), Zimbabwe (30 kt), Canada (12 kt) and in other countries (10 kt). The total world reserves are estimated at 100 kt (USGS 2020). Cesium reserves are known in Canada (120 kt), Zimbabwe (60 kt), Namibia (30 kt) and Australia (7.1 kt), with total known world reserves of 220 kt.

There are no deposits with proven reserves of rubidium and cesium in Ukraine, although traces have been found in some lithium deposits (Mykhailov et al. 2007).

Specifically, on the southern flank of **Zhovtorichenske deposit**, in metasomatic diopside quartzites of Gdantsivska Suite, the veins (0.1-0.5 m) of zonal structure enriched in pollucite are known. Their central parts are composed of coarse-grained ores with microcline, spodumene, pollucite, whereas endocontacts are fine-crystalline with apatite and rubelite. Numerous apophyses and branches up to 5 cm thick and up to 1.5 m long are characteristic, composed of an albite-pollucite aggregate with microcline and apatite. Pegmatites are composed of quartz, microcline and albite, the grains of spodumene, pollucite, rubelite, apatite, columbite, arsenopyrite, muscovite are noted. Spodumene is represented by short-prismatic crystals up to 1×4 cm (2-3%); pollucite – fine-grained aggregate of white-blue colour with metallic lustre. The size of apatite and rubelite crystals reaches 1 cm. Columbite and arsenopyrite are found in the form of rare crystals up to 3 mm in size.

In the **Stankuvatske deposit**, higher levels of content of rubidium and cesium were found in the biotitization zones at the contact of pegmatites with amphibolites (Rb_2O – 0.03-1.16; Cs_2O – 0.06-0.28%). In biotite from amphibole schists, the average content of Rb_2O is 1.38% (from 0.12 to 2.3%). At the contact of pegmatites with ultramafic rocks, phlogopite zones with a thickness of the first cm to 0.5 m, sometimes up to 8 m with an Rb_2O content of 0.06-1.80 are identified; Cs_2O – 0.10-0.50. They are composed of phlogopite, tremolite, anthophyllite, cummingtonite, blue-green apatite. The main concentrator of Rb and Cs is phlogopite with an average content of Rb_2O 0.76% (from 0.045 to 1.45%) and Cs_2O – 0.83 (0.34-1.61%).

In the **Polokhivske deposit**, increased concentrations of Rb and Cs are confined to recrystallized garnet-biotite and garnet-biotite-cordierite gneisses in exocontacts of pegmatite bodies, where content of Rb_2O is 0.04-0.12% (average 0.11%); Cs_2O – 0.02-0.05% (0.04%). The main mineral concentration of rare alkalis is in biotite (Rb_2O – 0.14-0.24%, Cs_2O – 0.057-0.093%).

In addition to these deposits, increased concentrations of rare alkalis have been encountered in a phlogopite zone at the contact of the Novomoskovskiy granite massif with ultramafic rocks of Konkska greenstone structure; in small intrusions of granites of Volyn and Azovian megablocks of the Ukrainian Shield; in hydrothermally modified granites of Perzhanske ore field (up to 740-2000 g/t of Rb_2O), as well as in groundwater of Donbas (Rb – up to 1.25 mg/l, Cs – up to 0.08 mg/l) and Kerchensko-Tamanskiy area (up to 0.36 – 4.0 mg/l).

CHAPTER 5. NON-METALLIC MINERALS

Ukraine has a large resource of non-metallic minerals, comprising deposits such as apatite, barite, bischofite, bromine, glauconite, saponite, salt, sulphur, phosphorite, graphite, kaolin, celite, zeolite, anhydrite, clay and sand, perlite and more.

As with metallic minerals, the degree of investment potential of non-metallic minerals may also be divided into four categories:

- traditional, which have been intensively developed in Ukraine for a long time, have significant explored reserves, and contribute significantly to the State budget (e.g., kaolin, foundry sands, construction and facing (decorative) stones and refractory clay);
- highly promising, occurrences with significant reserves or resources, but not yet developed or alternatively, developed in small quantities (e.g., graphite, potassium salts, abrasive raw materials (garnet), quartz raw materials, piezooptical raw materials);
- potential prospects, reserves or resources not yet properly defined, so the certainty of their development is undetermined (e.g., phosphates, apatite, fluorspar, glauconite, flux limestones and dolomites, limestones for sugar industry, bentonite clays, feldspar raw materials, facing stone and gemstone raw materials);
- unclear prospects, occurrences and small deposits whose scale does not suggest a significant resource, or comprise minerals not in demand on world markets (e.g., barite, boron, dawsonite, bromine and iodine, mineral sorbents, alumina, diamond, raw materials for the production of mineral paints, fluorine and sulphur).

5.1. Traditional Raw Materials

Traditional non-metallic minerals that are of strategic importance to Ukraine includes kaolin, foundry sands, building stones and refractory clay

5.1.1. Kaolin

It is used in paper, rubber, ceramic, porcelain-faience, metallurgical industries.

World kaolin production has stabilized at 38-40 Mt in recent years, the largest mining countries are China, USA, Germany, India, Czech Republic, which together provide 62% of world production, with Ukraine providing 4.7%. Iran and Russia are currently increasing their kaolin production (Table 5.1).

Table 5.1. World kaolin mining and reserves (World Mining Data 2021)

Country	Production, kt				
	2015	2016	2017	2018	2019
China	7,030.0	7,240.0	6,910.0	6,650.0	6,400.0
USA	5,810.0	5,290.0	5,450.0	5,350.0	5,060.0
Germany	3,733.7	4,740.0	5,168.0	4,930.0	4,760.0
India	4,770.0	4 110.0	4 100.0	4,400.0	4,400.0
Czech Republic	3,454.0	3,540.0	3,669.0	3,622.0	3,446.0
Ukraine	1,814.8	2,335.0	2,379.6	2,091.5	1,843.6
Iran	791.2	868.2	861.9	1,159.0	1,813.4
Russia	786.0	1,064.8	1,593.0	1,485.9	1,530.8
Brazil	1,809.0	1,737.0	1,771.0	1,550.0	1,471.6

Country	Production, kt				
	2015	2016	2017	2018	2019
Turkey	1,887.3	1,283.3	1,362.8	1,515.6	1,283.8
Other countries	6,484.7	6,844.7	7,044.0	7,869.6	6 647
Total	38 370.7	39,053.0	40 309.3	40,623.6	38,656.2

Ukraine is one of the most important kaolin-bearing provinces in the world, with about 150 deposits and occurrences of kaolin, usually of high quality. The SIMR records reserves of 42 deposits, of which 22 are developed. In 2020, production amounted to 1,569.6 kt. Total reserves of kaolin are estimated at 1,095.8 Mt (including reserves categories A+B+C₁+C₂ – amounting to 1,022.6 Mt), whilst total resources are estimated to be 4,500 Mt.

Kaolin deposits are located mainly in the Ukrainian Shield, where they are associated with the weathered crust after granitoids, but are also known in Trans-Carpathians and DDD (Fig. 5.1). They belong to two types: primary (basic and alkaline) and secondary.



Fig. 5.1. The distribution of kaolin deposits in Ukraine
(modified after Gurskiy et al. 2006b)

Deposits of primary kaolin in the weathered crust around Precambrian granitoids have a range of shapes depending on the degree of weathering. The deposit generally occurs between 5-42 m depth with a thickness range between 1.4-120 m (average 10-40 m). The deposits are generally characterized by chemical and physical zonation; the sequence from the base comprising variegated clays – alkaline kaolins – normal (basic) kaolins. Kaolin varieties may be distinguished according the content of Al_2O_3 thus, normal alumina ($\text{Al}_2\text{O}_3 < 39\%$) and high alumina ($\text{Al}_2\text{O}_3 > 39\%$); by SiO_2 – moderately siliceous (up to 65-70%) and siliceous ($> 70\%$) varieties; and by K_2O – normal (basic) ($< 2\%$) and alkaline ($> 2\%$).

The largest deposits of primary kaolins include Glukhovetske, Turbivske, Velykogadomynetske, Zhezhelivske, Prosyanyvske, Bilgorodske, Pologivske, Volodymyrske, Murzynske, Dibrovske, Chausivske and others.

The Glukhovetske deposit in the Vinnytsia region has been worked since 1901. It comprises Meso-Cenozoic primary kaolin bodies of kaolinite and kaolinite-hydromica zones around Lower Precambrian granites (Fig. 5.2). These are white rocks of flaky and pelitomorphic-flaky texture, banded and gneiss-like structure, medium plasticity, and greasy to touch. They form subhorizontal, stratiform bodies, their thickness ranging from 1-48 m (average 22.6 m). Overburden comprises soil, Quaternary loams, sands and clays, and Neogene variegated clays with a total thickness of 1-6 m to 16-29 m. The chemical composition of the Glukhovetske kaolin is given in table. 5.2.

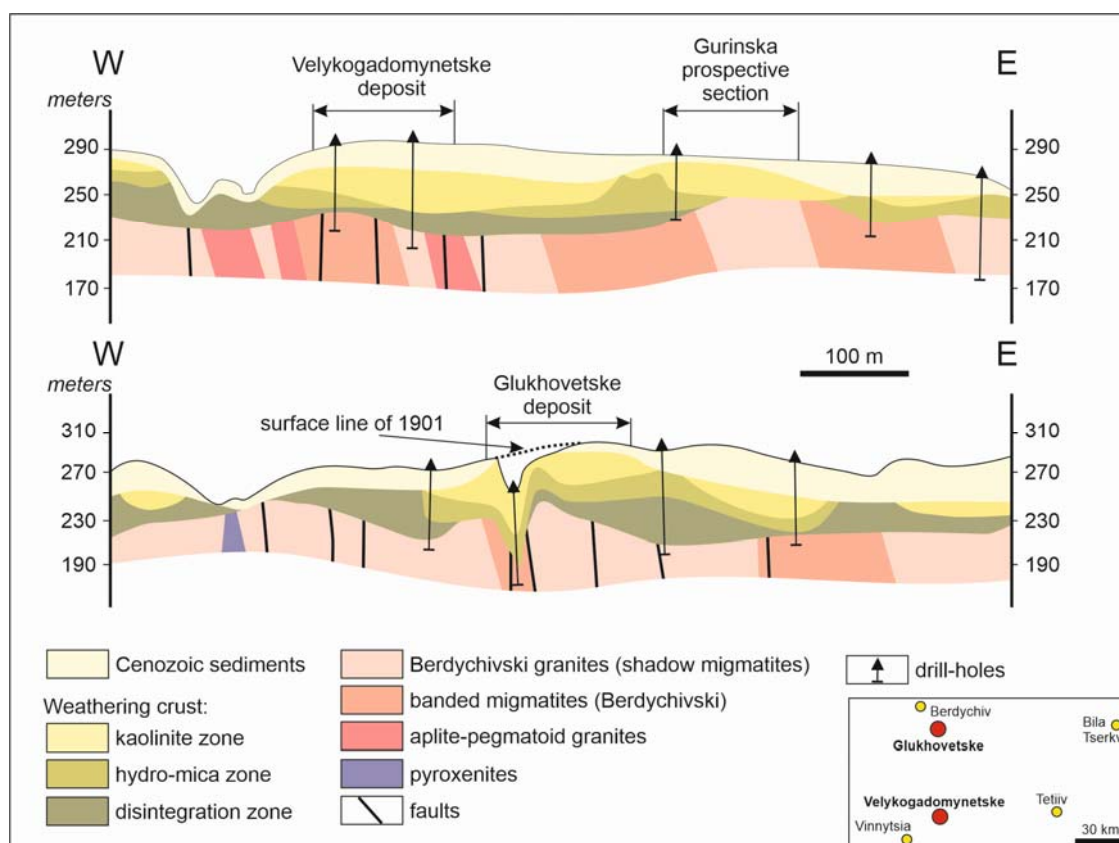


Fig. 5.2. Cross-sections of the weathered crustal zones in the Glukhovetske and Velykogadomynetske deposits (modified after Mykhailov et al. 2008a)

Table 5.2. Chemical composition of kaolin (%)

Component	Glukhovetske		Velykogamodynetske	Turbivske	Zhezhelivske
	from to	average	average	from to	from to
SiO ₂	60.4-72.6	67.7	69.09	48.7-68.7	55.14-67.62
Al ₂ O ₃	22.5-28.7	23.0	20.96	20.7-33.8	20.62-28.38
Fe ₂ O ₃	0.1-1.87	0.4	0.26	0.14-2.6	0.4-6.7
TiO ₂	0.34-1.7	0.6	0.34	0.2-2.5	0.4-1.61
CaO	0.02-0.07	0.05	0.03	0.12-1.6	0.14-0.83
MgO	0.02-0.25	0.03	0.106	n.a.	0.11-1.2
MnO	n.a.	n.a.	0.05	n.a.	n.a.
K ₂ O	0.12-1.46	0.3	2.26	0.04-3.1	0.1-1.7
Na ₂ O	0.01-0.2	0.03	0.077	n.a.	0.07-0.15
P ₂ O ₅	n.a.	n.a.	0.017	n.a.	n.a.
SO ₃	0.02-0.03	0.02	-	n.a.	0.01-0.1
LOI	6.3-10.7	7.9	6.40	6.7-12.7	6.5-11.6
Humidity	11.6-27.2	n.a.	n.a.	16-30.6 (18.7)	18.5-20.6
Fire resistance	1690-1740°	n.a.	n.a.	1710-1750°	1580-1670°

The main minerals are kaolinite (47-71%) and quartz (10-45%). Besides these, hydromica, goethite and hydrogoethite, microcline, accessory apatite, monazite, zircon, leucoxene, and magnetite are noted. In general, the kaolin deposits are characterized by high quality and can be used to produce sanitary ware and household tin-glazed pottery (faience).

In 01.01.2020, the reserve categories A+B+C₁+C₂ amounted to 107,658.9 kt; the deposit being developed by PJSC “Glukhovetskiy Mining-Beneficiation Kaolin Plant” (Section 1) and “AVK Ukrainian Kaolin Society” LLC (Section 2).

The Velykogadomynetske deposit in the Vinnytsia region comprises a zoned kaolin layer with a thickness of 1-89 m (average 19-25 m). The upper zone is further divided into an upper normal kaolin and a lower alkaline kaolin (see Fig. 5.2). Overburden comprises soil, Quaternary and Neogene loams, clays and redeposited kaolin with a total thickness of up to 38 m (average 13.5-23.7 m). According to its quality, kaolin can be used to produce rubber products, paper and cardboard, ceramics, electrothermal silumin and ultramarine, chemicals, cables and cosmetics.

In 01.01.2021, reserve categories A+B+C₁+C₂ amounted to 300,300.6 kt. The deposit is being developed by “Ukrainian Kaolin Company” LLC (section 1) (special permit № 1104 of 17.10.1997) and “AKV Ukrainian Kaolin Society” LLC (Vinnytska site) (special permit № 5198 of 14.10.2010).

The Turbivske deposit in the Vinnytsia region (see Fig. 5.2) comprises primary kaolin bodies, 2-25 m thick (13 m on average), covered by Quaternary clays and loams 0-25 m thick (13 m on average). These kaolin deposits are generally fine-grained with relics of granular textures; they comprise kaolinite – 6-90% (usually 75-85%), quartz – 10-35%, leucoxene – 5-7%, iron hydroxides – 1%, hydromica – 2%, as well as minor amounts of garnet, monazite, zircon, apatite, xenotime and ilmenite. Kaolinite is pelitomorphous, fine-grained, vermiculite-like. Based on these parameters, these deposits can be used for the production of sanitary ceramics and as filler in the

production of rubber, plastics, cardboard, paper and more. In 01.01.2021, the reserve categories A+B+C₁+C₂ amounted to 6,862.6 kt. The deposit is developed by PJSC "Turbivskiy Kaolin Plant" (special permit № 2766 of 27.08.2002).

The Zhezhelivske deposit comprises primary kaolin bodies up to 36.8 m thick (average 17.6 m) confined to the weathered margins around granitoids. They are covered by soils and Quaternary and Cenozoic loams and clays. The overburden varies in thickness from 1.2-3.1 m in valleys and up to 15-16 m over the watershed.

The composition of kaolins is given in Table 5.3, and based on these parameters, these kaolins are suitable to produce rubber products, paper and cardboard, and cater for the needs of the ceramic industry.

In 01.01.2021, reserve categories A+B+C₁+C₂ amounted to 23,716.7 kt. The deposit is being developed by "Zhezhelivskiy Kaolin" LLC (special permit № 4888 of 03.02.2009).

Other deposits have a similar structure and composition.

Deposits of secondary kaolins are also concentrated mainly in the Ukrainian Shield: Novoselytske, Kirovogradske, Pologivske, Volodymyrivske, Murzynske, Oboznivske and others.

Table 5.4. Chemical composition of kaolins in Novoselytske and Pologivske deposits

Oxide	Contents, wt. %	
	Novoselytske	Pologivske
SiO ₂	25.22-71.60	46.4-54.5
TiO ₂	-	0.8-1.2
Al ₂ O ₃	-	32.9-45.5
Al ₂ O ₃ +TiO ₂	36.76-70.14	-
Fe ₂ O ₃	0.21-7.63	0.6-4.5
MgO	0.06-0.28	-
CaO	0.05-0.14	-
Na ₂ O	0.07-0.38	-
LOI	13.25-25.39	-

Table 5.3. Composition of kaolins in Zhezhelivske deposit

Mineral	%
Kaolinite	47-71
Quartz	24-48
Potassium feldspar	1-3
Biotite	0.5-2.0
Leucoxene	0.5-2.0
Minor ilmenite, accessory and ore minerals	<0.5

The Novoselytske deposit comprises two layers of secondary kaolin in a Lower Cretaceous sedimentary sequence. The deposit of economic importance is 0.4-24 m thick and lies below 35 m thick overburden comprising brown coal, sand and clay. The kaolin with an admixture of hydrargillite comprises grey, silt-grade material, its chemical composition is given in Table 5.4. It was worked by the Vatutinskiy refractory plant, however the deposit is now exhausted. This kaolin was used for the manufacture of refractories and porcelain-faience.

The Kirovogradske deposit comprises a layer in the clays of the Paleogene Buchatska Suite. It is 0.4-30 m thick (averaging 6-7.5 m), covered with a sequence of sands, loams and clays 3-49 m thick. The kaolin comprises 5 varieties, among which a high-alumina variety is distinguished with Al₂O₃+TiO₂ – 27-45%, Fe₂O₃ – 1.8-3.0%. The kaolin has a fire resistance between 1670-1770°C. Whilst the deposits are yet to be worked, as of 01.01.2021, the reserves amount to 8,730.0 kt.

The Pologivske deposit consists of a 3.7m thick layer of dark-grey, kaolinite refractory clays covered with layers (0.2-20 m) of "pure" white kaolins. The average depth of deposit is 30-40 m. The clays are mostly low-iron, high-alumina (see Table 5.4), and are fire resistance rated between 1670-1750°C. Reserves are estimated at

7.397.7 kt; the deposit is being developed by “Mineral Mining Company” LLC.

The Volodymyrivske deposit comprises layers and lenses of kaolin, between 0.2-17.0 m thick (averaging 3.8 m), occurring at a depth of 2.5-35.2 m. The kaolins are heterogeneous in colour and composition. White, homogeneous, dense; grey, light- and yellow-gray, dense; dark-grey, and spotted varieties are distinguished.

The Murzynske deposit is of Aptian-Albian age, and comprises pale-grey, grey, dark-grey, occasionally white, cream, or violet-grey secondary kaolins between 1-23.4 m thick (averaging 4.21-5.03 m). This sequence is overlain by Cretaceous-Quaternary clays and loams with a thickness of 3.75 to 81.4 m (averaging 18-33 m). The kaolin overlies Aptian-Albian sands and sand-kaolin rocks. The kaolin comprises kaolinite (80-95%), minor halloysite (up to 3%), quartz (1-10%), as well as hydromica, feldspar and ilmenite. Iron hydroxides are also noted whilst pyrite and marcasite are sometimes found. Reserve categories B+C₁ are estimated to 10,985.3 kt. The deposit is worked by open-cast mining by the “Vatutynskiy Refractory Plant” LLC.

In summary, kaolin resources of Ukraine provide excellent, international investment opportunities.

5.1.2. Foundry Sands

These are used in metallurgy for the manufacture of molds and rods. Ukraine has significant resources of foundry sands, whose deposits are known in the coastal and marine sediments of the Eocene Buchatska Suite in the Oligocene Kharkivska Suite of Donbas (Gusarivske, Bantyshivske, Shabelkivske, Malynivske, etc.); in the continental marine sediments of Poltavska Series and in the Neogene and Quaternary alluvial sediments of DDD (Chasiv-Yarske, Ripetske, Vyshnevske, Starovirivske, Malynivske, Pokotylyvske, etc.) and of the Ukrainian Shield (Bantyshivske, Malyshevske, Orlovske, Khoroshivske, Taromske, Dnipropetrovske, Maloviskivske, Novoselivske, Polozske, Orikhivske, etc.); in the Tortonian and Sarmatian sediments of the Volynska Plate (Voloshchynske, Yatsynivske, etc.), and in the Buchatskiy Stage sediments at the margins of the Voronezkiy Massif (Fig. 5.3). They comprise lenses and layers generally ranging from 1-5 m thick but locally, can be up to 40 m thick. They occur at depths between 1-6 m, but locally may be as deep as 51 m.

More than 200 deposits of foundry sands are known, of these 21 deposits are recorded by the SIMR, 10 deposits are developed. Total reserves are estimated at 826.1 Mt (including 820.3 Mt in categories A+B+C₁+C₂). Production in 2020 amounted to 1,292.9 kt (Mineral Resources of Ukraine 2020).

The national resources of foundry sands are estimated at 12.5 billion tons (Gurskiy et al. 2006b).

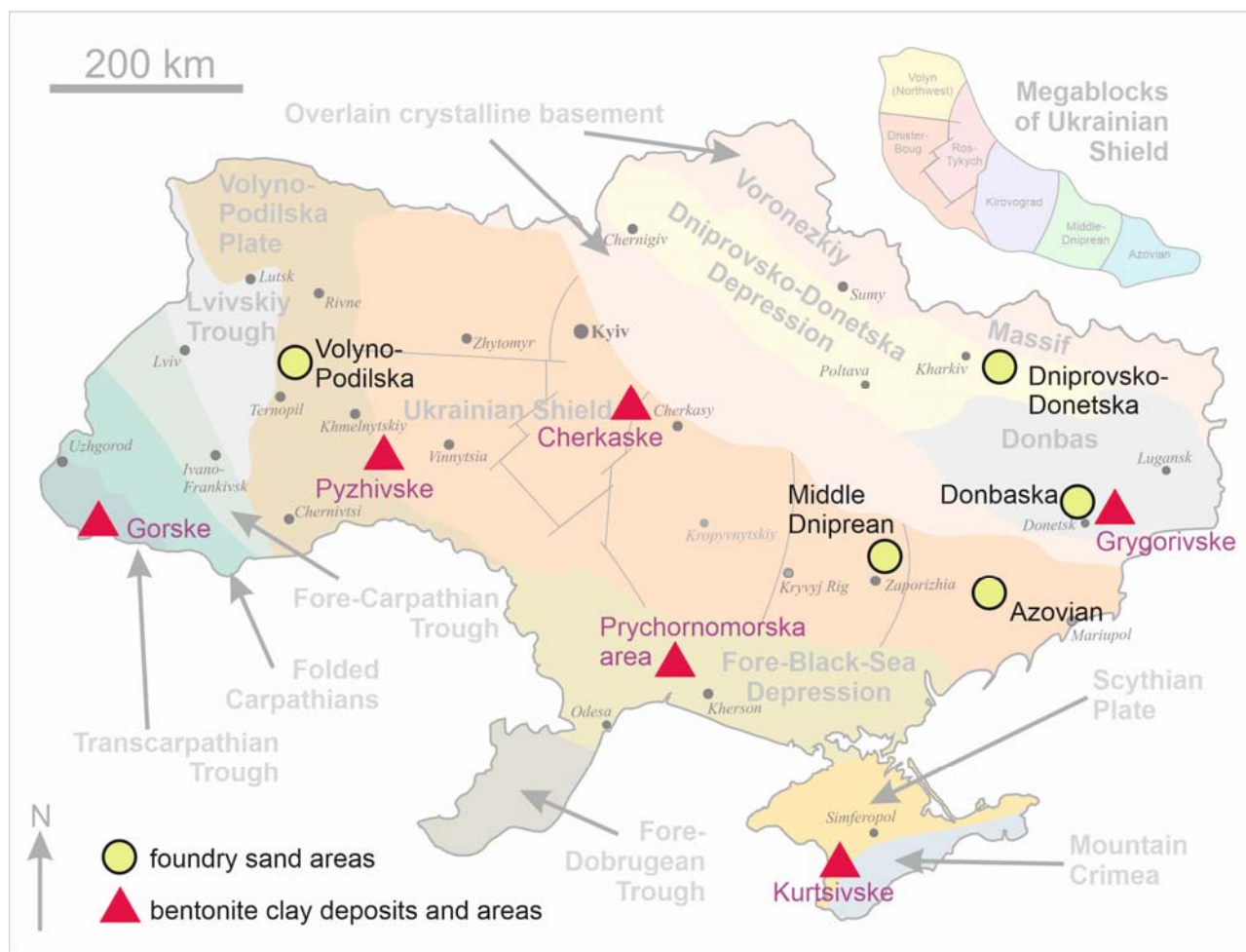


Fig. 5.3. Distribution of foundry sand and bentonite clay deposits (modified after Gurskiy et al. 2006b)

The Gusarivske deposit comprises homogeneous quartz and slightly clayey yellow coarse-grained sands between 7.5-31.7 m thick. Additional details are provided in the section “Quartz raw materials”.

The Bantyshivske deposit comprises 2.5-14.3 m thick, glauconite, quartz, and clay sands with interbedded clays of the Kharkivska and Buchatska Suites. The silica content of the sand fraction ranges between 77.86-96.6%, whilst the clay component is between 0.22-2.0%; the fire resistance is rated at 1730°. The estimate of this resource is 102 Mt.

The Chasiv-Yarske deposit comprises Kharkivska Suite sands, which lie on Cretaceous and Paleogene sediments. The sands are semi-greasy with between 10-20% of clay. The homogeneous fraction in clay-lean sands is 75.5-95.7%, with a gas permeability of between 76-232 conventional units and a fire resistance between 1650-1690°C. The homogenous fraction in semi-greasy sands is 51.6-87.5%, the clay component between 10-18.4% and fire resistance rated between 1630-1650°C. The composition of sand is: quartz – up to 93%, with lesser amounts of carbonate, glauconite, ilmenite, leucoxene, rutile, sillimanite, disthene and tourmaline. The chemical composition of the sand is: SiO_2 – 82-91%, Fe_2O_3 – 0.25-2.47%, $\text{Al}_2\text{O}_3 + \text{TiO}_2$ – 1.23-3.16%. The sequence is overlain by fine-grained well-sorted quartz sands of Poltavaska Series (1-15 m thick). The upper horizons of deposit comprise high-

quality quartz sands (up to 3 m thick), which are used in glass production whilst the clay-rich layers are used for refractory products.

5.1.3. Building Stones

They are used for various types of construction works for instance, for roads (as chipped stones, bridge and curb stones, paving stones and roadside edging), as loose aggregate and rubble (for foundations, for road construction and crushed stone as a filler for concrete), crushed rock to sand-grade (used in decorative concrete, to make window sills, stairs, facade cladding and for the manufacture of roofing, asphalt and pavement); special purpose stones (for heat-, acid- and alkali-resistant applications).

The construction industry uses natural stones, which belong to three genetic groups of rocks: sedimentary, metamorphic and igneous.

The SIMR of building stone records 947 deposits, whose total reserves amount to 8,820.5 million m³ (including 8,626.9 million m³ in categories A+B+C₁+C₂). Of these, 428 deposits are being developed; 39.0 million m³ were extracted in 2020 (Mineral Resources of Ukraine 2021).

Deposits of building stone occur in the Ukrainian Shield region (granites, diorites, charnockites, gneisses, migmatites, quartzites, marbles), the Volyno-Podilska Plate (basalts, sandstones, limestones, marbled limestones, travertine, gypsum), the Fore-Black-Sea Depression (limestones), the Carpathians (granite-gneisses, marbles, marbled limestones, andesite-basalts, volcanic tuffs), the Crimea (marbled limestones, shell rock), and in the Donbas (metamorphosed sandstones, limestones) (Fig. 5.4).

In the Ukrainian Shield, a range of deposits are developed including granite, diorite, gabbro, gneiss, and quartzite:

- In the Zhytomyr region: Klesivske, Perzhanske, Ovruchske, Korostyshivske, Bekhivske, Malynske, Leznikivske and others,
- In the Kirovograd region: Trykrativske, Oleksandrivske, Aktivske, Erastivske, Balanivske, etc.;
- In the Dnipropetrovsk region: Nedayvodske, Kolomoivske, Velyka Gleyuvatka, etc.;
- In the Zaporizhzhya region Yantsivske, Peredatochne, Zaporizke, etc.;
- In the Pryazovian region Karanske, Khlibodaryivske, Andriivske and others.

Deposits of sandstone, limestone, and basalt are exploited:

- In the Donbas: Braunivske, Sanzharske, Monakhivske, Valyanivske, Balka Kamyshevaska
- In the Crimea, the largest extraction locality is at Sharkhynske, working granodiorites and the Marmurove deposit of marbled limestones.
- In the Trans-Carpathians, andesites are extracted at Rokosivske, Korolivske and Klenovetske, rhyolites at Kosynske and perlite at Muzhyivske.

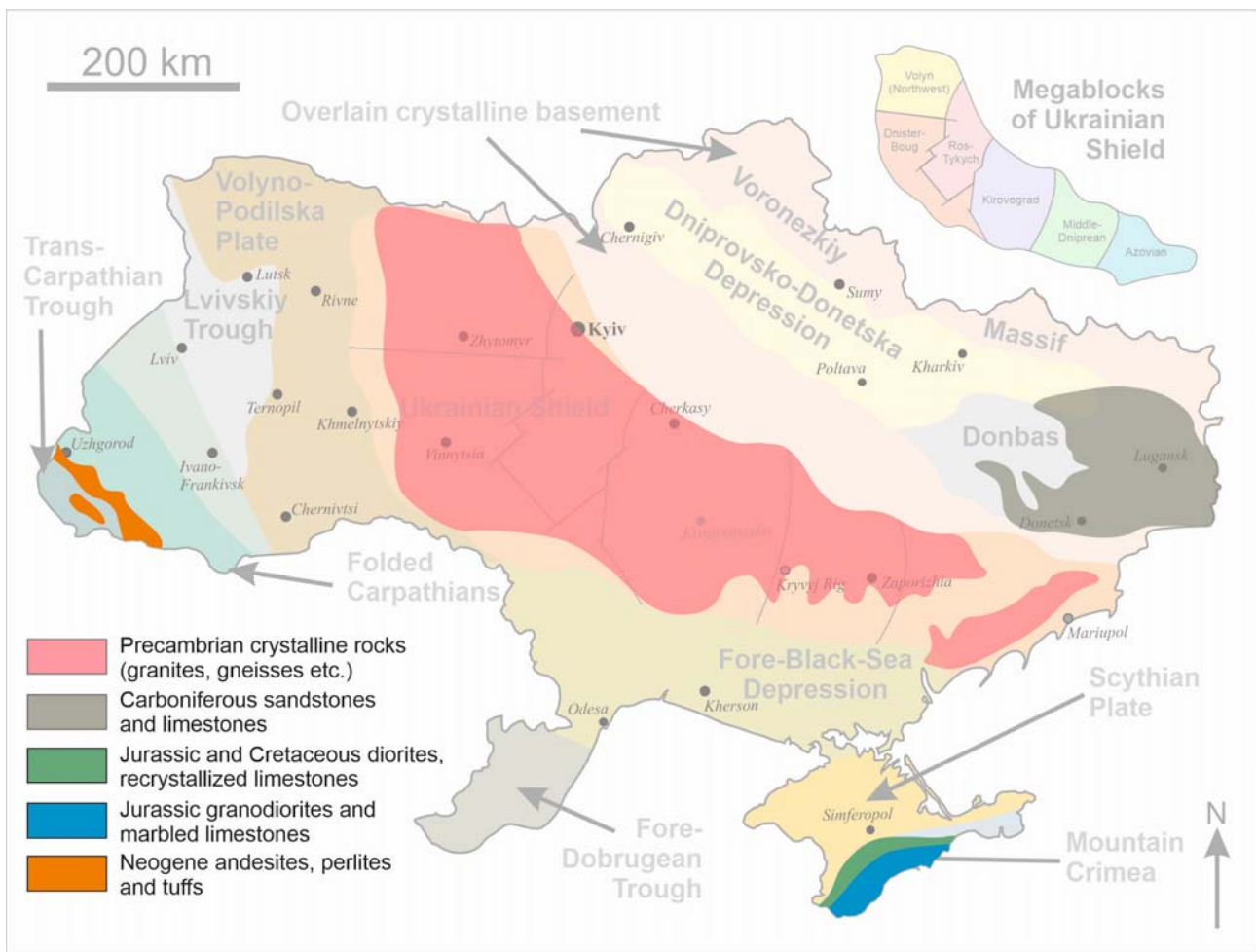


Fig. 5.4. Potential sources of building stones in Ukraine (modified after Mykhailov et al. 2008a)

5.1.4. Facing (Decorative) Stones

As their name implies, they are used to enhance the external and internal architecture of buildings and similar constructions (for instance, window sills, columns and other stone furniture). Exterior uses include garden and park sculptures, paving slabs, borders, cobblestones, monuments with their associated socles, plaques and in some landscape projects.

The SIMR of facing (decorative) stone records 255 deposits of which 137 are being developed. Total reserves are estimated at 392.9 million m³ (including 373.8 million m³ in categories A+B+C₁+C₂). In 2020, production amounted to 587.6 thousand m³ (Mineral Resources of Ukraine 2021).

The main enterprises producing facing (decorative) stones are listed in Table 5.5:

Table 5.5. Main enterprises producing facing (decorative) stones (Mineral Resources of Ukraine 2021)

Enterprise	Deposit	Production in 2020, thousand m ³
“Leznykivskiy Quarry” LLC	Leznykivske, granite	36.44
SE "Kirovgeologiya"	Bystriivske, gabbro	27.46
Noksen LLC	Anastasiyivske, granite	27.38
"Block" LLC	Gubenkivske-2, gabbro	21.54
"Granite LTD" LLC	Bukynske (Pivdenna section), gabbro	18.73
"Nevyriivskiy Labradorite" LLC	Gannivske, labradorite	17.03
“Buky” LLC	Ivanivske, gabbro	16.37
“Kamyana Pich Quarry” LLC	Kamyana Pich, Labradorite	12.71

Ukraine is rich in various facing (decorative) stone types, due to the Nation's diversity of rock types and structural complexity.

Potential areas of decorative stone extraction are (Fig. 5.5):

- The Ukrainian Shield (granite, granosienite, granodiorite, gabbro, labradorite, quartzite, marble).
- The Donbas (marble, marbled limestone, sandstone, gypsum, anhydrite).
- The Carpathians (marble, marbled limestone, andesite, tuff).
- The Crimea (marbled limestone, trails, diorite) and
- The Volyno-Podilska Plate (sandstone, gypsum, travertine, marbled limestone).

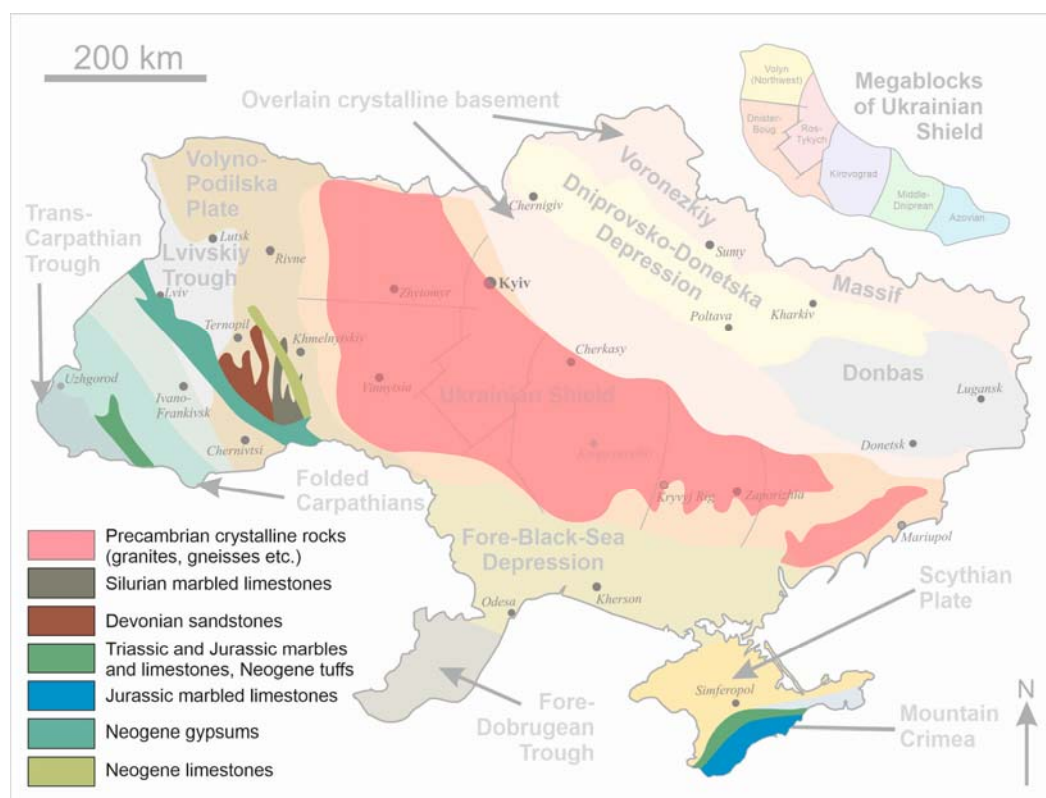


Fig. 5.5. Potential sources of decorative stones of Ukraine (modified after Mykhailov et al. 2008a)

The main occurrences of facing stones are in the Ukrainian Shield, with the Archean granites of Mokromoskovskiy, Tokivskiy, Demurinskiy Complexes, and Paleoproterozoic ultrametamorphic granitoids of Berdychivskiy, Zhytomyrskiy, Umanskiy, Kirovogradskiy, Saltychanskiy, Anadolskiy Complexes and the large plutons composed of gabbro, anorthosites, granites, rapaki granites, syenites and granosienites.

Gabbro and gabbro-norites occur at Slipchytske, Golovynske, Bukynske, Gorbulyvske deposits in the Zhytomyr region, and in the Bronislavske and Yasnogorske deposits in the Rivne region. Gabbroids of the Korostenskiy and Korsun-Novomyrgorodskiy Plutons are being developed at Slipchytske, Bukynske, Bystriivske, Yampilske, Torchynske, Shadurivske, Gubenkivske and Slobidske .

The Slipchytske deposit comprises greenish-black, medium-grained gabbro-norite and coarse-grained labradorite, which are suitable for facing slabs, monuments, blocks, cobblestones, rubble and aggregate. It is worked in opencast quarries. In categories A+B+C₁ the reserves of gabbro-norite are estimated at 11.4 million m³, and labradorite – 8.4 million m³.

Labradorites are confined mainly to the Korostenskiy Pluton, where three main types may be distinguished based on their decorative properties:

- a dark-grey and black Golovynskiy-type, with grain size up to 10-12 cm, with blue, green-blue and golden iridescence (for instance, localities such as Golovynske, Fedorivske, Gorbulyvske, and Slobidske in Zhytomyr region);
- a pale-grey and grey Turchynskiy-type, with grain sizes up to 3 cm, with blue and silver iridescence (for instance, localities such as Syniy Kamin, Kamyana Pich, Guta Dobrynske in the Zhytomyr region and Likarivske in Kirovograd region);
- a grey, pale-grey Kropyvnyanskiy-type, usually medium-coarse-grained, sometimes slightly porphyritic, but without iridescence (for instance, localities such as Kropyvnyanske, Vaskovytske and Isakivske in the Zhytomyr region).

The Kamyanobridskiy, Golovynskiy, Osnykivskiy, Dobrynskiy labradorites which have the most intense iridescence, are in most demand on the international market. The grey and pale-grey, iridescent labradorites of Syniy Kamin and Kamyana Pich deposits are also extremely decorative having an appearance similar to the Norwegian “Blue Pearl” larvikites.

The Golovynske deposit in the Zhytomyr region comprises labradorite lenses developed within the Paleoproterozoic granites, gabbro-norites and gabbroids. The porphyritic labradorite is dark-grey to black, uneven and coarse-grained. The phenocrysts occur as prismatic crystals of plagioclase, iridescent in bright-blue and blue shades. Mineralogical composition and physico-mechanical properties of labradorite are shown in Table 5.6. Blocks up to 5-6 m³ in size are mined in the quarry. Utilising labradorite of this type is very popular around the world (as pedestals of monuments, subway decoration and for office buildings). In categories A+B+C₁+C₂, the labradorite reserves are estimated at 11.5 million m³.

Table 5.6. Composition and properties of labradorites in Golovynske deposit

Mineralogy		Physico-mechanical parameters	
Mineral	Avg. wt. %	Parameter	Value
Labrador	59.00	Bulk density, g/cm ³	2.61-2.94
Pyroxene	23.11	Water absorption, %	0.1-1
Olivine	10.21	Compressive strength, kgf/m ²	1175-2308
Biotite	0.40	Abrasion resistance, g/cm ²	0.5-1.4

In terms of their decorative properties, the granites are categorised into 4 types:

- pale-grey, grey granites with faint blue and green-blue shades, fine- and medium-grained granularity of the Zhytomyrskiy and Antonivskiy types (such as at Boguslavske, Yantsivske, Umanske, Saltychanske, Zhytomyrske, Chovnivske and Mochulyanske in the Zhytomyr, Zaporizhya and Kyiv regions);
- medium- and coarse-grained, porphyritic granites of similar colour (such as at Korostyshivske, Kostyantynivske, Kudashivske, Zhezhelivske, Klesivske, Pokostivske and Tanske in Zhytomyr, Kirovohrad, and Mykolaiv regions);
- red, pink, brown and grey-pink granites of varying shades and structure as in the Zhytomyr (localities: Omelyanivske, Leznykivske, Didkovytske and Kornynske), in Kirovograd (localities: Kapustynske, Voynivske and Orikhivske), in Mykolaiv (localities: Novodanylivske and Trikratnenske), in Dnipropetrovsk (Tokivske), and in Rivne (Osmalynske) regions;
- grey-green (localities: Maslivske and Kubynske).

In terms of decorative attractiveness, the most valuable are the red and pink granites of the third group. Granites from Kapustynske are trademarked "Rosso Santiago" whilst the pink-red coarse-grained granite from Omelyanivske is trademarked "Rosso Toledo". Both have gained international recognition as they are similar to those elite granites of Finland ("Carmen Red"), Sweden ("Vanga"), and Brazil ("Capao Bonito").

The highly decorative and physical-mechanical properties of the Voynivske, Mezhyritske, Didkovytske and Tokivske granites have also enhanced their international market prospects.

The Omelyanivske deposit in the Zhytomyr region comprises Paleoproterozoic, red-pink, coarse-grained rapakivi-like granites, with an intricate crystallographic pattern due to the colour and macro-texture its constituent minerals. The mineralogical composition and physico-mechanical properties of granites are given in Table 5.7, The reserves of deposit are estimated about 3.2 million m³. This granite is well-suited for polishing and is used for facing buildings and structures. The deposit is worked by opencast quarrying.

Table 5.7. Composition and properties of granites in Omelyanivske deposit

Mineralogy		Physico-mechanical parameters	
Mineral	Avg. wt. %	Parameter	Value
Microcline	20-80	Bulk density, g/cm ³	2.60-2.64
Plagioclase	10-30	Water absorption, %	0.15-1.03
Quartz	15-70	Compressive strength, MPa	62.7-147.8
Others	up to 10	Abrasion resistance, g/cm ²	0.23-0.97
		Porosity, %	0.31-2.48

The Lyznytske (Leznikivske) deposit in Zhytomyr region has been worked since 1898. It comprises essentially red, medium-grained granites of the Korostenskiy Complex, which have high decorative properties. These granites were used in the facing of monuments in Yalta, Chisinau and other cities, but recently, is used only for rubble and aggregate products due to uneven color and low block yield. The granite has a colour range of pink-red to red and it has a medium-grained texture. The mineralogical composition and physico-mechanical properties of granites are shown in Table 5.8, These granites are overlain by sands and loams with an average thickness of 3 m. In categories A+B+C₁, the reserves are estimated to be 18.3 million m³. Currently, the granite is worked in three opencast quarries ("Leznikivsky Quarry" LLC).

Table 5.8. Composition and properties of granites in Lyznytske (Leznikivske) deposit

Mineralogy		Physico-mechanical parameters	
Mineral	Avg. wt. %	Parameter	Value
Microcline	80	Bulk density, g/cm ³	2.65
Quartz	15	Water absorption, %	0.18
Biotite	5	Compressive strength, MPa	140-260
Others	up to 1	Abrasion resistance, g/cm ²	0.24

The Kornynske deposit in the Zhytomyr region has been worked since 1937. It comprises grey, pink-grey porphyry granites of Zhytomyrskiy Complex. Large (up to several metres) xenoliths of biotite gneisses and amphibolites, veins of aplittoid or pegmatoid granite give a peculiar look to these granites. The pedestal of the monument to Bogdan Khmelnytskyi in Kyiv is faced with this granite and it was also used in the construction of metro stations in Moscow, Kyiv, St. Petersburg, as well as in the facades of buildings. The granite is suitable for facing materials, dimension products, rubble and aggregate. In categories A+B+C₁+C₂, reserves of the deposit are estimated to be 12.9 million m³. It is being worked by the quarry of PJSC "Kornynskiy Quarry Leopard" (special permit № 2992, issued on 12.05.2003 valid until 15.12.2036).

The Tokivske deposit in the Dnipropetrovsk region is in the central part of the Archean Massif of the same name. It comprises microcline, potassium granites. These are characterised by pale and pink-grey, pink-red, medium- and coarse-grained slightly porphyry-like granites of the "Rosso Santiago" trademark with xenoliths of

hornblende gneiss, veins of quartz and pegmatoid granite. They have been used for facing stone (monuments, houses and metro stations in Kyiv). In categories A+B+C₁, reserves are estimated to be 73.8 million m³. Nine licensed sites have been identified, some of which are being developed.

The Kapustynske deposit comprises bright red, porphyroblastic granite of Novoukrainskiy Complex. It is one of the best varieties of facing and decorative stone and is widely used to decorate the facades of houses, subway stations and other buildings in Kyiv and other cities of Ukraine. It is exported in significant quantities. The reserves of deposit are about 12.0 million m³.

Marbles and marbled limestones are widespread in the Ukrainian Shield (for instance, the Koziivske, Radomyshlske, Negrebivske deposits), in the Trans-Carpathians (Velykokamyanske, Novoselytske, Dilovetske, Golovatytske, Malorozynske, Gora Sokolyna, Polunske deposits), in Donbas (Khrystyshche, Korulka, Karakubsk, Dokuchaevske, Novopavlivske), and in Crimea (Gasprynske, Balaklavske, Biyuk-Yankoiske, Karanske, Marmurova Balka).

Table 5.9. Physico-mechanical properties of limestones in Velykokamyanske deposit

Parameter	Value
Bulk density, g/cm ³	2.68-2.69
Compressive strength, MPa	128-150
Abrasion resistance, g/cm ²	1.47-2.77
Block strength, m ³	0.5-2.5

The Velykokamyanske deposit in Trans-Carpathian region comprises marbled Upper Jurassic limestones which display a range of colours and clasticity – crinoid pink, red and various hues of yellow, brecciated or conglomeratic. The properties of limestones are given in Table 5.9. The reserves are estimated at about 0.5 million

m³. These limestones polished, can be used for interior decoration of buildings and structures.

Other noteworthy deposits comprise moss, oolite and numulite limestones of white and yellowish-white colour in the Crimea (Bodrasko-Almyske, Skelyaste, Krymbalske, Inkermanivske, Bilogorske); travertine – in the Khmelnytskyi region (Velykokuzhelivske); tuffs – in the Trans-Carpathians (Beretyanske); sandstones – in the Ternopil region (Budaniivske, Zastinkivske, Terebovlyanske), Lugansk region (Troitske), and Ivano-Frankivsk region (Gorodnytske, Babynske); gypsum and anhydrite – in Transnistria (Trostyanetske, Kolokolynske, Pryozerne, Mamalyzke, Zhuravniivske, Dobrivlyanske). These evaporites have a high decorative value in construction and architecture.

The Velykokuzhelivske deposit in the Khmelnytskyi region comprises pale-grey travertine with variable cream to pink colour shades. It displays fine-, medium- to large- and porous texture, often with numerous voids. The most valuable variety is fine-grained. The properties of travertine are given in Table 5.9. Travertine is used for interior decoration; more dense varieties are used for exterior decoration.

The Beretyanske deposit in Trans-Carpathian region comprises pale-green, fine-grained, dense, Lower Miocene tuffs. Their thickness varies from 10-15 to 120-200 m. The properties of tuffs are shown in Table 5.10. Good workability and high decorativeness allow to use them for interior decoration of buildings, in garden and

park construction and manufacturing mosaic plates.

Table 5.10. Physico-mechanical properties of travertine in Velykokuzhelivske deposit and tuffs in Beretyanske deposit

Parameter	Velykokuzhelivske, travertine	Beretyanske, tuffs
Bulk density, kg/m ³	1.67-2.18	2.11
Compressive strength, MPa	21.3-30	118
Water absorption, %	4.9-14.5	2.56
Porosity, %	18.4-35	7.0

Thus, Ukraine provides excellent potential for building and decorative stone extraction. The highly decorative properties of these warrant international interest.

5.1.5. Refractory Clays

These are used by the metallurgy industry as they withstand the very high temperatures (in excess of 1,000°F [538°C]) in the manufacturing processes. They are also used in the wider ceramics industries.

Ukraine has huge reserves of refractory clays, whose deposits have been explored in the Donetska Folded Structure, the Ukrainian Shield and in the Dniprovsko-Donetska Depression. The main area of refractory clays occurs in the Donetska Folded Structure, where more than half the nation's refractory clay reserves are concentrated.

These refractory clays have high ductility, good binding capacity, good refractory and reaction inertness along with varying sintering qualities. These properties are provided by kaolinite-hydromica composition, as well as an admixture of halloisite and other aluminosilicates. High plasticity and dispersion of refractory clays determine their unique high quality in the production of electroceramics, fine ceramics, and synthetic rubber. They are used in the glass and porcelain industries for the manufacture of special refractory capsules.

According to the domestic classification (Standard 9165-75) the fire resistance of clays is subdivided into: fire-resistant – not lower than 1580°C; refractory – from 1350°C to 1580°C; fusible – less than 1350°C.

Refractory clay is a high-alumina substance, with an alumina content of more than 39.5%; however, with some clays, the alumina content is reduced to 15-20%. The content of silica is like kaolinite, that is less than 45-46.5%. Iron oxides and sulfides are present in small quantities. Harmful impurities are calcite, gypsum, siderite, manganese and titanium compounds.

Clays suitable for refractory products are used in ferrous metallurgy (lining of iron-cast furnaces, blast furnaces and cowper stoves), in mechanical engineering, chemical, oil refining and other industries (for the production of special bricks, crucibles).

The SIMR records 31 deposits of fire-resistance clays, with total reserves estimated at 1,079.6 Mt (including 952.7 Mt in categories A+B+C₁+C₂). Of these, 20

deposits are being developed; in 2020, 4,547.9 kt of raw materials were extracted (Mineral Resources of Ukraine 2021).

Besides specific fire-resistance varieties, there are numerous other refractory clays in Ukraine: for instance in the Donbas, DDD, Ukrainian Shield, VPP and in the Trans-Carpathian Depression. In DDD and Donbas, mudstone and siltstone bodies are associated with Lower Permian Kartamyshska Suite sediments, Jurassic rocks, and with the Neogene Poltavaska Suite. The thickness of these occurrences varies from 0.6 m to 63.5 m. In VPP, the beds and lenses (0.3-27 m thick) of clays and mudstones are of Neogene age. In the Trans-Carpathian Depression, clay layers (0.5-18.9 m thick) are confined to Quaternary sediments, and in the Ukrainian Shield, the layers of refractory clays (up to 20.6 m thick) are associated with Neogene and Quaternary sediments.

These refractory clays are characterized by high fire resistance (1350-1580°C) and ductility, wide sintering range, alumina content – 18-24%, silica – 50-60%, iron oxides – 10-12%. There are two main types of mineral composition: hydromica (at Chasiv-Yarske, Novoraiske and Druzhkivske) and kaolinite (at Pyatykhatske, Kirovogradske, Ozernyanske and Glukhivske).

The SIMR of these particular refractory clays records 21 deposits with total reserves estimated to be 175.7 million ton (including 150.3 Mt in categories A+B+C₁+C₂). Five deposits are being worked; in 2020, total extraction from these was 210.2 kt (Mineral resources of Ukraine 2021).

The main exploitation of refractory clays is in the Donbas, where such deposits as Chasiv-Yarske, Novorayske, Veselivske, Oktyabske, Toretske, Andriivske, Novoshveytsarske, Novooktyabske, Pologivske, and Pyatykhatske are known, as well as others.

The Chasiv-Yarske deposit, located in the Donetsk region comprises a sheet-like body of refractory clay, 0.3-15 m thick, sometimes up to 60 m (average 3-8 m), within the Neogene Poltavaska Suite mostly comprising quartz sands. Overburden thickness here is 1-40 m. The clays have high plasticity and binding capacity, a low number of coloured oxides and the sintering temperature ranges between 1580-1730°C. The clay composition is given in Table 5.11. The deposit is being worked in 5 quarries; reserves in the undeveloped parts of this deposit are estimated at 40 Mt. Clays are used to produce refractories, and in the mechanical engineering, and oil industries; the best varieties are utilised for the porcelain, electrical-technical and electronic industries.

Other sites, such as Popasnyanske, Artemivske, Kurdyumivske, Karlivske, Virolubivske, and Donske are in the same area.

The Novorayske deposit of the Donetsk region comprises a 0.1-5.85 m thick productive layer confined to the Neogene Poltavaska Suite developed in the Kalmius-Toretska Depression. The layer is made up of four clay horizons, of these, the third horizon (up to 4 m thick), is composed of pale-grey sandy, high-quality clays with high ductility (plasticity number up to 43), binding capacity, low sintering temperature (up to 1200°C), and high fire resistance (up to 1710°C). The clay chemical and mineral compositions are presented in Table 5.11. The overburden

thickness is 0.1-56 m. The reserves of these clays are estimated at 88 Mt (including 54.5 Mt in categories A+B+C₁). The deposit has been worked since 1959 by the Druzhkivske Mining Administration. The clays are suitable for the metallurgy, porcelain, glass, oil and gas, electrical-technical, electronic industries.

Table 5.11. Chemical and mineral composition of clays in Chasiv-Yarske and Novorayske deposits

Oxide	Chasiv-Yarske	Novorayske	Mineral	Novorayske
	Contents, wt. %			Contents, wt. %
SiO ₂	14.9-36.7	47.08-78.5	Hydromica (illite)	29-33
TiO ₂	-	0.79 -3.92	Montmorillonite	6-8
Al ₂ O ₃	-	12.8-35.69	Quartz	11-47
Al ₂ O ₃ +TiO ₂	22-35	-	Kaolinite	24-51
Fe ₂ O ₃	0.4-3.0	0.5-9.47		
MgO	-	-		
CaO	-	0.7-0.76		
Na ₂ O	-	-		
Na ₂ O+K ₂ O		0.6-3.3		
LOI	-	1.6-12.30		

Other sites, such as Oktyabske and Andriivske deposits are in the same area. The estimated combined resource of these is up to 150 Mt.

The Veselivske deposit, Donetsk region, is located on the south-western limb of Druzhkivsko-Konstantynivska Anticline. The productive sequence 1.5-6.5 m thick and comprises five horizons of fire and refractory (upper horizon) clays. The average overburden thickness is 13.5 m. The clays are of high-grade, partly belonging to white-fired varieties – their reserves are almost exhausted. These clays can be used to produce high-quality porcelain and ceramics.

Other sites, such as Novoshveitsarske, Druzhkivske, Andriivske, Abramivske, Troychate, Gruzsk, and Oktyabske deposits are in the same area.

The following deposits are known in the Ukrainian Shield: Pologivske, Volodymyrivske, Kirovohradske, Shostakivske, Ivano-Blagodatnivske, Kamyanetske, Pyatykhatske, Saksaganske, Veseli Terny, Novopetrivske, and Devladiivske.

Table 5.12. Chemical composition of refractory clays and kaolin in Pologivske and Volodymyrivske deposits

Oxide	Contents, wt. %	
	Pologivske	Volodymyrivske
SiO ₂	48-56	56-58
Al ₂ O ₃	26-37	35-38
Fe ₂ O ₃	1.2-2.5	<1.5
MgO	minor	minor
CaO	minor	minor
Na ₂ O	minor	minor

ceramic products, in foundries and many other industries. The deposit has been

The Pologivske deposit of the Zaporizhzhya region comprises refractory clays and secondary kaolin beds in the sediments of Miocene Poltavsk Suite, where the clays occurs in the lower part of the bed, and kaolin forms the upper part. The composition of refractory clay and kaolin is given in Table 5.12. The fire resistance is rated between 1650-1770°C. These clays and kaolins are widely used in the manufacture of refractory and ceramic products, in foundries and many other industries. The deposit has been

exploited since the 1920s and is currently being mined by “Mineral Mining Company” LLC.

The Volodymyrivske deposit of secondary kaolins found in the Donetsk region comprises a sheeted body in the Miocene Poltavka Suite sand-clay sediments at a depth of 2.5-35.2 m. The thickness of the formation is from 0.2 to 17.0 m. The kaolin is of high quality with a fire resistance of between 1710-1730°C; its chemistry is presented in Table 5.12. It is used for the manufacture of fireclay and refractory products. The deposit has been in operation since the end of the XIX century.

5.2. Highly Promising Types of Raw Materials

Other non-metallic minerals of strategic, economic importance are graphite, potassium salts, abrasive, quartz and piezo-optical raw materials.

5.2.1. Graphite

In electrical engineering, graphite is used to produce galvanic cells, alkaline batteries, electrodes, movable contacts, refractory products, as well as for the manufacture of heating elements, contact brushes and pantographs for various electric machines, brake pads, steel smelting, foundry works.

World reserves of graphite are cited at 300 Mt, the largest reserves being in China, Brazil and Mozambique, with large reserves in India, Russia, Canada and Ukraine. World production has stabilized at 1.1 million tonnes in recent years, with China currently producing the most (62% of world graphite production). Mozambique and Madagascar are steadily increasing their production whilst production in India and Canada is declining (Table 5.13).

Table 5.13. World graphite mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
China	780.0	780.0	625.0	630.0	700.0	73.0
Mozambique		0	0.8	104.0	153.0	25.0
Brazil	81.8	61.7	95.0	96.8	81.8	72.0
Madagascar	8.1	9.2	13.3	47.9	53.4	1.6
North Korea	40.0	47.0	50.0	45.0	45.0	2.0
India	135.5	122.4	33.6	39.0	32.0	8.0
Russia	13.2	12.4	19.5	11.9	17.5	n.a.
Canada	30.0	21.0	14.0	11.0	11.0	n.a.
Ukraine	10.0	12.0	13.0	15.0	10.0	n.a.
Turkey	0	0	4.0	16.8	10.0	90.0
Other countries	28.1	34.0	28.1	23.9	19.4	28.4
Total	1,126.7	1,099.7	896.3	1,041.3	1,133.1	300.0

Ukraine is a large graphite-bearing nation. The main deposits are confined to the geological structures of the Ukrainian Shield and are located in four areas: Pobuzkiy

(Zavallivske in the Kirovograd region), Kryvorizkiy (Petrivske and Balakhivske in the Kirovograd region), Volynskiy (Burtynske in the Khmelnytskyi region), and Pryazovskiy (Troitske in the Zaporizhzhya and Mariupolske in the Donetsk regions) (Mykhailov et al. 2021c).

The total reserves of graphite in these deposits are estimated at 343 Mt of ore and 19.8 Mt of graphite (Table 5.14). Of these, two deposits are currently being developed, namely: Zavallivske and Balakhivske, licensed to “Ukrainian Supply Group” LLC and PJSC “Zavallivsky Graphite Plant” in the first locality and “Pobuzhzhya Development” LLC in the second. Output in recent years has been extremely variable (Table 5.15).

At the same time, proposals for licensing were opened for mining (Gorodnyavska site – in March 2021, the license was sold for UAH 44.8 million) and for exploration (Khmelivska site) in Burtynske deposit, Khmelnytskyi region, as well as for exploration of Mlynkivska prospect in the Kirovograd region (Investment Atlas of Subsurface User 2021).

Table 5.14. Reserves of graphite deposits, kt (Mineral Resources of Ukraine 2021)

Deposit	A+B+C ₁		C ₂	
	ore	graphite	ore	graphite
Burtynske	113,390.9	6,584.7	64,964.1	3,822.7
Zavallivske	79,928.3	5,030.5	14,613.0	744.2
Balakhivske	23,936.0	1,302.0	18,469.0	820.0
Petrivske	7,523.0	540.0	1,696.0	115.0
Mariupolske	3,440.0	135.0	1,347.0	41.0
Troitske	2,027.0	163.0	252.0	14.0
Total	230,245.2	13,755.2	101,341.1	5,556.9

Table 5.15. Dynamics of graphite production in Ukraine in 2010-2020, kt

Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Ore	-	18.7	91.9	28.1	104.0	111.2	103.0	263.5	218.9	27.4	93.1
Graphite	-	0.9	7.0	2.0	8.0	7.9	6.1	13.9	12.2	1.5	5.2

In addition, numerous other, potentially exploitable, graphite occurrences are known: Kosharo-Oleksandrivske, Pivdenno-Khashchuvatske, Dubynivske in Pobuzkiy area; Babenkivske, Lozovatske, Ovnyanske – in Kryvorizkiy area; Temryutske, Karatyukhske, Sachkynske – in Pryazovskiy area; Makharynetske, Dubovetske in Volynskiy area).

The Zavallivske deposit in the Kirovograd region is confined to Archaean biotite-graphite gneisses of the Kashchuvato-Zavallivska Suite, which constitutes the limbs of a large synclinal fold of the north-western to west-north-western direction (Fig. 5.6). About 40 layered ore bodies of variable length, 200 m to 1200 m, and thickness, 3.5 m to 80 m, are distinguished. Graphite in the ores is coarse-grained (2-4 mm), evenly distributed, and its content is 6-14% (average 6.5%). Total reserves of graphite ore are estimated at 95.3 Mt, and graphite – 5.8 Mt.

The deposit is developed by the open-cast mining method. Zavallivskiy Plant with an annual capacity of 800 kt of graphite ore or 35 kt of graphite concentrate was built nearby. In the early 1990s, output exceeded 40 kt, then began to decline sharply and is now at the level of 4-8 kt of graphite concentrate per year.

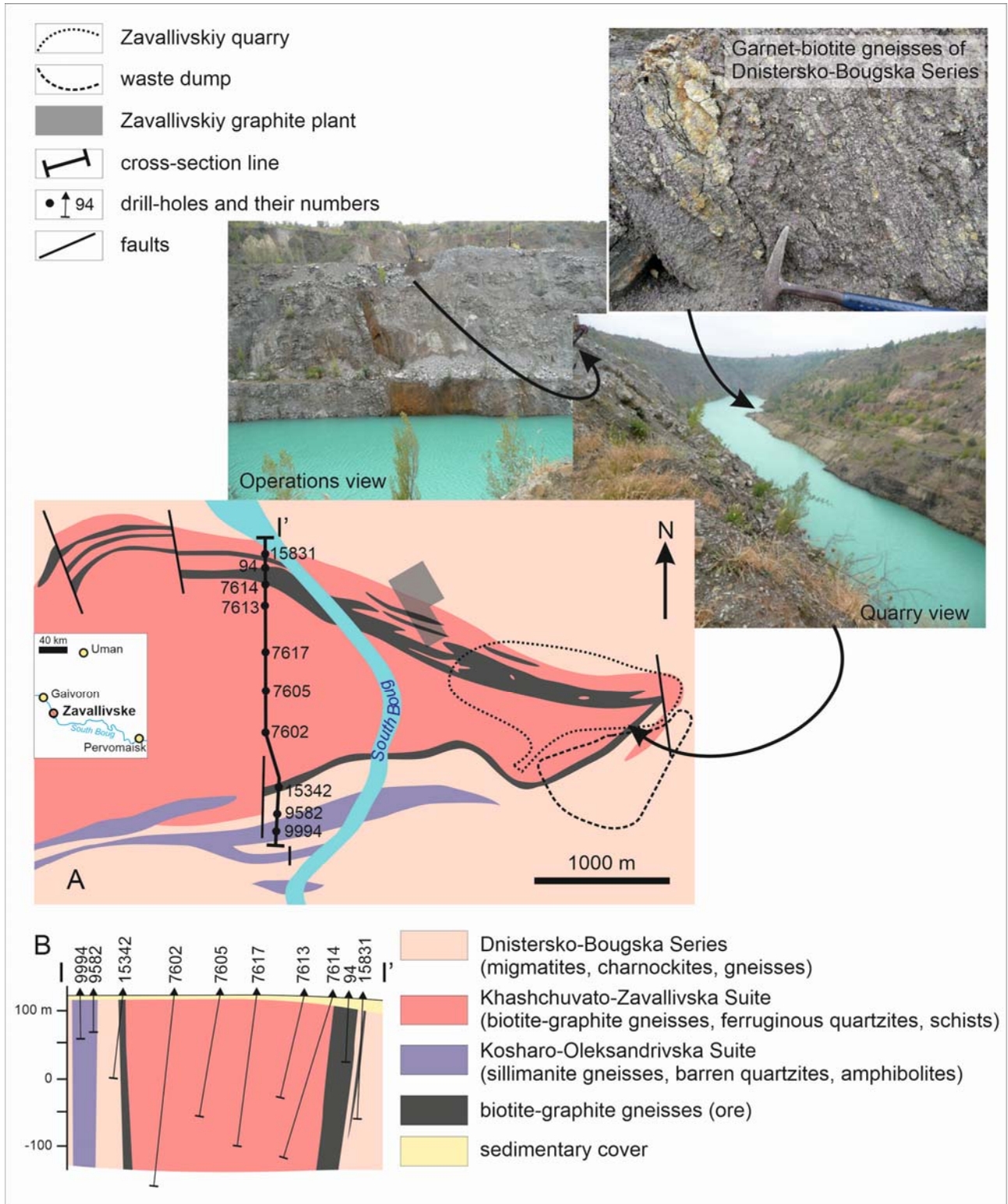


Fig. 5.6 . Geological map (A), cross-section(B) and images of the Zavallivske graphite deposit (modified after Mykhailov et al. 2008a)

The capacity of both the quarry and the plant allows it to sharply increase the production of graphite concentrate, which meets the requirements of instructional documents (Ukrainian Standard 7478-57, Table 5.16) for raw materials for the production of galvanic cells and alkaline batteries. The coarse-grained graphite obtained by ore flotation of deposits is used in production of active masses of alkaline batteries. Requirements for graphite are regulated by Ukrainian Standard 18-53 (see Table 5.16).

Table 5.16. Requirements of Ukrainian Standards for graphite concentrate and graphite

Parameters	Standard 7478-57	Standard 18-53
	Graphite concentrate	Graphite
Ash, %	10-14	up to 2
Humidity, %	up to 1	1
Volatile substances yield, %	up to 1	n.a.
Copper, %	up to 0.05	n.a.
Impurities of cobalt, nickel, lead, arsenic	traces	n.a.
Residue on the sieve 0.15 mm, %	n.a.	up to 15
Residue on the sieve 0.063 mm, %	n.a.	up to 30-50
Contaminants	n.a.	not allowed

The Petrivske deposit in the Kirovograd region is represented by a graphite-bearing pile some 1.2-1.3 km long and 200-250 m wide developed at the contact of crystalline limestones and gneisses of Rodionivska Suite, of the Archean-Paleoproterozoic Ingulo-Inguletska Series, cut by veins of the Inguletskiy Granite Complexes. Ore bodies with a thickness of 7-50 m, are composed of graphite gneisses that contain mostly fine-grained graphite (from 0.001 to 2-5 mm in size), varying in amount from 2-15% (average 7.18%). In the upper part of the column the ores are altered into loose, poorly consolidated, kaolinized clays with graphite lenses and veinlets (1.3-6.0%).

The Balakhivske deposit in the Kirovograd region is represented by a layer up to 600 m thick found in gneisses of the Rodionivska Suite. There are 5 ore bodies present with a thickness of 10 to 300 m, and varying in length from 400 to 2890 m, traced to a depth of 300 m. The SIMR has approved ore reserves for categories B+C₁ in the amount of 23,936 kt, category C₂ – 18,469 kt; and graphite of 1,013 kt (B+C₁) and 820 kt (C₂). Special permit for subsurface use (graphite ore mining) № 6345 of June 13, 2019 (Southern site) was granted to “Pobuzhzhya Development” LLC for a period of 20 years.

The Burtynske deposit of the Khmelnytskyi region is located in the zone of graphite-bearing gneisses that are up to 18 km long; an ore body is up to 49 m thick, and has an average graphite content of 6.7%. The ore is easily beneficiated, the concentrate yield with crystalline graphite is 90-95%. The deposit can be developed by open-cast mining method. The reserves of graphite ore in deposit are estimated at 187,728.2 kt, graphite – 10,683.1 kt (including 113,390.9 kt of ore, and 6,584.7 kt of graphite in category A+B+C₁, and 64,964.7 kt of ore and 3,822.7 kt of graphite in category C₂).

With an object of licensing, proposals are currently open for the ***Khmelivska site*** of Burtynske deposit with an area of 143.3 hectares. In total, 9 sites were discovered and prospected in the deposit area, of these the most promising was Burtynska site with prognostic resources of graphite ore 423.2 Mt, graphite – 25 Mt, and other promising 4 sites (Gorodnyavska, Matroska, Khmelivska, Lisova), while the total reserves and resources of graphite ore by categories C_2 and P_1 were determined at 350 Mt (Investment Atlas of Subsurface User 2021).

The ore sequence is located on the northeastern limb of the Shepetivska Anticline belonging to the Volyn megablock of the Ukrainian Shield, and is composed of Lower Precambrian graphite-biotite gneisses and migmatites. The following zones are distinguished (top-down):

- complete kaolinization – primary (structural) kaolins 1.5-30 m thick (average 10 m), where loose graphite ores are observed;
- partial kaolinization, disintegration and increased fracturing with a thickness of 10-75 m (average 50 m), where semi-porous, strongly fractured graphite ores are developed;
- unaltered graphite-biotite gneisses and migmatites with massive ores.

Mineral composition of ores is as follows: graphite, feldspar, quartz, biotite, sericite, kaolinite, nontronite, montmorillonite, chlorite, hydromica, iron hydroxides; accessory – sulfides, apatite, garnet, ilmenite, zircon, monazite. Graphite is represented by fine dissemination, scaly aggregates and interbeds along host rock gneissosity. Graphite is evenly distributed, although sometimes enriched layers and bunches are found. The content of graphite ranges from 4.4 to 11.9%, the average content is 5.76%. Reserves were not yet calculated for this site (Investment Atlas of Subsurface User 2021).

The Troitske deposit is confined to the band of graphite gneisses of the Temtyutska Suite, which stretches for 25 km along the western limb of Berestovetska Syncline. The layers of graphite gneisses form two ore zones with a thickness of 10 to 300 m, which extend for 3.5 km. In the ore batches with a thickness of 5-140 m, are heterogeneous in composition, and graphite content varies from 2 to 17%.

The Mariupolske deposit is composed of Archean graphite-bearing gneisses intercalating with amphibolites, quartzites and carbonate rocks, cut by sub-alkaline granitoids and syenites of the Paleoproterozoic Pivdennokalchytskyi Complex. The ore-bearing zone is traced for 950 m with a width of up to 250 m. It includes 6 ore bodies, three of which may be of industrial importance. The average graphite content is 3.92%.

In terms of graphite resources, scale of deposits and quality of raw materials, Ukraine is able to meet the needs of European graphite industry for "green technologies" at the stage of industrial operation of the known deposits. Currently, the greatest investment interest corresponds to the Khmelivska site of the Burtynske deposit, where license proposals are open.

5.2.2. Potassium Salts

These are used primarily as mineral fertilizers, but also used in the chemical industry.

World reserves of potassium salts exceed 3.2 billion tons, they are found in many countries (Canada, Russia, Belarus, etc.), where the salts are intensively extracted. World production is 40-43 Mt per year (Table 5.17).

Table 5.17. World mineral production and reserves of potassium salts (World Mining Data 2021; USGS 2020)

Country	Extraction K ₂ O, kt					Reserves, K ₂ O, Mt
	2015	2016	2017	2018	2019	
Canada	11,461.5	10,789.7	12,562.7	14,023.9	12,643.3	1,000
Russia	6,840.0	6,480.0	7,300.0	7,055.0	7,368.0	600
Belarus	6,467.9	6,180.1	7 101.8	7,346.1	7,348.3	750
China	5,714.0	5,783.0	5,534.0	5,452.0	5,902.0	350
Germany	3,109.9	2,750.8	2,963.6	2,754.1	2,615.3	150
Israel	1,297.0	2,093.1	2,126.7	2,149.3	1,852.9	Big
Jordan	1,436.6	1,222.1	1,415.3	1,486.0	1,516.5	Big
Chile	1,179.6	1,303.8	1,238.6	991.2	683.5	100
Spain	668.0	672.2	557.5	635.5	600.1	68
USA	740.0	510.0	480.0	520.0	510.0	220
Other countries	1,323.6	1,091.5	1011.5	976.1	689.4	
Total	40 238.1	38 876.3	42 291.7	43,389.2	41,729.3	>3,200

In Ukraine, potassium salts are developed mainly in Fore-Carpathian Trough, specifically in Fore-Carpathian potassium-bearing basin, where they are confined to Kaluski layers of the Neogene Stebnytska and Vorotyshchenska Suites. They form sheeted and lenticular bodies with a variable thickness of 3-120 m, developed at depths of 600-700 m. By chemical composition, chloride or sulphate-free salts are composed of sylvinite and carnallite; sulphuric-acid or sulphate salts are dominated by kainite, langbeinite, polyhalite, schoenite; mixed sulphuric-acid – chloride salts are also distinguished. The content of K₂O varies from 9 to 21%.

The SIMR records reserves of 13 deposits, where 3,627.4 Mt of ore and 411.0 Mt of K₂O are estimated by categories A+B+C₁+C₂. These reserves however are considered unreliable because they are obsolete, most were approved in 1948-1960, often without detailed exploration, and some based on pre-WWII materials of Polish geologists, without taking into account changes in hydrogeological, ecological and other conditions (Mineral Resources of Ukraine 2021). Therefore, they need to be re-evaluated. Until 2007, salt extraction was carried out at Kalush-Golynske deposits in the Ivano-Frankivsk region (OJSC “Oriana”) and Stebnytske deposits in the Lviv region (State Mining-Chemical Enterprise “Polymineral”), but since then the deposits have not been developed.

The Stebnytske deposit of potassium salts in the Lviv region was discovered in 1834 and has been developed and mined since 1922 (Fig. 5.7).

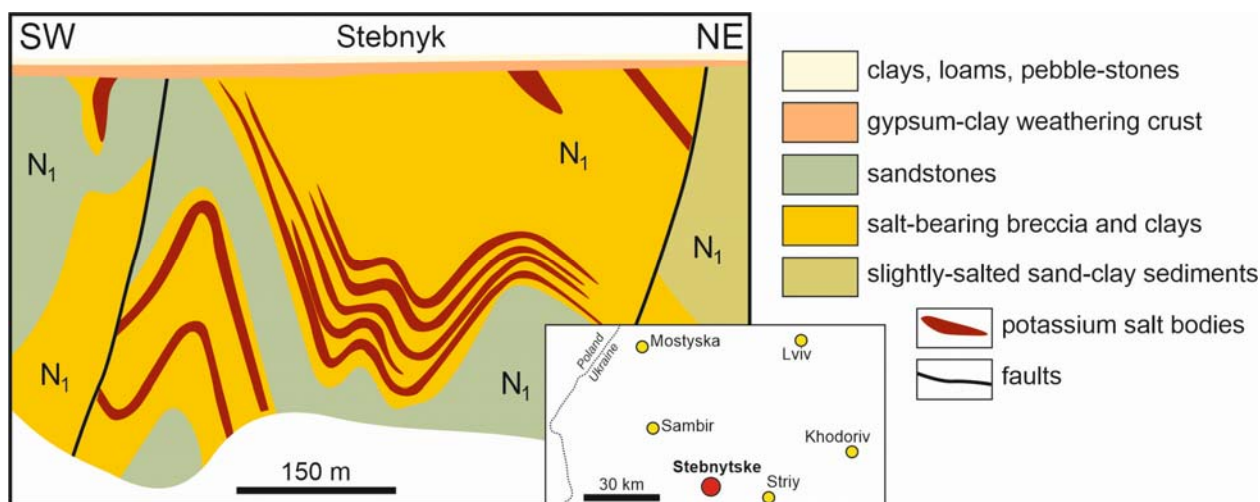


Fig. 5.7. Cross-section of the Stebnytske potassium salt deposit (modified after Mykhailov et al. 2008a)

The thickest body is the second horizon, consisting of six main beds. Rock-forming minerals are halite, kainite, langbeinite, sylvine, impurities include polyhalite and kieserite; secondary minerals include anhydrite, shoenite, gypsum, epsomite and carnallite. Kainite, langbeinite and sylvine can form crystalline mixtures with halite. Kainite occurs in the form of fine-grained aggregates, parallel-fibrous and radial-fibrous formations. The Stebnytskiy Potash Plant, which produced potassium magnesium, used to operate on the basis of the deposit. However, due to a number of environmental problems, salt production was suspended. The reserves of crude salt at the deposit are amounted to 1,519.1 Mt (including 1278.1 Mt by category A+B+C₁).

The Kalush-Golynske deposit is represented by potassium salts' bodies in Miocene Golynska (Upper Stebnytska) Suite (Fig. 5.8). Sylvinite horizons are located in salt-bearing rocks and are composed of banded red, pink and white sylvine with admixtures of anhydrite, polyhalite and carnallite. Kainite bodies consist of thin kainite, kainite-halite, halite and polyhalite-clay beds. In the Golynska Syncline, the number of potassium-bearing horizons is greater. By mineral composition, they are divided into carnallite, kainite, sylvinite and langbeinite-kainite horizons with admixtures of halite, polyhalite, kieserite. The Kaluskiy Chemical and Metallurgical Plant used to operate on the basis of the deposit, producing mineral fertilizers in the form of potassium chloride (KCl), potassium sulphate (K₂SO₄), potassium-magnesium sulphate (K₂SO₄+MgSO₄), polyhalite residue, magnesium chloride (MgCl₂×2H₂O), sodium sulfate (Na₂SO₄), and as a by-product – rock and technical salt. Reserves of ore deposits are amounted to 448.2 Mt (including 442.6 Mt by categories A+B+C₁).

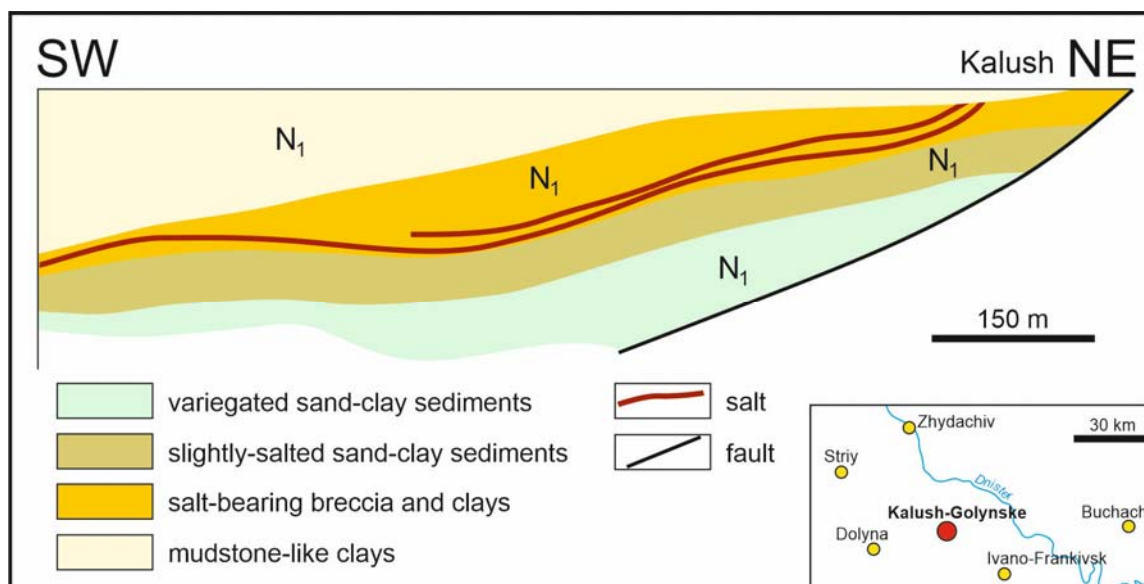


Fig. 5.8. Cross-section of the Kalush-Golynske deposit (modified after Mykhailov et al. 2008a)

In addition to above, a number of other potassium salt deposits are known in the Fore-Carpathians, namely: Boryslavske, Dobrogostivske, Pomyarky, Ulychne, Nyniv, Dregolukske, Girke, Rosylnyanske, Starunske, Markivske, Molodkivske, Kadobna, Trostyanetske, Tura Velyka, Morshynske, but they are not ready for development.

In DDD, occurrences of potassium salt were detected in 16 salt domes, but only in Romenskiy dome was economic potassium content (KCl up to 39%) detected at a relatively shallow depth (300-500 m), the rest of occurrences are at a depth of 1.5-2 km. This allows us to consider DDD as a promising region for the search for deposits of potassium salts.

In the Donetskiy Basin, two potassium-bearing zones were encountered in salt-bearing sediments of the Lower Permian Kramatorska Suite in the Bakhmutska and Kalmius-Toretska Depressions: the upper zone is sylvinite-carnallite, up to 60 m thick and the lower one is sylvinite (70-100 m). Potassium salts are represented by carnallite, sylvinite, polyhalite and langbeinite, they occur in the form of interbeds and individual layers, as inclusions in the solid mass of rock salt. The beds are of small thickness, 0.3-4.8 m, but are characterized by a high content of KCl in sylvinite (21.3%). Depth of occurrence is 600-1000 m. Prognostic reserves are estimated at 1 billion tons.

5.2.3. Abrasive Raw Materials (Garnet)

Due to its significant hardness (6-7 on the Mohs scale, microhardness 920-1560 kg/mm²), garnets are used as an abrasive material, as well as in construction as an additive to cement and building materials.

World production of garnet raw materials is about 1,200 kt, most of which is produced by Australia (a third of world production), China, South Africa, India, and the United States (Table 5.18).

Table 5.18. World garnet mining production and reserves (USGS 2020)

Country	Production, kt		Reserves, kt
	2018	2019	
Australia	360	400	Big
China	290	310	Big
South Africa	278	190	n.a.
India	162	150	13,000
USA	101	93	5,000
Other countries	60	60	6,500
Total	1,251	1,203	>24,500

Ukraine has a strong base of abrasive garnet, two types of garnet deposits and occurrences are known: igneous and metamorphic. The first type is associated with Archean-Proterozoic granites, represented by the Slobidske and Loznenske deposits, and the Zhigalivske, Mykolaiskiy, Guliivskiy and other occurrences of the Volynska area; the second type is known in the Precambrian schist-gneiss units of the Pobuzka (Zavallivske deposit, Shamraivskiy, Bogdanivskiy, Lozovatskiy occurrences); Pryazovska (Dragunskiy, Bilotserkiivskiy, Verkhnyotokmatskiy occurrences) and Kryvorizka (Zhovtyanskiy occurrence) areas (Fig. 5.9)

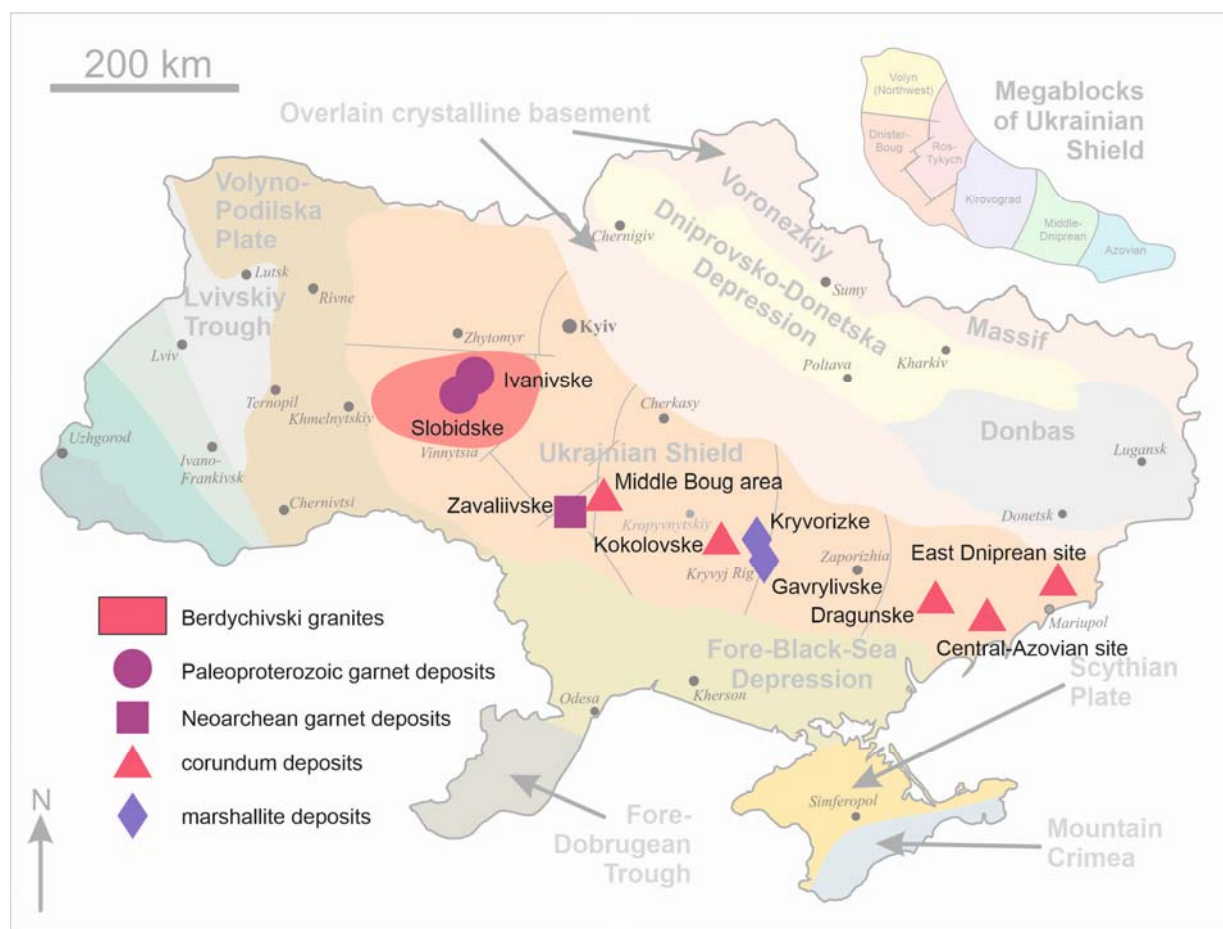


Fig. 5.9 . Distribution of deposits and occurrences of associated abrasive raw materials (modified after Mykhailov et al. 2008a)

Table 5.19. Mineral composition of biotite-garnet granites of the Berdychivskiy Complex in Slobidske deposit

Mineral	Contents, wt. %
Feldspars	45-55
Quartz	20-30
Biotite	5-10
Garnet	10-20
Cordierite	7-10
Ilmenite, magnetite, pyrite	minor

dominated by quartz and feldspar. The thickness of weathering crust over crystalline rocks – kaolinized gruss (0-2.7 m) and Quaternary loams (0-9.5 m) – averages 3.1 m.

The ores are represented by two types: massive biotite-garnet granites and products of their weathering. The deposit was explored to a depth of 13.7 to 29.1 m, the average thickness of weathered ores is 3.5 m, massive – 18.2 m. The garnet content varies from 14.5 to 16.0%, an average of 15.2%. Its composition is quite homogeneous (Table 5.20), and garnet microhardness is 1400-1560 kg/mm². The total abrasive ability by monocorundum is 45-52%, the initial 81-87%. In terms of microhardness, abrasiveness, mechanical strength, heat resistance, garnet deposits can be used for polishing of products made of wood, leather, rubber, fine polishing of glass and finishing of soft metal wares. The accompanying mineral is quartz feldspar used as raw materials for the glass industry, suitable for the manufacture of sheet glass (1st and 2nd grades). Reserves of abrasive garnet are amounted to 801.0 kt (including 673 kt by categories A+B+C₁); quartz feldspar raw materials amount to 2,053 kt.

The Ivanivske deposit located in the Vinnytsia region is composed of similar biotite-garnet granites. Garnet of both deposits is identical in physical and mechanical properties. Ivanivske deposit used to be operated by OJSC “Ivanivskiy Spetskaryer”, which produced crushed stone for road construction. During granite processing into rubble, up to 19-26% (with its content in the initial ore of 15-20%) enriched in garnet sieve fraction of less than 5 mm was formed. From every 100 thousand m³ of rock mass in the process of enrichment 25-30 thousand m³ of screening was obtained, which contained 7-8 kt of garnet. From this screening it was also possible to obtain quartz-feldspar concentrates for the glass industry in the amount of at least 16-18 kt. The garnet of Ivanivske deposit can be used for the abrasive industry.

The Zavallivske deposit is composed of biotite-graphite and biotite-garnet gneisses and quartzites. There are two ore zones of graphite- and garnet-bearing gneisses (northern and southern) up to 3.7 km long, and 150-390 m thick. They consist of rhythmically-layered quartzites, biotite-graphite and biotite-garnet gneisses, garnet-quartz gneisses and calciphyres, which occur in the form of layered or lenticular bodies with swells, pinches and branches. The strike of the sequence is 290-300°,

The Slobidske deposit in the Vinnytsia region is composed of biotite-garnet granites of the Berdychivskiy Complex. These are grey and light-grey medium-grained rocks, their mineral composition is given in Table 5.19. Migmatized varieties display banded structure with alternating dark bands (1-2 cm), enriched with biotite and garnet, and light ones,

Table 5.20. Composition of garnet in Slobidske deposit

Variety	Contents, wt. %
Almandine	61
Pyrope	31
Grossular	7
Spessartin	1

dipping subvertically (80-90°). Garnet-biotite gneisses occur in the form of bands, lenses, up to 1 km long, and 1-2 to 100 m thick, often of complex configuration. The garnet content in productive pile is 6-31%, on average – 15%. In the primary kaolin of weathering crust, garnet is completely destroyed and replaced by iron hydroxides. In the zone of gress-clay rocks, it is highly-fractured, often easily rubbed and broken with your fingers. In weakly weathered garnet-biotite gneisses, the garnet (almandine) is practically unchanged, represented by grains 0.1-1.0 mm in size, and their clusters (see Fig.5.6, top-right image). By physical and mechanical properties garnets are similar to those of Slobidske deposit; garnet concentrate meets the requirements for concentrates for the production of polishing powders for leather and glass. The reserves of garnet-biotite gneisses are amounted to 18.5 Mt, garnet – 3.1 Mt. Deposit is developed by PJSC “Zavallivskiy Graphite Plant”.

Table 5.21. Mineral composition of biotite-garnet granites in Loznenske deposit

Mineral	Contents, wt. %
Quartz	25-35
Plagioclase	30-50
Potassium feldspar	5-20
Garnet	10-15
Biotite	5-10

exceed 5-7 mm, more often 2-4 mm. Granite rock-forming minerals are listed in Table 5.21; accessory minerals include zircon, sphene, monazite and ore minerals (pyrrhotite, magnetite, occasionally ilmenite).

Garnet is pink, sometimes red, glassy, with an uneven breakage, rounded, sometimes rhombodecahedral shape and fractured rough surface. It is composed of a mixture of minerals listed in Table 5.22. The content of garnet in the rock ranges from 9.2 to 17.4%, on average – 12.1%, and garnet resources are estimated at 7.6 Mt.

The Loznenske deposit in the Vinnytsia region is represented by an arch-like body of biotite-garnet granites, elongated in the north-eastern direction for 700 m and a width of 550 m. These are grey medium-coarse-grained dense rocks with the point- and spot-like inclusions of garnets, whose size does not

Table 5.22. Composition of garnet in Loznenske deposit

Variety	Contents, wt. %
Almandine	66-68
Pyrope	28-30
Spessartin	1
Andradite	2-3
Grossular	up to 1

5.2.4. Quartz Raw Materials

These are used for the production of glass, ceramic and refractory wares, ferrosilicon, and silicon metal. Quartz raw materials include quartz sands, rhyolites, and vein quartz with a SiO₂ content of at least 95%.

Annual world production of silica is estimated at 120-150 Mt, the United States produces the most (25-30 Mt); followed by Germany, France, Australia and Spain (5-10 Mt each); Great Britain, the Netherlands, Brazil, Italy, Belgium, Canada, South Africa, Australia (2-5 Mt each), plus China, and the FSU countries.

In Ukraine, quartz raw materials are represented by deposits of quartz sands, that occur in the form of lenses and layers from 2-40 m thick, which are known in the

DDD and Donbas regions in Oligocene Berekska Suite sediments; in the VPP in Neogene sediments, and in the Ukrainian Shield – in continental Quaternary sediments. In addition, a deposit of rhyolites is known in Trans-Carpathians, and in the Ukrainian Shield and Donbas with occurrences of vein quartz (Fig. 5.10).

The SIMR records 42 quartz sand deposits (of which 14 are being developed) with total reserves of 329.9 Mt by categories A+B+C₁+C₂ and one Ardivske rhyolite hosted deposit with reserves of 20.7 Mt by categories A+B+C₁. In 2020, the production of quartz sands amounted to 1,421.7 kt (Mineral Resources of Ukraine 2021).

Quartz sands are one of the main types of quartz raw materials. They are associated mainly with the three epochs of weathering crust development: Paleogene, Oligocene-Miocene and Pliocene-Quaternary. The most important deposits are Gusarivske, Avdiivske, Novoselivske and Berestovenkivske in Kharkiv; Velykoglibovyske and Voloshynske in Lviv; Novomykhaylivske in Donetsk; and Papirnyanske in the Chernihiv regions.

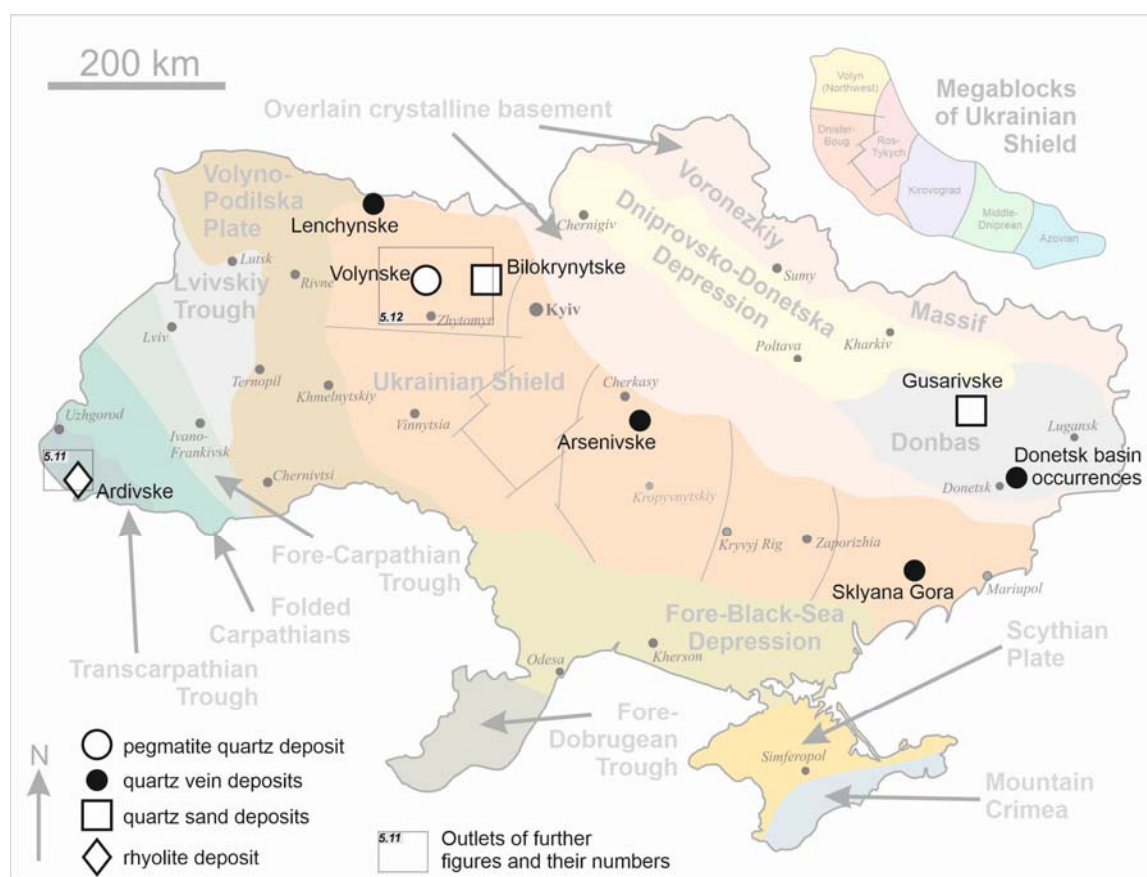


Fig. 5.10. Distribution of quartz deposits
(modified after Mykhailov et al. 2008a)

The Gusarivske deposit in the Kharkiv region has been developed since 1933. The deposit is complex; the sands are suitable for the production of silicon carbide (quartz raw material) and for use as foundry sands.

The productive sequence of the Paleogene Buchatska Suite is represented by coarse-grained, quartz, slightly clayey sands, which form a relatively homogeneous,

subhorizontal body up to 3 km long and 5.0 to 24.5 m thick. Overburden rocks (fine-grained glauconite-quartz sands of Kharkivska Series) vary in thickness from 6.3 m to 52.8 m (average 20.9 m).

Reserves of quartz sand are 56.1 Mt by categories A+B+C₁, and 42.5 Mt by category C₂.

For the Western section of the deposit, reserves are approved by the State Commission of Ukraine on Mineral Reserves with the protocol № 4292 of 14.02.2018 as: foundry sands – 47,907 kt by categories A+B+C₁, and 12,620 kt by category C₂; abrasive raw materials – 30,300.79 kt by categories A+B+C₁; brick and tile raw materials – 625 thousand m³ by categories B+C₁.

Deposit is being worked out by OJSC “Gusarivskiy MBP”, special permit for subsurface use № 776 issued on 12.02.1997 (Western area, extraction of foundry sands) extended by order № 183 of 23.02.2021 till 08.02.2037.

The Avdiivske deposit of quartz sands in the Donetsk region is represented by quartz uniform-fine-grained sands of the Poltavaska Suite, covered with Quaternary loams and clays (2.5-21.0 m thick). The rocks are banded, spotted in places; color is light or white with a yellowish shade. Five sand layers are distinguished, of which 2, 3 and 4 are raw materials for the glass industry. The quartz content in these layers reaches 97-99.5%. Particle size distribution and chemical composition of quartz are given in Table 5.23. The bulk of the sand consists of colorless angular and angular-rolled quartz grains. Single flakes of muscovite, grains of potassium feldspar, carbonates, and chalcedony are also noted. The leading assemblage for the heavy fraction is sillimanite-kyanite (up to 40-50%), with lesser amounts of rutile, zircon, tourmaline, staurolite, andalusite, tremolite, and chlorite. Sands are well beneficiated by flotation and washing with further classification.

Table 5.23. Particle size distribution and chemical composition of quartz in Avdiivske deposit

Fraction, mm	Contents, %	Oxide	Contents, wt. %
> 0.5	0-0.46	SiO ₂	97.28
0.5-0.25	0.1-9.7	TiO ₂	minor
0.25-0.1	90.20-99.46	Al ₂ O ₃	1.66
<0.1	0.01-10.58	Fe ₂ O ₃	up to 0.2-0.3
		MnO	minor
		MgO	0.06
		CaO	0.18

The Velykoglibovyske deposit in the Lviv region is composed of Miocene Tortonian fine-grained quartz sands, light-grey with yellowish and greenish interbeds, which lie on the Upper Cretaceous marls and are covered with lithotamnium limestones and Quaternary loams. The length of sand layers is 800-1500 m (average 1040 m), width is 350-800 m (average 500 m), thickness is 3.1-13.1 m (average 9.7 m), and overburden thickness is 3.0-15.2 m (average – 9.28 m). Composition of sands and particle size distribution of quartz are shown in Table 5.24. The bulk density of the sands is 1.66 g/cm³, the loosening coefficient is 1.30, and the natural humidity is 2.3-3.6%. The sands of this deposit, even without beneficiation, are suitable for the

production of window glass, they are easily beneficiated by flotation and can also be used as foundry and construction sands. Reserves of quartz sands estimated by 01.01.2021 amounted to 7975.7 kt by category A+B+C₁.

Table 5.24. Mineral and chemical composition of quartz sands and particle size distribution of quartz in Velykoglibovyske deposit

Quartz sands				Quartz	
Mineral	Contents, wt. %	Oxide	Contents, wt. %	Fraction, mm	Contents, %
Quartz	96.05-99.7	SiO ₂	94.98-99.66	> 0.5	2.75-4.0
Carbonates	up to 1.6	TiO ₂	0.02-0.17	0.5-0.25	41.73-49.15
Feldspars	up to 1	Al ₂ O ₃	0.1-0.28	0.25-0.1	44.07-51.88
Glauconite	0.2	Fe ₂ O ₃	0.03-0.2	<0.1	2.67-3.63
		MgO	0.01-0.44		
		CaO	0.01-2.19		
		Na ₂ O+K ₂ O	0.04-0.24		

Deposit is developed by “Lviv Mekhsklozavod Trading and Mining Company” LLC, a special permit for mining, № 903, was issued on 30.05.1997, and then extended until 30.05.2037.

In addition to quartz sand, the rhyolites known in the Berehivske Hills of the Trans-Carpathians can be used as quartz raw materials.

The Ardivske deposit in the Trans-Carpathian region has been explored (Fig. 5.11); it is composed of Miocene Tortonian and Sarmatian rhyolites and perlites confined to the volcanic dome of the Ardivskiy paleo-volcano. The bulk density of expanded perlite "sand" is 150-180 kg/m³ in average. The deposit can be developed by open-cast method. In addition to perlite rocks, the clays suitable for the production of bricks, tiles, hollow stones, and blocks were studied at the deposit. The reserves of the deposit (protocol of the State Commission on Mineral Reserves of the USSR dated 05.10.1961 № 3462) are 9,336 thousand m³ by categories A+B+C₁. The deposit is not being developed.

Another source of quartz raw materials may be vein quartz, whose occurrences are known in the Ukrainian Shield and Donbas.

The Volynske chamber pegmatite deposit in the Zhytomyr region (to be described below) is one of the most important sources of quartz raw materials.

Occurrences of quartz are known in the Azovian (Sklyana Gora), Ingulskiy (Arsenivskiy), Middle Dniprean (Apostolivskiy) megablocks of the Ukrainian Shield, and in Donbas.

The Sklyana Gora occurrence is a large quartz vein 500 m long and 50 m thick. Quartz is light-grey, slightly transparent, massive, contains inclusions of feldspar, tourmaline, muscovite. Prognostic resources of quartz are though to be the first millions of tons.

The Arsenivskiy occurrence is represented by a large quartz body in granites of Korsun-Novomyrgorodskiy Pluton with a length of 700 m with prognostic resources of 2100 kt.

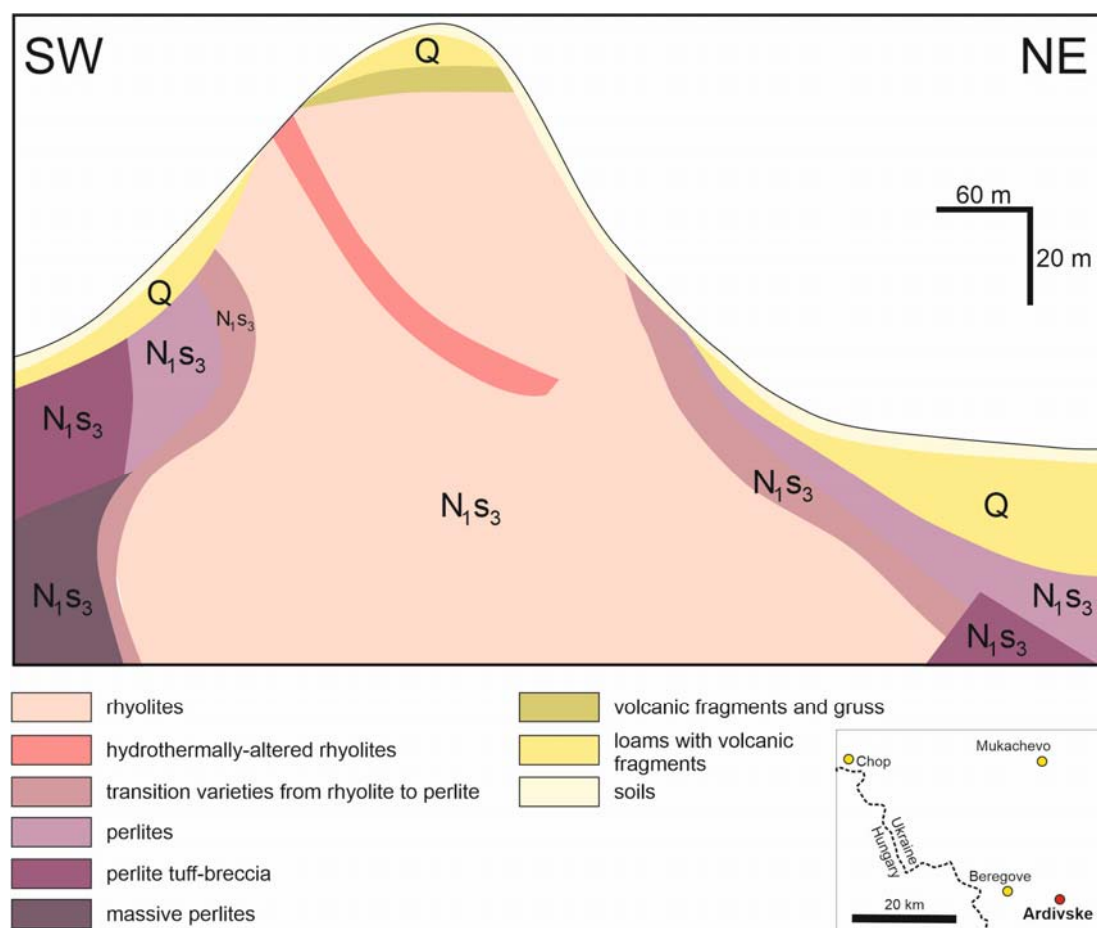


Fig. 5.11. Cross-section of the Ardivske deposit (modified after Gurskiy et al. 2006b)

5.2.5. Piezooptical Raw Materials (Piezoquartz)

Piezoelectric crystals as electromechanical transducers are widely used in radio engineering, electro- and ultraacoustics, piezometry and in many other fields of science and technology that require the transformation of electrical processes into mechanical and vice versa.

The SIMR records the Volynske deposit in Zhytomyr region, where the mineral is represented by piezoquartz, rock crystal for smelting, quartz for cutting, morion, topaz, which are used in the jewelry and piezooptical industries. PJSC "Quartzsamotsvity" received a special permit for geological study with research and development of the Northern part of the Volynske deposit (Mineral Resources of Ukraine 2021).

The Volynske chamber pegmatite deposit in the Zhytomyr region is located in Paleoproterozoic gabbro-anorthosites and rapakivi granites of the Korostenskiy Pluton (Vasylyshyn et al. 1996; Yakovleva, Kamenchuk 2004). Pegmatites of the chamber type are confined to the western endocontact of granites with rocks of mafic composition and form a zone 22 km long and 0.3-1.5 km wide. They are associated with rapakivi-like Leznykivski granites. Their structure is clearly zonal, the following zones are distinguished from periphery to the center: graphic pegmatites, pegmatoid

pegmatites with feldspar, grey quartz, and free growth of crystals (cavity zone) (Fig. 5.12).

The bulk of quartz crystals are confined to the cavity zone, where they occur in a loose or dense aggregate composed of individual crystals, their intergrowths, quartz and feldspar fragments, cemented with opal, chalcedony, quartz, clay. The sizes of the crystals are different. Along with small individual grains, giant crystals weighing 10 tons and more, up to 2-3 m in size occur. Most crystals have a zonal or zonal-sectoral structure.

The quartz core is located in the central part of pegmatite above the cavity zone. Its shape is lenticular, with a thickness of 1-2 to 10-15 m. The cavity zone up to 5 m in size and 30-40 m³ by volume is developed below. The large, beautifully faceted crystals of quartz, topaz, beryl are formed in the cavity zone. Main minerals include quartz, feldspar, mica, with secondary minerals topaz, beryl, opal, chalcedony, fluorite, siderite, hydromica, chlorite, phenakite, rare – pyrite, ilmenite, zircon, rutile, amethyst, tourmaline, monazite, etc. (up to 96 minerals counted in total).

The deposit was intensively developed in the last century and served as the main source of piezoquartz raw materials of the Soviet Union. Information on piezoquartz reserves is confidential.

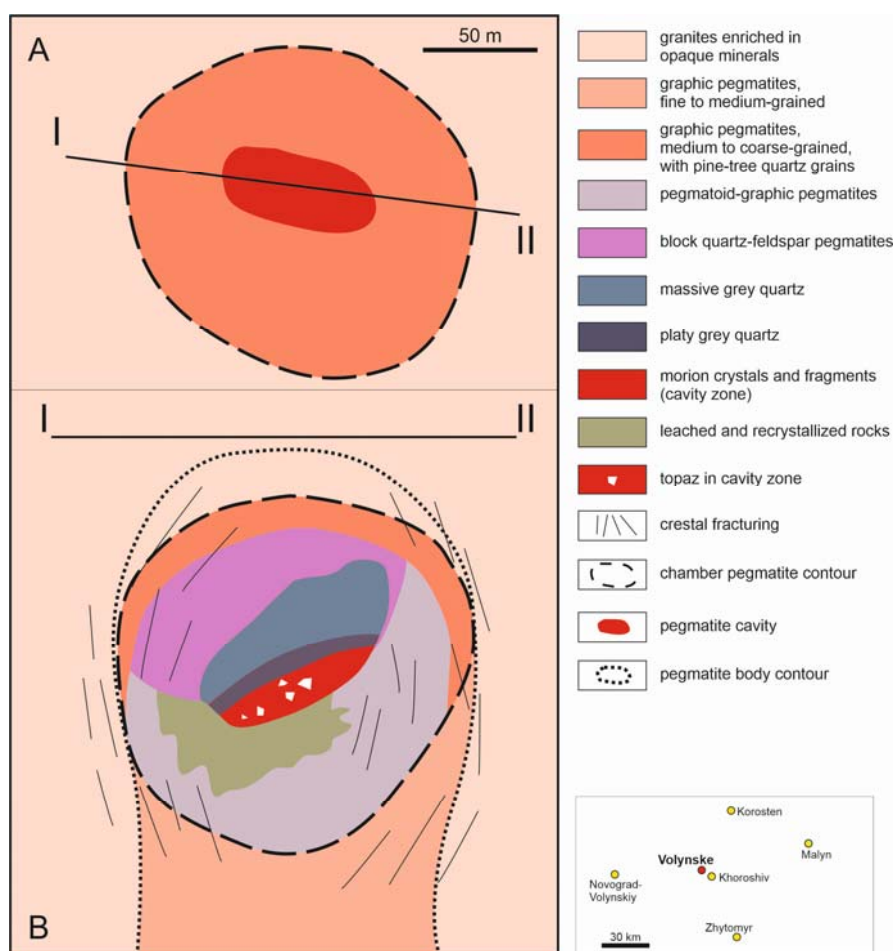


Fig. 5.12. Plan view (A) and internal structure (B) of the pegmatite chamber of the Volynske deposit (modified after Vasylyshyn et al. 1996)

5.3. Promising Types of Raw Materials

The following types of non-metallic minerals that are of strategic importance for the economy of Ukraine are considered to be promising: phosphorites, apatite, fluorspar, glauconite, limestones for the sugar industry, flux limestones and dolomites, bentonite clays, feldspar raw materials, gemstone raw materials.

5.3.1. Phosphorites

They are used for the production of phosphate fertilizers, phosphorus and various compounds in the chemical, sugar, food and other industries.

World reserves of phosphates reach 69.2 billion tons, which are concentrated mainly in Morocco (over 70% of world reserves), as well as in China, Brazil, Saudi Arabia, USA) and others. World phosphate production in recent years is declining from 83 Mt in 2015 to 71 Mt in 2019. The main extractive countries are China, Morocco, USA, Russia, etc., in recent years phosphate production has grown in Morocco and Vietnam, but decreased in China (Table 5.25).

Table 5.25. World phosphate mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, P ₂ O ₅ , kt					Reserves, ore, Mt
	2015	2016	2017	2018	2019	
China	42,611.7	43,319.4	36,939.6	28,897.8	27,997.2	3,200
Morocco	8,388.7	8,601.0	10,490.1	10,960.2	11,267.5	50,000
USA	7,710.0	7,615.0	7,840.0	7,250.0	6,547.0	1,000
Russia	4,485.0	4,797.0	5,148.0	5,304.0	5,382.0	600
Peru	4,241.4	4 013.2	3,211.1	3,917.1	4,214.8	210
Jordan	2,667.5	2,557.2	2,780.0	2,567.2	2,951.5	1,000
Brazil	2,167.0	2,046.0	2,083.0	1,980.3	1,828.5	1,700
Saudi Arabia	1,530.0	1,620.0	1,701.0	1,633.2	1,714.8	1,400
Vietnam	877.0	942.8	1,376.4	1,299.7	1,395.5	30
Tunisia	936.2	1,062.4	1,145.3	812.8	1,124.7	100
Other countries	7,273.7	7,312.8	6,978.8	6,880.7	6,682.1	9,949
Total	82,888.2	83,886.8	79 693.3	71,503.0	71,105.6	69,189

In Ukraine, phosphorite mineralization is developed in the form of nodules, concretions, pebbles in layers 0.5 to 10-15 m thick that occur in Cretaceous, Paleogene and Neogene marls, mudstones, chalk sands in VPP, DDD, northeastern margin of the Ukrainian Shield and southwest margin of the Voronezhkiy Massif, in the Indolo-Kubanska Depression. The content of P₂O₅ in ores is 4-26%. The most promising are granular, yellow-granular (P₂O₅ 4.0-7.6%) and concretionary phosphorites (34-38%) of VPP, as well as phosphate-containing brown iron ores of the Kerch Peninsula (P₂O₅ 0.3-1.44%).

The SIMR records 5 deposits and 4 occurrences of phosphorus ores with total reserves (A+B+C₁+C₂) 474.7 Mt of ore, and 15.1 Mt of P₂O₅; mining has not been

carried out in recent years (Mineral Resources of Ukraine 2021). In previous years, phosphorites were mined at the Karpivske deposit in Donbas, and the Myliatynske deposit in the Volyn-Podillya region. Other deposits of interest include Vyazoviy Yar (Kharkiv region), Ratnivske (Volyn region), Zhvanske (Vinnytsia region), Kopytkivske (Rivne region). In addition, the Verbske technogenic deposit of phosphorite-glaucanite ores in the Khmelnytsky region is also known, with reserves of 250 kt of ore and 26.7 kt of P_2O_5 .

The Ratnivske deposit of nodular phosphorites in the Volyn region was discovered in 1980. It is composed of Paleogene Obukhivska Suite and Quaternary sand-gravel-pebble rocks with phosphorite nodules. In total, 14 bodies of redeposited phosphorites were identified. The content of nodules varies from 6 to 80%, the content of P_2O_5 in nodules – from 2.44 to 14.54%, in the ore – from 0.58 to 10.88%. The underlying rocks are chalk-like marls and chalks of the Cretaceous Zdolbunivska Suite. Deposit can be developed by open-cast method.

Proposals for licensing are approved for the Postupelska site of the Ratnivske deposit with an area of 29.0 hectares, which is located in its southwestern part.

Phosphorite deposits are suitable for the production of mineral fertilizers. Inventory reserves of phosphorites by category B+C₁ are: in ore – 4,190.4 kt P_2O_5 , in nodules – 391.02 kt P_2O_5 (protocol of the State Commission on Mineral Reserves of Ukraine № 1693 of 20.01.2009). The deposit is not being mined.

Other promising deposits of nodular phosphorites include occurrences of Volyn (Poliska, Stakhoshynska, Pivnevskaya, Tanyushivska, Novoburlutska, Bantyshevskaya, Zalimanivska sites with prognostic resources of 335 Mt P_2O_5), Krolevetska (reserves 2.93 Mt P_2O_5), and Serechno-Budska sites in Sumy region, with promising formations in the Kanivska site, Pobyzhya and others areas. Resources of P_2O_5 in phosphorites of these areas exceed 100 Mt. Also promising are the northern and southern margins of the DDD, composed of sediments of the Kanivska and Kyivska Suites (Konyatynska, Latyshevskaya, Myropilska sites with total prognostic resources up to 600 Mt P_2O_5).

The Osykivske deposit of granular phosphorites in DDD is confined to Campanian sandy marls and quartz-glaucanite sandstones (1-14 m thick) with phosphorite grains, micro-nodules and concretions (P_2O_5 2-13%). At the column bottom a granular-pebble or pebble horizon is observed up to 0.5 m thick with P_2O_5 content up to 10%. The reserves of deposit are estimated at 7.7 Mt of P_2O_5 (average P_2O_5 content of 5.06%).

Occurrences of granular phosphorites in Cenomanian sediments are known in the south-western rim of the Ukrainian Shield – Manevysko-Klevanska, Zdolbunivsko-Ternopilskaya and other promising sites with prognostic resources of 600 Mt P_2O_5 (content 5%, layer thickness – 2 m). Several promising areas have been identified on the left bank area of the Dnister River (Zozulnytska, Khmelnytska, Fashchiivska, Dunayevetska) with prognostic resources P_2O_5 122 Mt (cutoff grade 4%, layer thickness 0.9-2.2 m). The thickness of phosphorite-bearing horizon decreases in the southern direction from 2.2 to 0.9 m. The total resources of P_2O_5 in granular phosphorites are estimated at 80-90 Mt.

The Zhvanske phosphorite deposit in Vinnytsia region is represented by weakly cemented phosphorite-bearing quartz-glaucinite sandstones, less often pebbles 0.3-4.8 m thick (average 1.4 m), with 3-10% P_2O_5 , which is spread over an area of 15 km² (Fig. 5.13).

In the deposit, Cenomanian sediments are productive and include two layers: the lower and upper. The lower one is composed of dark-green glauconite sandstones with spherical well-rolled "Podolski" phosphorites, their small fragments and phosphoritized sponges. The upper layer is also composed of glauconite sandstones with accumulation of primary sandy phosphorites. Productivity of phosphorite layer is 160-470 kg/m², reserves of P_2O_5 (C₂) – 5 378 kt. Ores of the Zhvanske deposit are heterogeneous, by their composition and content of P_2O_5 they are divided into several groups. The main components of productive layer are the primary sandy phosphorite nodules with a low content of P_2O_5 (up to 6%), and small fragments of spherical phosphorites with a high content of P_2O_5 (30-36%). The deposit can be developed in a cost-effective adit underground method, profitability of the enterprise can be 30%, the return on investment – up to 3 years. The high efficiency of Zhvanski phosphorites as mineral fertilizers is due to the high content of glauconite (up to 50%). The total content of P_2O_5 in the ore is about 14%. The depth of the phosphorite layer in the deposit is from 70 to 100 m. With annual production of 550 kt of ore, the yield of phosphorite powder with a content of 8% P_2O_5 is 400 kt. The term of supply of reserves (LOM) is 50 years. The degree of exploration of the deposit is quite high – a dozens of adits were passed over there during the exploration work in the 50s of the last century.

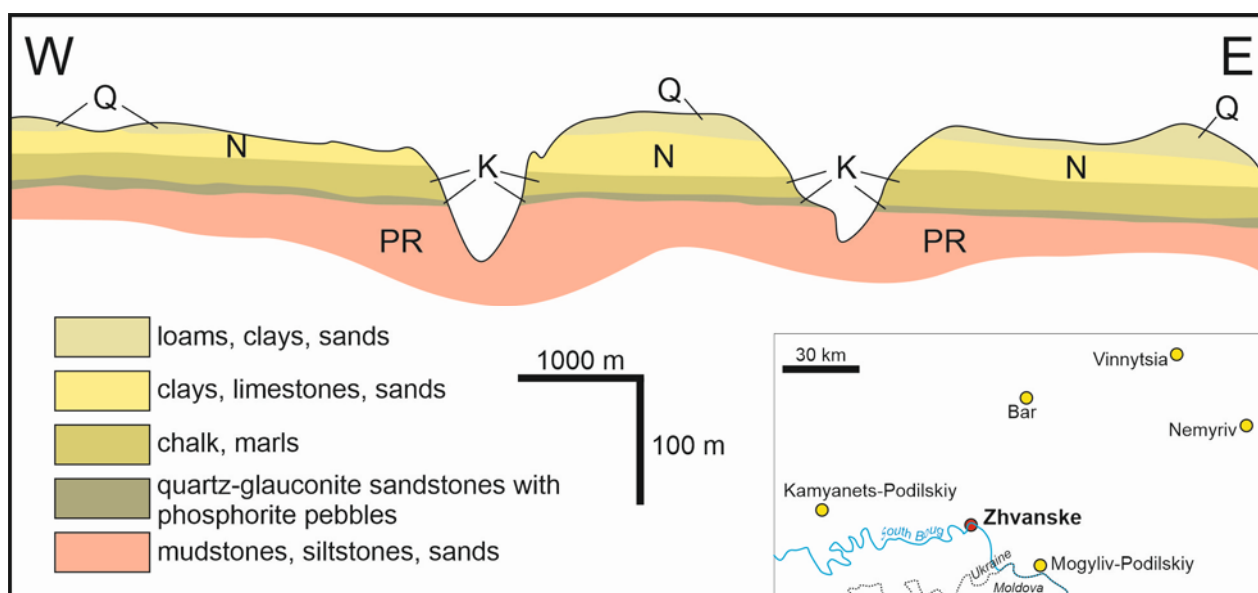


Fig. 5.13. Geological cross-section of the Zhvanske deposit (modified after Mykhailov et al. 2008a)

The Phosphorite-bearing brown iron ores are developed in Miocene Cimmerian marine sediments of the Kerchenskiy Iron-Ore Basin. The ores are composed of hydroferrichlorite, ferrimontmorillonite, hydrogoethite ("brown" ores), lepto-chlorite ("tobacco"), in places vivianite, which causes their increased phosphorus content. Ore

horizons lie almost horizontally, their thickness varies from a few meters at the basin margins to 25-30 m in the axial part. Phosphate minerals are represented by vivianite, kerchenite, apatite, kurskite, collofane. There are 11 known deposits, of these, reserves of three deposits are recorded by the SIMR (A+C₁, Mt): Kamysh-Burunske (ore – 176.1; P₂O₅ – 3.9; average content 2.09%), Eltigen-Ortelske (ore – 14.6; P₂O₅ – 4; 2.45%), Kyz-Aulske (ore – 109.3; P₂O₅ – 2.4; 2.17%). Until 1992, the deposits were developed by the Kamysh-Burunskiy Iron Ore Plant (annual capacity of 5.7 Mt of ore), now they are suspended.

5.3.2. Apatite

It is also used as a phosphorus raw material for the production of mineral fertilizers, phosphates, phosphorus, and phosphoric acid.

In Ukraine, apatite ores are developed in the complex ilmenite-apatite (Kropyvnyanske, Stremygorodske, Torchynske, Fedorivske in Zhytomyr region and Nosachivske in Cherkasy region), as well as rare-metal-apatite deposits (Novopoltavske in Zaporizhya region, and Davydkivske in Zhytomyr region). Special permits were issued to PJSC “Volynska Mining and Chemical Company”, “Valky-Ilmenit” LLC, and “TioFab” LLC for the development of the Novopoltavske, Stremygorodske and Nosachivske deposits.

The SIMR records 7 deposits with total reserves (A+B+C₁+C₂) of 3,295.6 Mt of ore and 96.2 Mt of P₂O₅. Apatite is not being mined.

The Stremygorodske deposit is described in the section “Titanium”. As for apatite ores, three ore layers are distinguished by their composition (top-down): primary kaolin 3-25 m thick, with an apatite content of 35.9 kg/t on average; weathered gabbro-norite 10-30 m thick, with apatite content from 25 to 109 kg/t (average 30 kg/t); fresh gabbro-norite of indefinite thickness, with an apatite content of 3-75 kg/t (average 23.9 kg/t). The ore body is covered by sandy-clay sediments with a thickness of 18.7 to 38.3 m (average 31.78 m). The deposit can be developed by the open-cast method. Apatite and ilmenite from primary kaolins and weathered gabbro-norite are of practical interest. Apatite is represented by a mixture of fluorine-chlorine- and hydroxyl-apatite, and fluoroapatite quantitatively predominates. The size of apatite grains is 0.2-0.8 mm. The grains are often in close intergrowth with small ilmenite grains, which significantly complicates the separation of pure apatite concentrate. The content of apatite in the rock is about 10%, ilmenite – 15-20%. When developing the deposit, one can get 150 kt per year of apatite concentrate. Reserves of P₂O₅ by categories A+B+C are 31.8 Mt.

The Novopoltavske rare-metal-apatite deposit is described in the section “Rare earths”. As for apatite, the main ore-bearing rocks are carbonatites (Fig. 5.14). The content of P₂O₅ in complex carbonatite ores averages 5.2%, ores are easily beneficiated, with apatite concentrate containing 37% P₂O₅, and 1.45% of rare-metal elements.

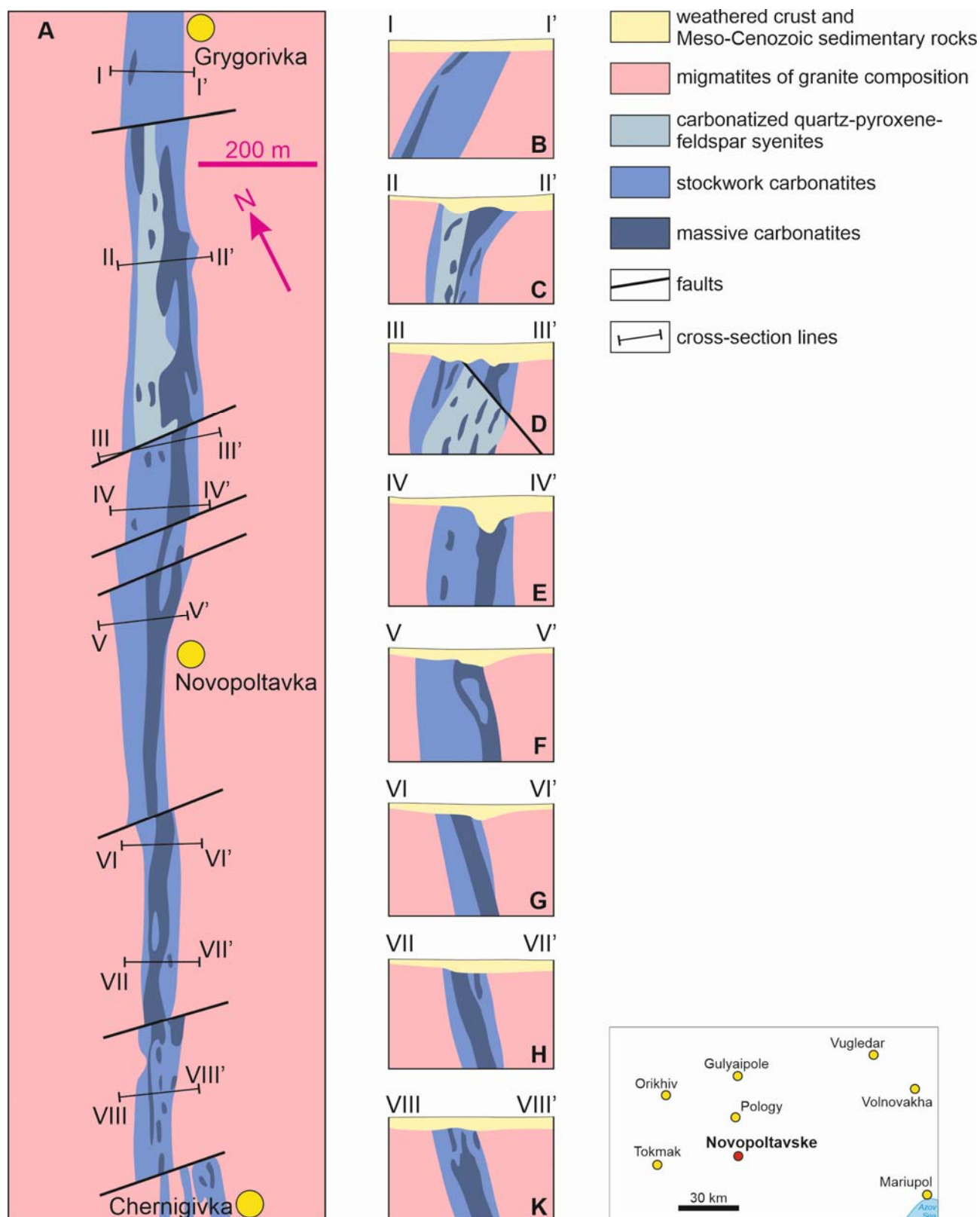


Fig. 5.14. Geological map (A) and cross-sections (B-K) of the Novopoltavske deposit (modified after Mykhailov et al. 2007)

Rare-metal-apatite ores are represented by dense coarse-grained apatite-carbonate (calcite, dolomite with admixtures of olivine, pyroxene, amphibole, phlogopite), and in the upper part by carbonatite rocks – loose apatite-silicate varieties. Apatite, as the most stable mineral, is accumulated in the weathering crust. Apatite in carbonatites

occurs in disseminated grains 3-5 mm in size, in contact zones of carbonatites with phenites – massive aggregates, and in veinlet zones of phenite carbonatization the long-prismatic apatite is developed. In calcite, dolomite-calcite carbonatites, the colorless, greenish, and greenish-blue apatite is widespread. The ore reserves amount to 955.5 Mt with an average content of P_2O_5 5.2%.

5.3.3. Fluorspar (Fluorite)

Fluorite is a complex raw material, primarily a flux raw material for metallurgy. In addition, fluorite is used in the chemical, glass and electronics industries. Fluorite is also considered to be a strategic raw material, as fluorine is important for organic fusion and nuclear physics. It is needed for the production of nuclear fuel, for the separation of uranium into isotopes ^{238}U and ^{235}U . Fluorine compounds with oxygen or halogens are strong oxidants, used in the combustion of rocket fuel and jet engines. In addition, it is used for the manufacture of refrigeration equipment, in the processing of aluminum and uranium.

The world's reserves of fluorspar are 310 Mt, the largest reserves are concentrated in Mexico, China, South Africa, and Mongolia. World production has a general tendency to increase from 6.3 Mt in 2015 to 7.7 Mt in 2019 with slight fluctuations. The largest extractive countries are China (52% of world production), Mexico (25%), as well as Mongolia, Vietnam, South Africa, Spain and other countries (Table 5.26). It is interesting to note the rapid growth of feldspar production over the years in Mexico (from 0.6 Mt in 2015 to 1.9 Mt in 2019), as well as the steady, albeit slow growth of production in Mongolia and Canada.

Table 5.26. World fluorspar mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
China	4,400.0	3,800.0	3,800.0	3,500.0	4,000.0	42.0
Mexico	624.6	659.8	741.7	1,959.7	1,931.5	68.0
Mongolia	280.3	248.9	319.3	555.2	699.4	22.0
Vietnam	214.0	218.9	234.9	238.7	238.0	5.0
South Africa	121.3	177.0	218.4	230.0	210.0	41.0
Spain	130.6	130.1	154.9	176.2	170.0	10.0
Canada	n.a.	n.a.	0	20.0	80.0	n.a.
Germany	57.7	52.6	45.4	49.2	80.0	n.a.
Morocco	80.9	73.9	75.5	87.9	73.2	0.32
Iran	39.3	70.8	55.3	55.0	54.8	3.4
Other countries	353.0	148.8	98.1	84.6	127.1	118.28
Total	6,301.7	5,580.8	5,743.5	6,956.5	7,664.0	310.0

Fluorspar reserves in Ukraine amount to 3.9 Mt of CaF_2 , but own production of fluorite is not yet underway. The use of fluorspar in Ukraine does not exceed 60 kt per year, of which 25-30 kt are used by the metallurgical industry, while Ukraine's needs for fluorite are met by imports from Tajikistan, Russia and Southeast Asia.

In Ukraine, 5 areas with fluorite mineralization are known (Fig. 5.15) (Mykhailov, Kurylo 2010a):

- Middle Transnistrian area of VPP (Bakhtynske deposit, Novoselivskiy, Perekorynetskiy, Vyshcheolchedaivskiy, Posukhivskiy, Skazynetskiy, Voevodchynskiy occurrences, etc.);
- Suschano-Perzhanska zone of Volyn megablock of the Ukrainian Shield (Tsentralne, Yastrubetske, Zakhidno-Yastrubetske occurrences);
- Kirovograd area of Ingulets megablock of the Ukrainian Shield (Bobrynetskiy and other occurrences);
- Azovian megablock of the Ukrainian Shield (Petrovo-Gnutivski occurrence, Kalmiuska Tectonic Zone);
- junction zone of the folded Donbas and Azovian megablock of the Ukrainian Shield (Pokrovo-Kyreivske deposit, Voykivskiy and Balka Vodyana occurrences).

Of these deposits, the most interesting are the Bakhtynske and Pokrovo-Kyreivske deposits, their reserves and resources are shown in Table 5.27.

Table 5.27. Summary of fluorite reserves and resources of the Bakhtynske and Pokrovo-Kyreivske deposits

Commodity	Reserves, kt			Resources, kt
	C ₁	C ₂	Total	
Ore	6,084.5	14,110.3	20,194.8	10,800
CaF ₂	1,820.7	2,087.8	3,908.5	-



Fig. 5.15. Distribution of fluorite and staurolite zones, deposits and occurrences (modified after Gurskiy 2008)

The Bakhtynske deposit is located in the Middle Pobuzhia area, in the Bakhtynska Depression on the western margin of the Ukrainian Shield. This area is composed of Riphean and Meso-Cenozoic platform sediments. Fluorite mineralization is associated with the sequence of Ediacaran Olchedaivski sandstones, represented by stratiform subhorizontal crescent-shaped and isometric bands 4-9.4 km long, 1-3.5 km wide, depth – from 21.3 to 118.5 m. The sequence includes 20 ore bodies with an average thickness of 0.75-1.45 m, located one above the other or en-chelon (Fig. 5.16).

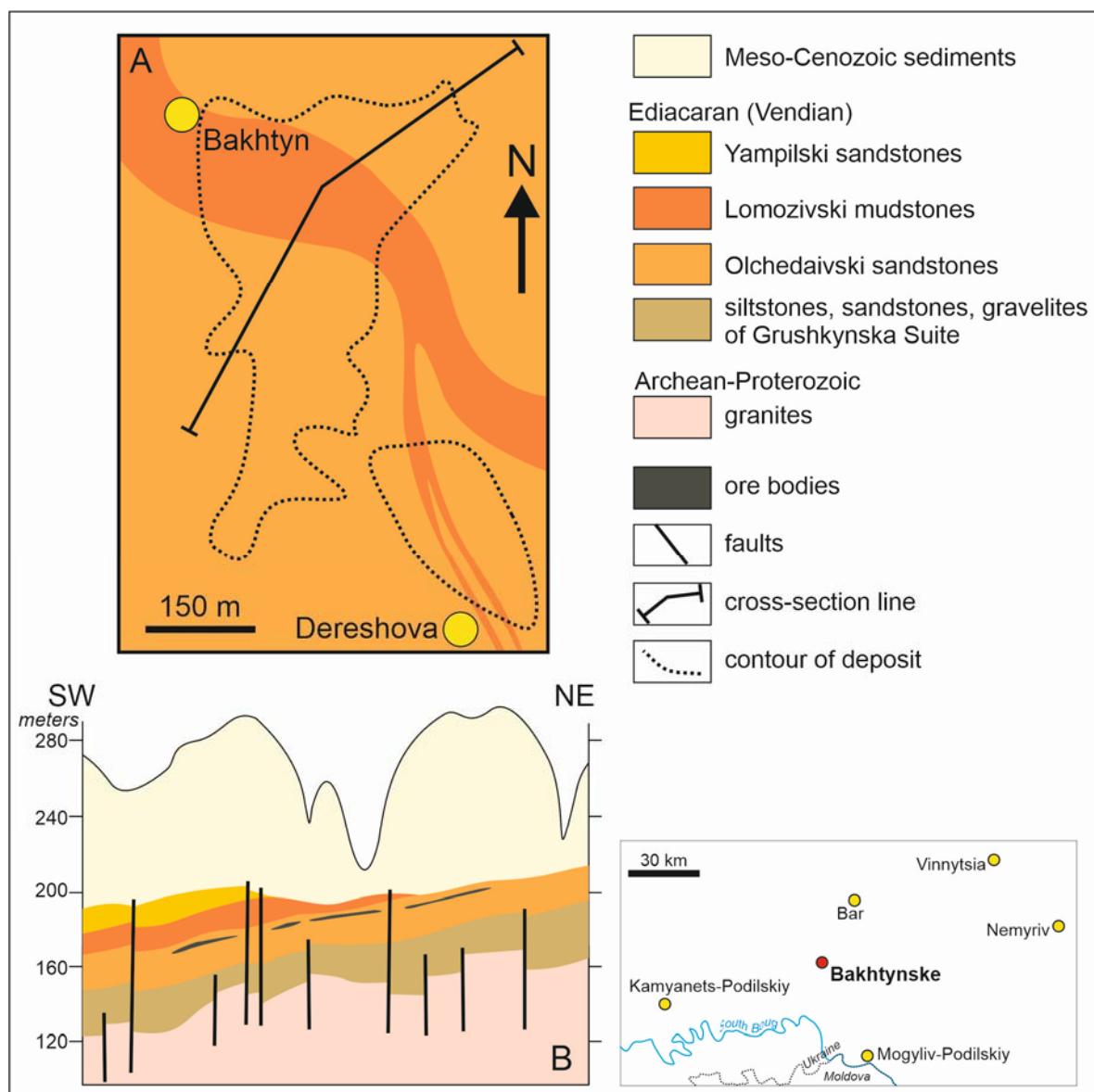


Fig. 5.16. Geological map (A) and cross-section (B) of the Bakhtynske deposit (modified after Gurskiy et al. 2006b)

The ores belong to the fluorite-carbonate type, disseminated and veinlet varieties are distinguished. Fluorite replaces hydromica and calcite cement of sandstones and partially clastic material – feldspar and quartz. The veinlet type is subordinate. The main minerals are fluorite and calcite, with minor quartz, dickite, and pyrite. The

colour of fluorite is purple, of varying saturation; there are clusters of colorless, greenish and honey-yellow grains. The ore structures are mostly evenly disseminated. In the case of intensive fluorination of sandstones ($>25\%$ CaF_2), they display cockade or spotted structure: fluorite cement of intergrowths are developed in the form of rounded grains (0.7-1.5 cm).

The ores are low-grade, complex, without harmful impurities, fluorite content is 11-41% (average 17.1-20.6%). The mineral composition of ores is given in Table 5.28, and summary of reserves in Table 5.29. The high-quality fluorite concentrate of the FF-95-A grade, ceramic feldspar, quartz feldspar and quartz concentrates can be obtained from fluorite, feldspar and quartz that are of industrial importance (Table 5.30).

Table 5.28. Mineral composition of ores in Bakhtynske deposit

Mineral	Average ore	Technological type ore
	Contents, wt. %	
Quartz	54.9	51.9
Potassium feldspar	18.4	16.4
Plagioclase	3.5	3.5
Fluorite	14.2	20.6
Calcite	2.7	2.7
Clay and illite	5.3	3.3

Table 5.29. Breakdown of reserves and resources of the Bakhtynske deposit

Commodity	Reserves, kt			Resources, kt
	C ₁	C ₂	Total	
Ore	4,257.5	13,710.3	17,967.8	10,800
CaF_2	589.7	1,920.8	2,510.5	-

Table 5.30. Chemical composition of Bakhtynskiy fluorite concentrate (%)

Product	CaF_2	CaCO_3	SiO_2	P	S
Fluorite	99.3	0.01	0.35	0.003	0.007
Concentrate FF-95-A	97.0	1.0	2.0	0.015	0.05

The Bakhtynske deposit is not being developed, although the engineering and geological conditions of deposit are generally favourable, and it is prepared for test-industrial development. The geological structure of deposition, morphology, style of occurrence, composition of ore bodies and hydrological conditions has been studied in detail for the construction of mining enterprise. Therefore, this deposit is the most promising for production of fluorspar concentrates. In addition, the deposit is complex with the possible production of feldspar and quartz concentrates (Shepel, Kuzmenko 2002). Bakhtynske deposit is supposed to be developed by underground (shaft) method. The mine productivity will be 500 kt of ore per year. The mine will operate for 29 years. The annual productivity of the beneficiation plant by concentrate will be about 90 kt.

Technological tests of ores have revealed that the ore is a complex raw material, while three high-quality marketable products can be obtained using preliminary beneficiation by X-ray luminescence separation and foam flotation methods. The following minerals are of industrial importance: fluorite, feldspar, quartz. The method of foam flotation was chosen as the main method of beneficiation. The X-ray luminescent method of preliminary beneficiation was developed by “Egont” LLP that allows involvement of low-grade ores in development.

The beneficiation scheme developed by Kryvyj Rig Technical University is taken for the basic economic calculations as the most economical. It assumes fluorite concentrate with a mass fraction of CaF_2 92.5% with separation rate 85.1% and a yield of 13.1%. From the tailings of fluorite flotation when using magnetic separation and feldspar flotation, the feldspar concentrate is obtained with a mass fraction of SiO_2 – 4.5% and a yield of 16.7% at $\text{Na}_2\text{O}+\text{K}_2\text{O}$ – 15.02%, as well as the quartz concentrate with a mass fraction of SiO_2 more than 97% and a yield of 50%.

Concomitant minerals associated with Neogene-Quaternary overburden include loams, clays, sands, detritus-oolite limestones.

Galena-sphalerite mineralization is also widespread at the deposit. Economic accumulations of polymetallic sulfides occur in single cases, although increased contents of Cu (up to 0.063%), Ba (up to 0.32%), Ti (up to 1%), Pb and Y are recorded in the Vendian (Ediacaran) and Lower Precambrian rocks.

Other occurrences of fluorite mineralization are also known in the Bakhtynske ore field (Table 5.31).

Table 5.31. Fluorite deposits and occurrences of Bakhtynske ore field

Deposits and occurrences	Occurrence style, prognostic parameters	Composition, grade	Prognostic resources by category P₂, Mt
Bakhtynske	Horizontal bodies with an area of 20 km ² , average thickness of 1 m	Fluorite 15.64-23.84%; quartz, calcite	-
Starogutivskiy	Horizontal bodies with an area of 9 km ² and up to 0.6-2.4 m thick	Fluorite up to 34%; quartz, calcite; zinc up to 12.8%	14.4
Zolotogirskiy	Horizontal bodies with an area of 1 km ² and up to 3 m thick	Fluorite 19.27%; quartz, calcite	-
Dereshkovskiy	Horizontal bodies with an area of 0.4 km ² and a thickness of 0.75 m	Fluorite 15.6%; quartz, calcite	-
Posukhivskiy	Horizontal bodies with an area of 1-3 km ² and a thickness of 0.6-4.8 m	Fluorite 5-19%; quartz, calcite	-
Perekorynetskiy	Horizontal bodies with an area of 5 km ² and up to 0.3-4.1 m thick	Fluorite 16.4%; quartz, calcite	38.4
Vinozhskiy	Steeply-dipping zone of vein-disseminated mineralization 600 m long, 100 m by dip, up to 1.8 m thick	Fluorite – up to 42.9%; quartz, calcite, galena, sphalerite, chalcopyrite; PbO – up to 2.25%, ZnO – up to 1.32%	-

Deposits and occurrences	Occurrence style, prognostic parameters	Composition, grade	Prognostic resources by category P ₂ , Mt
Nemerchynskiy	Horizontal bodies with an area of 4 km ² and up to 0.4-1.7 m thick	Fluorite 13-16%; quartz, calcite	17.4
Skazynetskiy	Horizontal body of small area, up to 2.5 m thick	Fluorite up to 15%; quartz, calcite	43.7

The Novoselivskiy and *Perekorynetskiy* occurrences are located 4 km northwest of the Bakhtynske deposit. In the *Vyshcheolchedaivskiy* and *Posukhivskiy* occurrences, fluorite is also located in Olchedaivski sandstones. The nature of ores there is the same as in the Bakhtynske deposit.

The Skazynetskiy occurrence, located at the confluence of the Zhvana and Batoga rivers, is confined to the Yampilski sandstones. The ore body (up to 2.5 m thick) is located in the middle part of the column of Yampilski layers, represented by dense diverse-grained arkose sandstones. The maximum of mineralization is located near interbed fractures and cutting vertical fractures. Ores are characterized by spotty-layered structure. The average fluorite content in ores is 15%.

The Voevodchynskiy occurrence is associated with the brecciation zone of the north-western extension (320°), 10-15 m thick. Fluorite fills thin veins (1-3 mm) that cement individual sandstone fragments in the breccia. The fluorite content is 31.4%.

The Vyshcheolchedaivskiy occurrence is represented by fluorite veins and veinlets in Olchedaivski sandstones cut by the systems of northwestern (310-320°) and northeastern (60°) fractures. The vein walls are filled with fine-grained calcite, their inner zone – with an aggregate of fluorite and calcite. Fluorite is represented by aggregates of small (1 mm) cubic crystals; the brushes are formed in semi-open fractures, oriented perpendicular to the fracture surface. The vein thickness is 1-2 cm, and fluorite content is 25-30%. Next to the calcite-fluorite fractures, the host sandstones are often fluoritized, fluorite forms intergrowth cement over there, and fluorite content decreases with distance from the fractures. The thickness of fluoritized sandstone zone near fractures is 5-10 cm (up to 25-50 cm). Fluorite is bright-purple, green, purple, blue, yellow. The latest generations of fluorite are characterized by uncolored well-faceted cubic crystals up to 4-5 mm in size in the cavities of calcite-fluorite veins or in host rocks.

Some thin fluorite veinlets in Olchedaivski sandstones have been discovered by wells near Perekoryntsi, Zherebylivka, and Lomozova villages; in Yampilski sandstones – near Lypchany village. Similar fluorite occurrences were found in the crystalline basement (Voevodchyntsi, Bakhtyn, Murovani Kurylivtsi, Kurazhyn, Olkhivka villages). They are found in pink aplite-pegmatite granites, migmatites, garnet-biotite granites, but are mostly spatially associated with fluorite mineralization in Olchedaivski sandstones. The mineral composition of ores is simple, homogeneous, consisting mainly of calcite and fluorite, occasionally with minor kaolinite and pyrite. Fluorite fills thin fractures (up to 1 mm, occasionally 1-2 mm) with uneven bumpy surface. Sometimes a series of parallel veins (2-3) are observed,

which cement the zones of tectonic fracturing (Murovani Kurylivtsi village). The vein fluorite mineralization extends to a depth of only 50-70 m below the surface of crystalline basement.

Insignificant fluorite content was recorded by wells in the north-west of central Transnistria in sandstones of Volynska Series near Velyki Zozulintsi (depth 346-369 m), Ivanivka (494.0-495.8 m), Rublyany (141-152 m; 270.5-275.8 m), Khonkivtsi (199.0-201.0 m) villages.

Several promising fluorite occurrences have been identified in the Sushchano-Perzhanska zone: Tsentralniy, Yastrubetskiy and Zakhidno-Yastrubetskiy.

The Tsentralniy occurrence. Located in metasomatites of the Sushchano-Perzhanska zone, in the western endo- and exocontacts of the Yastrubetskiy Massif, the Tsentralniy ore zone extends over an area of about 1 km² and has been traced for almost 3 km in the south-western direction with a maximum width of 0.5 km. The host rocks include biotite-feldspar- and feldspar-metasomatites, and microclinites, where accessory fluorine-zirconium-rare-earth mineralization is observed. It is most widely developed in quartz-biotite-muscovite greisens and microclinized syenites. Fluorite mineralization accompanies greisenized zones in the Perzhanski granites, where replacement of feldspars and plagioclase by quartz and sericite is followed by later-stage fluoritization. Ore bodies are of sheet and lenticular shape, from a few centimetres up to 25 m thick, and can be traced for up to 850 m horizontally and for 70-110 m down-dip. The ore-bearing zones are spatially associated with faults.

The main ore minerals are fluorite, zircon, cyrtolite, bastnaezite, parisite, monazite, xenotime. The fluorite content varies from 1 to 53.8%, with grades of 25-32% prevailing, and average content of 28%. Fluorite forms bunches and veinlets in the quartz feldspar groundmass, and is relatively free from inclusions of primary minerals. Fluorite forms bunches and veinlets in the quartz feldspar groundmass, it is relatively free from the inclusions of primary minerals. The feldspars in the ore are principally microcline (17-40%) and albite (11-25%). The fluorite ores contain rare earth elements, mainly of the yttrium group. Yttrium is concentrated in the fluorite, isomorphically replacing calcium in solid solution, and amounting to 0.55% of the elemental composition, with zirconium also forming 3.23% of the elemental composition.

Resources of category P₂ of the yttrium-fluorite ores of the Tsentralniy occurrence amount to 4 million tonnes, composed of 1.1Mt of yttrium-fluorite, 3.5kt of rare earth elements and 1.8Mt of feldspar concentrates. Integrated production of the deposits in the Sushchano-Perzhanska Zone could be highly profitable, especially as the price of fluorite concentrate containing 0.3-0.5% yttrium and lanthanides is much higher than that for pure fluorite concentrate. Further exploration of the ore occurrence is required, however,

The Yastrubetske occurrence. Located in the north-eastern part of the Yastrubetskiy syenite massif, this deposit of fluorite and rare elements is located mainly in greisenized quartz-mica schists and migmatites. The highest concentrations of fluorite (up to 50%) were recorded in dark-coloured muscovite schists. The occurrence is complex, with a mixture of fluorite-zirconium-rare-earth

mineralization. Fluorite mineralization is represented by veinlets and lenses concordant with or cross-cutting the host rock schistosity. The veinlets are typically 2-5 mm thick, sometimes up to 1-5 cm. They are discontinuous and often replaced by fluorite dissemination. The zones of fluoritization are up to 90 m thick, but CaF_2 concentrations are generally low, 1-2% to 10%. There are intervals with high fluorite content (from 17-25 to 44%), but the thickness of such enriched areas is not more than 1-2 m.

The Zakhidno-Yastrubetskiy occurrence. Located in the western exo- and endocontacts of Yastrubetskiy Massif, the host rocks of this occurrence are granites and syenites which have undergone intensive microclinization. The fluorite mineralization is mostly veinlet or disseminated. The thickness of individual fluorite bodies is from 0.1-0.5 to 20 m and the CaF_2 content is from 1% to 10 or 12%, sometimes up to 50%. The southern end of the Zakhidna-Yastrubetskiy occurrence lies close to the northern part of the Tsentralne occurrence and is assumed to be its northern extension.

The Bobrynetske occurrence. Located within the Novoukrainska Anticline and Ingulo-Inguletska Syncline in the Kirovograd region, the occurrence lies at the unconformity between footwall folded Paleoproterozoic rocks and hanging wall horizontal Meso-Cenozoic continental and marine sediments. The Precambrian crystalline rocks are represented by igneous and metamorphic formations that form the basement gently dipping towards the Fore-Black-Sea Depression. Host rocks include cataclased and mylonitized metasomatically altered granitoids, with varieties of these rocks including microcline-albite, and chlorite-hematite-microcline.

The mineralized zone has a total thickness of 800 m and has been traced for 4.6 km. In this thick zone, local structures have been identified with CaF_2 content close to economic grade, from 3 to 27.6%. The morphology of the ore bodies is complex. There are steeply-dipping veins with pinches and swells, which can be traced to a depth of 300 m, plate and lenticular bodies, accompanied by apophyses and parallel veins, as well as zones of stockwork mineralization.

Fluorite of the Bobrynetske occurrence is characterized by aggregates and concentric-zonal structures, alternation of multicolored bands of purple, yellow, white and green. In addition to fluorite, polymetallic sulphide- and copper-silver mineralization is found with high Mo, Pb, Sn, Cu, Au and Ag. Penalty impurities include SiO_2 (up to 0.04%), and P (0.24%).

The Bobrynetske fluorite occurrence belongs to the quartz-fluorite type with impurities of sulphides; it is hydrothermal in origin. It is believed that fluorite is the result of circulation of fluids saturated with fluorine through tectonic zones associated with the tectonic-magmatic activation of the Ukraine Shield in Paleoproterozoic time. Predicted resources for the Bobrynetsko-Kompaniivska zone as a whole amount to 18.6 million tonnes, with 4Mt in category P_3 and 1.7Mt in category P_2 .

A number of other structures with promise for fluorite mineralization are located in the Azovian megablock of the Ukrainian Shield, including the Petrovo-Gnutivskiy occurrence, the Kalmiuska Tectonic Zone, and others.

The Petrovo-Gnutivske occurrence. Located in the Kalmius River valley between Petrovske and Gnutovo villages, 18-20 km from Mariupol, the first discoveries of fluorite in this area were made in the 1940s by the Donetsk Complex Expedition (V.I. Kuzmenko). In the Kalmius River alkaline massif, several fluorite and fluorite-carbonate veins in granites and syenites were found associated with south-trending fractures and shear zones (Fig. 5.17). The occurrence is represented by one relatively thick (0.5-2.85 m) fluorite-carbonate vein and several thin fluorite veins.

The main fluorite-carbonate vein is exposed at the surface in the left bank of Kalmius River, 1.5 km from Petrovske village. It can be traced to 270 m. The main vein minerals are carbonates and fluorite, with quartz, chalcedony, and sulphides (sphalerite, galena, chalcopryrite, pyrite, etc.) also occurring.

Of the carbonates, calcite predominates, occurring in close intergrowth with parisite. The latter forms aggregates, lenses or bunches 0.8×0.6 cm in size, fine grains and spots on calcite background. The content of parisite in the ore bodies is from 25 to 75% and the content of rare earths 38.2% in average. It is believed that rare-earth fluorite-carbonate rock would compose about 8-10% of the total vein mass.

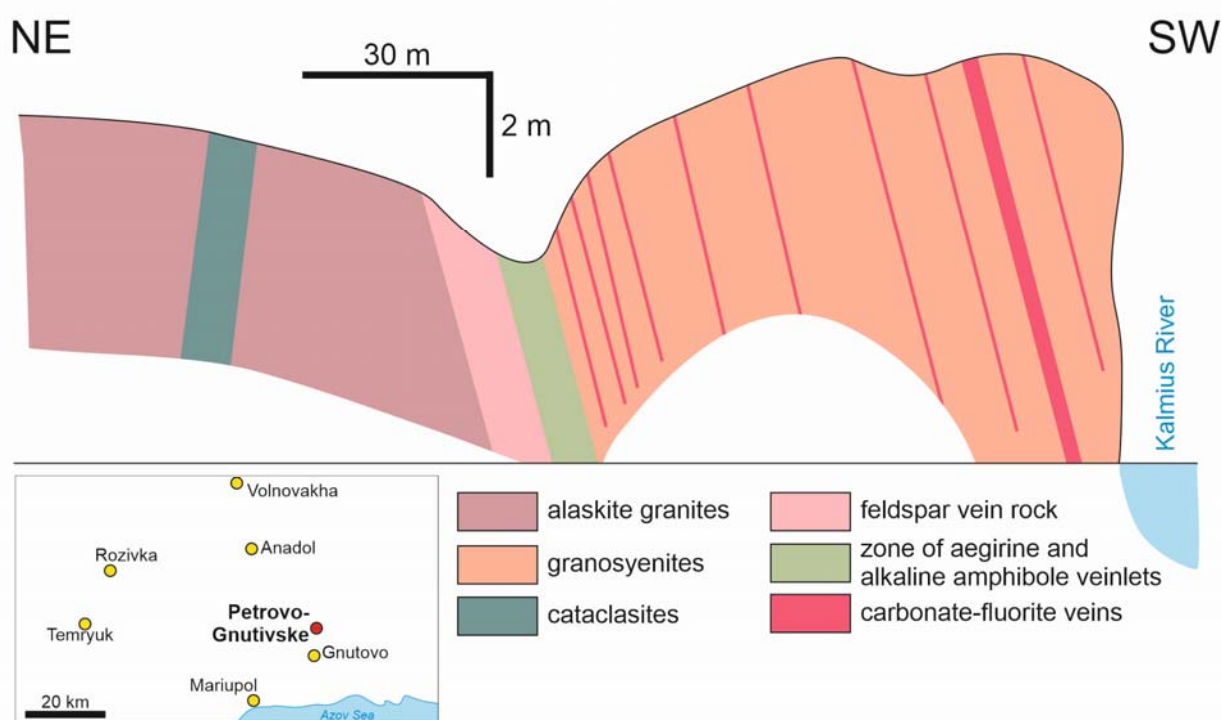


Fig. 5.17. Cross-section of the Petrovo-Gnutivske occurrence (modified after Panov 1981)

Fluorite occurs in bunches, lenses and bands up to 0.7 m wide in the carbonates. The average content of fluorite in the ore is 9%, and ore reserves are estimated at 28.5 kt. According to researchers, the occurrence is uneconomic even with the concomitant extraction of fluorspar, rare-earth elements and polymetals.

Several fluorite occurrences were found in the **Kalmiuska Tectonic Zone**, including Druzhba, Chermalyk-I and other sites.

The Druzhba site lies to the north of the neighbouring Petrovo-Gnutivskiy occurrence. The ore body is represented by a quartz-carbonate-fluorite vein (with rare-earth mineralization) 60 m long and 0.1 to 1.0 m thick, dipping steeply to the west (Panov 1981). The occurrence has no practical interest.

The Chermalyk-I site is located on the left bank of Kalmius Reservoir, 0.5 km from Zamozhne village. The fluorite occurrence has been known since the 1940s, and comprises a 20 m long sublongitudinal vein with a thickness of 0.2-0.5 m. The fluorite content reaches 10%, with rare earths comprising 0.1%. The extent of mineralization is uncertain due to insufficient exploration.

The Pokrovo-Kyreivske deposit, Voykivskiy and Balka Vodyana occurrences lie in the junction zone of folded Donbas and Azovian megablock of the Ukrainian Shield.

The Pokrovo-Kyreivske deposit is located in the Volnovaska Fault Zone within the junction zone of the folded Donbas and Azovian megablock, (Zaritskiy et al. 1973; Zaritskiy, Soloviev 1973). Feldspar ores were formed as a result of hydrothermal-metasomatic processes in limestones of the Lower Carboniferous Viséan-Tournaisian sedimentary sequence (Fig. 5.18). The thickness of overburden rocks is from 80 to 190 m. The deposit is composed of three ore bodies: Main, North and South.

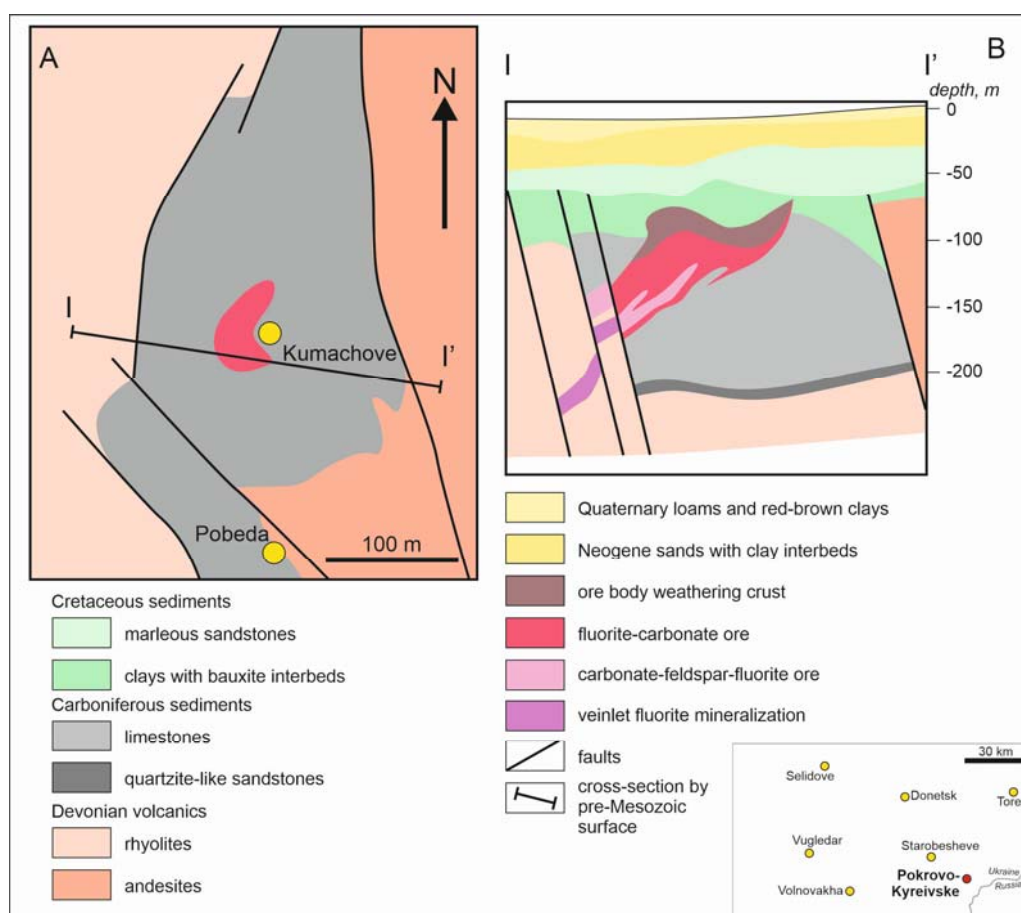


Fig. 5.18. Geological map (A) and cross-section (B) of the Pokrovo-Kyreivske fluorite deposit (modified after Mykhailov et al. 2008a)

The Main body is south-striking, lenticular in shape, 250 m long, 70-180 m wide, 4.4-70 m thick (average 40 m), dipping at 25-30° to the west, and is conformable to the host rocks.

Two types of ores are known: hard-rock ores associated with Tournaisian limestones, and deluvial-proluvial disintegrated ores 1.0-30.6 m thick in the lower part of overlying Upper Jurassic – Lower Cretaceous tuffogenic clays. The hard-rock ores are represented by two subtypes: carbonate-fluorite, formed as a result of limestone substitution by fluorite (CaF₂ content 65% in average), and carbonate-feldspar-fluorite formed by fluoritization of igneous rocks (average CaF₂ content – 45%).

Ore structures are massive, banded, breccia-shaped, or veinlet. The fluorspar is finely crystalline (up to 1 mm), purple, or rarely pale green, and closely associated with calcite. The ores also contain carbonates, feldspars (albite, potassium feldspar), quartz, sericite, chlorite, kaolinite, cinnabar, pyrite, galena, and other minerals.

The following ores may be distinguished:

- High-grade carbonate-fluorite ores suitable for beneficiation to produce metallurgical grade concentrates FC-95 (95% CaF₂), FC-85 (85% CaF₂) and, without beneficiation, FC-75 (73-83% CaF₂);
- Ordinary carbonate-fluorite (38-71% CaF₂) and carbonate-feldspar-fluorite (54.3% CaF₂) ores; and
- Weathered ores forming a “cap” over the hard-rock ores.

The ores can be beneficiated by the flotation method, as necessary.

The deposit belongs to the medium-temperature hydrothermal-metasomatic type. The temperature regime of mineral formation is estimated to have been 100 to 300°C.

Table 5.32. Breakdown of reserves of the Pokrovo-Kyreivske deposit

Commodity	Reserves, kt		
	C ₁	C ₂	Total
Ore	1,927	300	2,227
CaF ₂	1,231	167	1,398

The estimated reserves of the deposit are shown in Table 5.32. The deposit is not being mined. In terms of mineral reserves, the Pokrovo-Kyreivske deposit is high-grade, medium-, easily beneficiated, and located in an easily accessible area, close

to the industrial metallurgical centres of Ukraine. However, due to challenging hydrogeological and engineering-geological conditions, with the possibility of water penetration into the mine workings, the deposit remains undeveloped. It is estimated that water inflow will be 1200-1300 m³/year into an open pit, and 700-800 m³/year into an underground mine.. In addition, the deposit lies in an area with a shortage of water for both technical and domestic needs. The deposit was therefore excluded from the SIMR and placed in the State Register of Mineral Deposits as unprepared for industrial development.

In the **Voykivska site**, two zones of the north-western extension were found with quartz-calcite mineralization but only scarce fluorite dissemination.

In the **Balka Vodyana site**, numerous findings of hydrothermal-metasomatic and vein fluorite were detected in an area of 1.5 km².

According to calculations carried out for domestic fluorspar occurrences and deposits, the Bakhtynske and Pokrovo-Kyreivske deposits, Bobrynetskiy occurrence

and Suschano-Perzhanska zone are of highest value, in view of their degree geological and technical-economic study (Fig. 5.19).

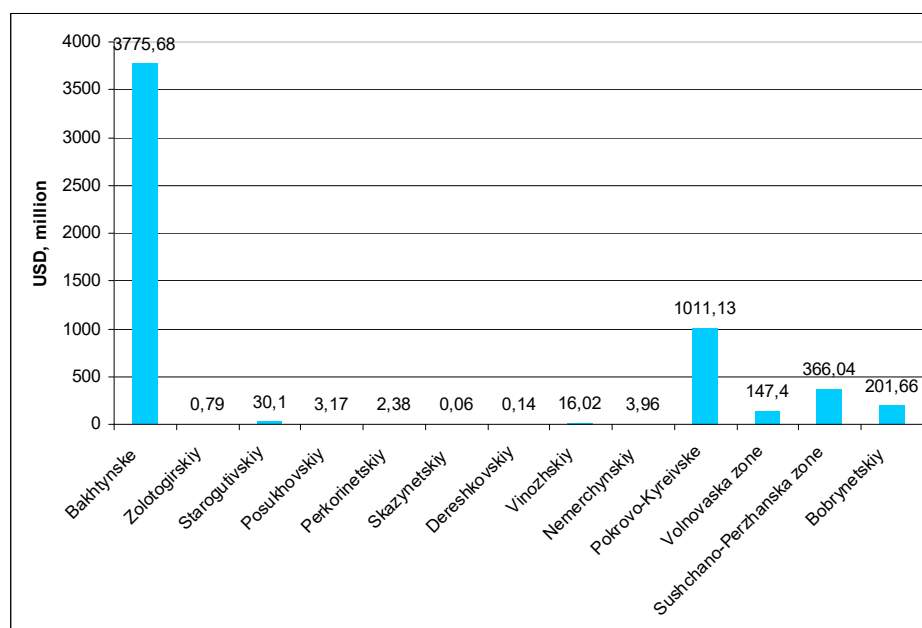


Fig. 5.19. The relative value of fluorite deposits and occurrences (modified after Mykhailov, Kurylo 2010a)

5.3.4. Glaucinite

It is used as a fertilizer, an additive in the production of animal feed, and an adsorbent for industrial water treatment and radionuclide-contaminated soils.

In Ukraine, deposits of glauconite sands have been encountered in Cenomanian sediments in the Khmelnytskyi region at the southwestern margin of the Ukrainian Shield. Known deposits include (Mineral Resources of Ukraine 2021):

- The Karachaivske deposit with predicted sand resources of 388.8Mt containing 230.5Mt of glauconite,
- The Adamivske-1 and Adamivske-2 deposits with glauconite reserves of 6 336Mt(A+B+C₁),
- The Verbske technogenic deposit with estimated glauconite reserves of 31.5kt.

Of these, last time mining was carried out at Adamivske-2 deposit only in 2013. In addition, in the Khmelnytsky region other deposits (Bystritske) and occurrences (Struzke, Tsyvkovetske, Velyko-Oleksandrivske, Pylypo-Oleksandrivske, Krutobridske, and others) are known, with total estimated glauconite resources of 40 million tonnes (Mineral Resources of Ukraine 2021).

The Karachaivske deposit of glauconite sands is confined to Upper Cretaceous Lower Cenomanian sediments. The deposits are 5-7 m thick and 5-15 m deep. The sands are dark-green, and contain 50-68.7% of rounded glauconite grains.

5.3.5. Flux Limestones and Dolomites

Carbonate rocks are used in many industries including the metallurgical complex, chemicals, sugar industry, construction materials, agriculture and others. The specifics and dynamics of the use of carbonate rocks differ for individual regions of the world depending on the structure of their industry. The main consumers are ferrous metallurgy, the gas industry (for desulphurization of gas flows), sugar production, agro-industrial complex (for soil treatment) and water supply (water treatment for domestic and technical needs).

The total world production of limestone is 430 Mt, of which the biggest amounts are extracted by China (70% of world production), as well as the United States, India, Russia and other countries (Table 5.33).

In Ukraine, deposits of carbonate rocks suitable for flux raw materials (limestones, dolomites, dolomitized limestones), have been explored in Dnipropetrovsk, Donetsk regions and the Autonomous Republic of Crimea. The SIMR records 23 flux limestone deposits with total reserves (as of 01.01.2021) in categories A+B+C₁ of 2,280.5 million tonnes, and in category C₂ of 319.4Mt, with additional estimated resources of 156.1Mt, Production in 2020 amounted to 4,272.1 thousand tonnes (Mineral Resources of Ukraine 2021).

The mining companies report fully adequate flux raw materials reserves, but are unsuitable for modern converter and electric smelting of steel and can be used only in the outdated blast-furnace – open-hearth process. A summary of the deposits is given in table. 5.34.

Table 5.33. World limestone production (USGS 2020)

Country	Production, kt	
	2018	2019
China	300,000	300,000
USA	18,100	18,000
India	16,000	16,000
Russia	11,100	11,000
Brazil	8,300	8,400
Japan	7,580	7,600
Germany	7,000	7,100
Republic of Korea	5,200	5,200
Turkey	4,700	4,700
Italy	3,600	3,600
Other countries	42,420	48,400
Total	424,000	430,000

Table 5.34. Characteristics of flux limestone deposits (Mykhailov, Kurylo 2010a)

Deposit	Region	Reserves, million tonnes	CaO content
Olenivske	Donbas	933.0	32.0-53.0
Novotroitske	Donbas	286.3	32.0-50.2
Karakubskie	Donbas	468.7	53.0
Pivnichno-Shevchenkivske	Donbas	187.9	32.0-54.0
Pervomaiske	Donbas	124.1	53.7
Stylske	Donbas	10.7	32.0
Rodnykivske	Donbas	15.0	58.0
Balka Bezvodna	Donbas	283.8	
Yamske	Donbas	10.5	30.0
Anenska Galma	Donbas	4.5	30.0
Kadykivske	Crimea		51.2
Gasfort	Crimea	347.1	54.3
Psilerakhske	Crimea		52.7
Zakhidno-Psilerakhska site	Crimea	329.0	54.3
Karanske	Crimea		54.8
Krasnopartyzanske	Crimea		53.8
Ivanivske	Crimea		54.7
Pivdenno-Bagerivske	Crimea		54.4
Skhidno-Bagerivske	Crimea		52.2
Agarmyske	Crimea		53.3
Laspinske	Crimea		54.3
Negrebivske	Korostyshivskiy area	32.9	
Kryvorizke	Kryvorizkiy area	111.0	
Zavadiivske	Ternopil region		
Kuzynske	Trans-Carpathians	56.6	30.3
Rososhske	Trans-Carpathians		

Among the flux limestone deposits, the largest reserves are in the Donetsk region, specifically, Olenivske, Stilske, Novotroitske, Karakubskie deposits.

The Olenivske deposits are composed of limestones (52-54% CaO), dolomitized limestones (36-47%) CaO, and dolomites, and was developed by Dokuchaivskiy Flux Dolomite Plant, with a quarry producing over 6 Mt per year. The deposits occur a number of sites, of which Central, Dolomitna, Eastern, and southern Eastern-Komsomolska sites were developed, while northern Eastern-Komsomolska, Basalieva Skelya, and Balka Bezvodna sites were not developed. The company has sufficient reserves for 100 years.

The Stylske deposit of flux and dolomitized limestones, together with the Olenivske deposit, was also developed by Dokuchaivskiy Flux Dolomite Plant.

The Novotroitske deposit, composed of limestones (45-55% CaO), dolomitized limestones (38-44% CaO), and dolomites, consists of 2 operating sites at Mekhrudnik and Western, and was developed by the Novotroitske Mining Administration since

1935, with production of 400 thousand tonnes per year. The deposit is complex, and construction stones and sands are mined in addition to flux limestones.

The Karakubske deposit, composed of limestones (52-55% CaO), and dolomitized limestones, was developed at four sites for flux limestone and construction rubble by the Komsomolske Mining Administration, with quarry production of 8 Mt per year. Remaining high-quality raw materials does not exceed 15-17 years supply.

Undeveloped deposits in Donbas include Pivnichno-Shevchenkivske and Pervomaiske (Petrivske). These deposits are recorded by the SIMR and reserves were approved by the State Commission on Mineral Reserves of the USSR, but not all these resources meet the new State standards.

The better quality limestones in Pivnichno-Shevchenkivske (53.5% CaO) and Petrivske (53-54% CaO) deposits meets the requirements, but there are challenges to their development due to the significant thickness of overburden rocks, remoteness from any mining administration, and location within the catchments of reservoirs on the Mokra Volnovakha River.

Undeveloped deposits in Donbas include Pivnichno-Shevchenkivske and Pervomaiske (Petrivske). These deposits are recorded by the SIMR and reserves have been approved by the State Commission on Mineral Reserves of the USSR, but the raw materials do not meet the new State standards.

The quality of limestones in Pivnichno-Shevchenkivske (53.5% CaO) and Petrivske (53-54% CaO) deposits meets the requirements, but their development is complicated due to the significant thickness of overburden rocks, remoteness from any mining administration, and location within the catchments of reservoirs on the Mokra Volnovakha River.

In Donbas, additional limestone resources may exist at the Olenivske, Novotroitske, Karakubske and Pivnichno-Shevchenkivske deposits.

The Rodnykivske flux limestone deposits, where preliminary exploration was carried out, Balka Vodyana, Pivdenno-Shevchenkivske and Pivdenno-Donetske deposits are also considered to be promising.

In Crimea, 14 flux and dolomitized limestone deposits have been explored and recorded: Psilerakhske, Kadykivske, Krasnopartyzanske, Skhidno-Bagerivske (under development); Pivnichno-Shevchenkivske, Balka Bezvodna, Pervomaiske, Karanske, Pivdenno-Bagerivske, Zhovtokamyanske, Gora Gasfort, Agarmyske, Laspinske and Ivanivske, which was prepared for industrial development. In the Crimean Mountains, explored resources at the Zakhidno-Psilerakhska site could significantly upgrade the raw material base of Balaklavska Mining Administration.

The Gasfort deposit, composed of a) sequence of Upper Jurassic limestones up to 600 m thick, is thought to be the most promising opportunity for the production of converter limestones. Resources identified amounted to 347 million tonnes, including 305Mt of flux limestones, of which 84% are suitable for converter production. However, the site is currently on care and maintenance due to environmental factors associated with the drinking water intake on the Chorna River near the deposit.

The Zakhidno-Psilerakhska site is a part of Karanske deposit promising for the production of high-quality flux limestones. It is composed of Upper Jurassic limestones, diverse in textural features and composition. The composition varies within the ranges given in Table 5.35.

Table 5.35. Chemical composition of limestones in Zakhidno-Psilerakhska site

Oxide	Wt. %
SiO ₂	0.22-34.77
R ₂ O ₃ (Al ₂ O ₃ +Fe ₂ O ₃)	0.33-6.52
MgO	<1.6
CaO	33.64-54.74
P	0.003-0.123
S	0.010-0.263
LOI	0.58-37.35

The principal reserves and all dolomite production for metallurgy (about 700 thousand tonnes per year) are concentrated in Donbas, in Carboniferous sediments of the Volnovakhska Zone, where the Stilske, Novotroitske, Olenivske, Pivnichno-Shevchenkivske, Karakubskie deposits are located. Estimated resources of dolomites and dolomitized limestones amount to 2 billion tons. The Stilske, Olenivske and

Novotroitske deposits are being developed. Unfortunately, the production from all deposits except Stilske, can be used only for blast furnace and open-hearth production.

Until 2014, six enterprises were engaged in the production of flux limestone in Ukraine, of which Komsomolske and Novotroitske Mining Administrations, Dokuchaivskiy Flux Dolomite Plant, and Balaklava Mining Administration specialized in the production of flux raw materials (Mykhaylov et al. 2008b).

The Komsomolske Mining Administration was the largest producer of flux limestone in Ukraine, providing up to 40% of the needs of metallurgical enterprises. The Mining Administration has two quarries (Central and Zhegolivskiy) and two crushing and processing plants based at the Karakubskie deposit.

The Novotroitske Mining Administration had been developing Novotroitske limestone and dolomite deposit,

The Dokuchaivskiy Flux Dolomite Plant had been developing Olenivske and Stilske limestone and dolomite deposits in four quarries: Central, Dolomitniy, Eastern and Stilskiy. The plant was the main producer of fired metallurgical dolomite and the only one in Ukraine for the production of powders for converter refractories. Products included carbonate rocks with high physical and mechanical properties (Table 5.36). The quality of carbonate raw materials meets the requirements of the industry for flux materials and refractories. The concentration of CaO+MgO is 53-55%, of phosphorus not more than 0.01% and of sulphur not more than 0.03-0.15%. The dolomites contain 15 to 18.5% MgO.

Table 5.36. Physical and mechanical properties of limestones and dolomites

Parameters	Limestones	Dolomites
Mechanical strength, kg/cm ²	1200-1500	1200-1300
Density, g/cm ³	2.5-2.6	
Porosity, %	0.72 to 8.8 (avg. 2.6)	
Natural humidity, %	0.1-0.6	

The Balaklavsk Mining Administration included Psilerakhskiy and Kadykivskiy quarries, which supplied raw materials to Balaklavskiy and Kadykivskiy crushing and processing plants, respectively. Until 2014, the company conducted additional exploration of Zakhidno-Psilerakhska site of Karanske deposit.

In addition, the **Krasnopartyzanske** limestone deposit in Crimea, had been developed by “Kerch Limestone” CJSC, with small production capacity. Limestones were also being quarried for construction raw materials (Evpatoria Building Materials Plant).

Determinations of the relationship between profitability of mining enterprises and the technical and economic characteristics of deposits was carried out at the Olenivske, Novotroitske, Karakubsk, Kadykivske, Psilerakhsk, Krasnopartyzanske limestone and dolomite deposits by the mining companies Komsomolska, Novotroitska, Balaklavsk Mining Administrations, Dokuchaivskiy Flux Dolomite Plant (Mykhailov et al. 2008a; Mykhailov, Kurylo 2010a). These found a direct relationship between the volume of raw material reserves and the tonnage extraction of minerals at the studied facilities.

The Karakubsk deposit (Komsomolska Mining Administration), has the best ratio of the volume of reserves and tonnage production of raw materials, to the critical indicators of income and profit of the enterprise, and deserves special attention.

Of the deposits in production, Olenivske contributes most to the national economy. Preliminary exploration has been carried out at the Gasfort, Balka Vodyana, and Pivdenno-Shevchenkivske deposits, and the most promising targets for development of flux limestones include the Rodnykivske deposit, the Balka Vodyana site of the Olenivske deposit and the Zakhidno-Psilerakhska site of the Karanske deposit.

5.3.6. Limestones for the Sugar Industry

In Ukraine, the main deposits of limestones suitable for use in the sugar industry are confined to the Upper Tortonian, Lower and Middle Sarmatian reef limestone massifs of Tovtrova Ridge in VPP (Fig. 5.20). They are represented by organogenic detrital limestones, which consist of fragments of lithotamniae algae, fragments of shells, fine detritus and clay material. In terms of chemical composition, they are of high quality and meet the requirements of sugar production technology.

The SIMR records reserves of 14 limestone deposits with total reserves of 323.2 million tonnes of categories A+B+C₁, and 11.0 million tonnes of category C₂. Of these, four are being developed with production in 2020 amounting to 1777.6 thousand tonnes (Mineral Resources of Ukraine 2021).

Almost chemically pure, strong, recrystallized organogenic-oolite, oolite-detritic, and oolite Sarmatian limestones are used as carbonate raw materials for the technological needs of sugar industry. By chemical composition, the content of CaCO₃ in limestone for this purpose should be not less than 95-98%, while MgCO₃ should not be more than 1.5-4.0% or Al₂O₃+Fe₂O₃ not more than 1.5%. Other deleterious impurities include silica, alkalis and calcium sulfate.

The most important deposits include Lysogirsk, Tsentralne, Zakupnenske-I

(Zamok), Bugaikha, Karachkivske, Neginsko-Verbetske, Bushanske, Studenivske (Khmelnyskiy region), Polupanivske, Gorodyske, Pidvysotske, Potutorske (Ternopil region), Malo-Lyubynske (Lviv region).

The Lysogirske and Tsentralne deposits are located in Chemerovetskiy area of the Khmelnytskyi region. Detailed exploration was conducted between 1968 and 2007, with reserves in categories B+C₁ reported as 40,949 kt at Lysogirske and 20,325 kt at Tsentralne.

Deposits are confined to the isolated heights of Tovtrova Ridge, and are composed of Tortonian-Sarmatian reef limestones (Fig. 5.20) recrystallized to various extents, fractured and karstified, and lying almost horizontally. The thickness of the Tsentralne deposit is 45-65 m, averaging 55 m, and of the Lysogirske deposit 75-95 m, averaging 80 m. Overburden of 0.1 to 10-15 m thick is represented by the soil layer and Quaternary and Sarmatian clay rocks. The bioherm limestone bodies of the deposits are ridge-shaped, elongated in the submeridional direction, 1400 m long and 400-500 m wide.

The chemical composition of the limestones meets requirements of the Standard TU-18-2-179-69 (Table 5.37). According to the results of physical and mechanical studies, the temporary resistance of limestones to compression in the dry state varies from 118 to 1700 kg/cm² (TU-18-2-179-69 assumes at least 100 kg/cm²). All samples withstood 15 freeze cycles. The density of the limestones is 2.3 t/m³, and average humidity is 0.83%.

The deposits were developed in 1975-2009, and by 01.01.2021 reserves amounted to 706.9 kt of limestone, including 410.9 kt of category B and 296.0 kt of category C₁.

Table 5.37. Content of chemical components in limestones

Component	Lysogirske		Tsentralne		Requirements TU-18-2-179-69
	Range	Average	Range	Average	
CaCO ₃	94.05-96.53	95.50	94.00-96.57	95.43	≥ 93.0
MgCO ₃	1.07-2.05	1.65	1.15-2.35	1.59	≤ 2.5
SiO ₂	0.87-2.45	1.43	1.05-2.10	1.53	≤ 2.5
Al ₂ O ₃ +Fe ₂ O ₃	0.31-1.21	0.60	0.42-0.93	0.60	≤ 1.5
K ₂ O+Na ₂ O	0.10-0.18	0.13	0.07-0.19	0.11	≤ 0.2
CaSO ₄	0.05-0.17	0.13	0.10-0.26	0.16	≤ 0.3

The Zakupnenske (Zamok) deposit was developed in 1932-1970 when about 20 Mt were mined, by 01.01.2021 reserves amounted to 20 thousand tonnes of category C₁. The deposit is formed of sheeted limestone bodies with a thickness of 19.2 to 87.8 m with a high content of CaCO₃ (95.10-99.63%), low MgCO₃ (less than 2.55%), Na₂O+K₂O less than 0.46%, R₂O less than 0.01% and R₂O₃ less than 0.20-1.29%. Indicators of physical and mechanical properties are as follows: water absorption 0.04-15.60%; compressive strength 42-695 kg/cm²; bulk density 2.12-2.40 g/cm³. By 01.07.1970, about 20 Mt of limestones were extracted from the deposit, and its development was stopped.

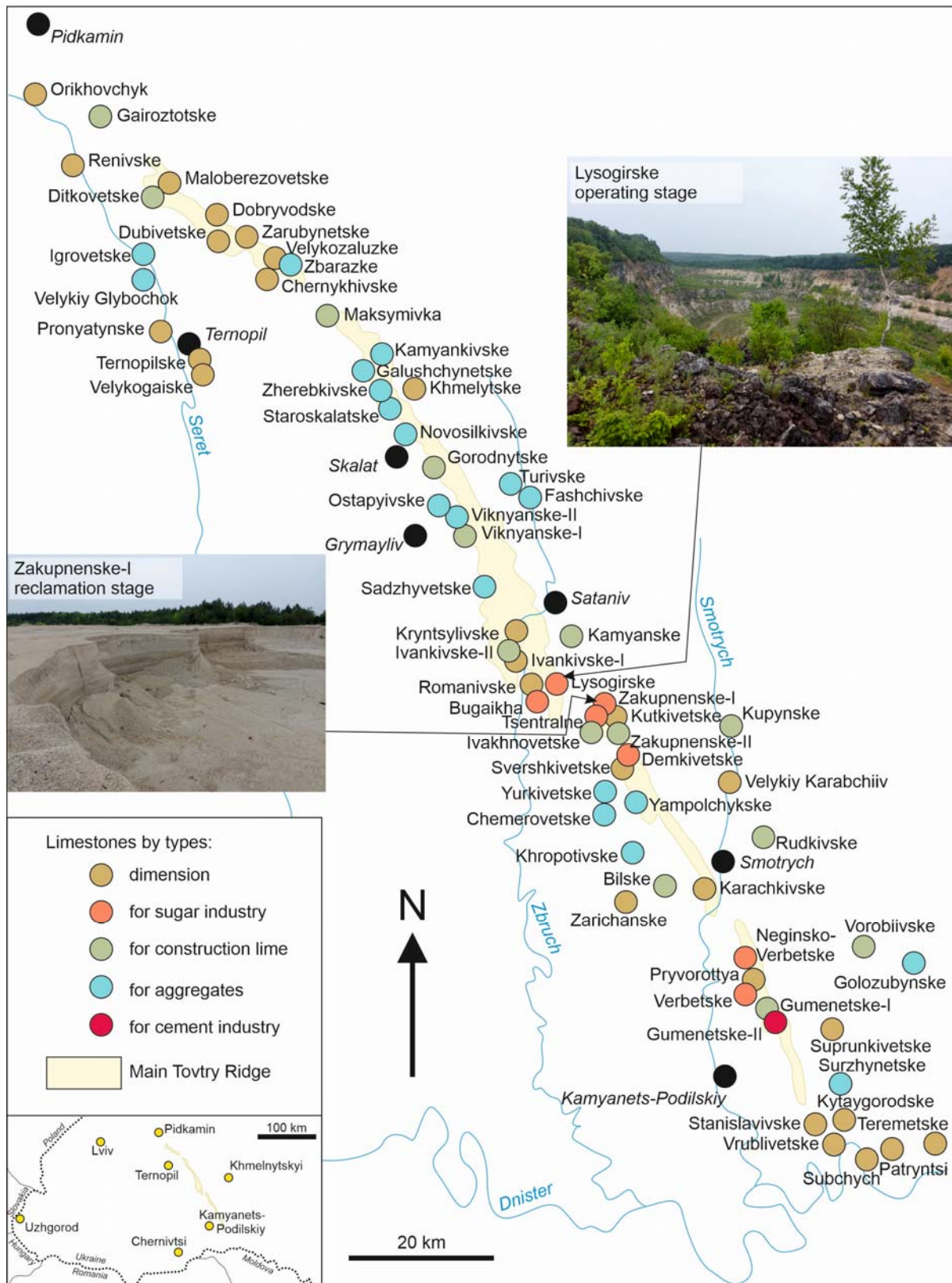


Fig. 5.20. Distribution of limestone deposits and their end-use purpose in the Podilski Tovtry (VPP) (modified after Moskalyuk, Brusak 2010).

Since then, the production waste in the form of limestone powder fraction 0-20 mm was stored in the Zakupnenskiy quarry, and by the end of 1999 17.45 Mt of

secondary raw materials and production waste (see left image in Fig. 5.20) had accumulated.

Until 1999, 3.72 Mt of screenings on an area of 30 hectares were used for technical reclamation, and in accordance with the acceptance certificate of 01.02.2001 the area was transferred to Zakupnenska Village Council for re-afforestation. In 2009, 13.73 Mt of limestone screenings were recorded as secondary resources.

5.3.7. Bentonite Clays

They are used to purify oils; clarify wine and fruit juices; in foundry production; production of iron ore pellets; production of molding mixtures, in drilling fluids; high-quality expanded clay; disposal of radioactive waste; cracking of oil and cleaning of refined products and white-burnt varieties – for the production of high-strength porcelain and faience wares; pharmacological and cosmetic products; production of high-quality paper.

World production of bentonite clays in recent years has been growing steadily, albeit slowly, from 18.2 Mt in 2015 to 21.9 Mt in 2019. Most are mined in China, the United States, India, Turkey and Greece, which together provide 76% of world production (Table 5.38). In recent years, India has sharply increased bentonite production (from 1.5 Mt in 2015 to 3.6 Mt in 2019), and Turkey has decreased from 3.1 Mt in 2015 to 1.5 Mt in 2019).

Table 5.38. World bentonite clay mining production (World Mining Data 2021)

Country	Production, kt				
	2015	2016	2017	2018	2019
China	3,650.0	5,600.0	5,600.0	5,600.0	5,600.0
USA	4,080.0	4,000.0	4,430.0	4,560.0	4 490.0
India	1,580.0	2,978.9	3,488.3	3,555.0	3,600.0
Turkey	3,134.9	1,744.9	1,481.6	1,332.0	1,533.5
Greece	1,123.3	883.2	1,087.8	1,365.4	1,394.0
Iran	436.0	356.0	517.5	423.6	761.1
Russia	498.0	589.6	669.7	714.0	720.0
Brazil	602.8	448.0	616.9	500.0	600.0
Germany	392.8	393.0	416.0	379.0	366.0
Czech Republic	369.0	374.0	254.0	277.0	357.0
Other countries	2,309.7	2,195.9	2,508.5	2,756.4	2,468.3
Total	18,176.5	19,563.5	21,070.3	21,462.4	21,889.9

In Ukraine, more than 100 deposits of bentonite clays are known, in: Ukrainian Shield (Cherkaske), Donbas, Fore-Carpathian (Pyzhivske, Berezhanske, Nemyrivske, Strutynske) and Trans-Carpathian depressions (Gorbske, Ilnytske, Kishtynske, Kopanske), VPP, and Crimea (Kurtsivske, Manguske). By mineral composition, montmorillonite (Kurtsivske and Kudrynske deposits in Crimea, Pyzhivske deposit in the Khmelnytskyi region), beidelite-montmorillonite (Cherkaske deposit in Cherkasy region, Berezhanske deposit in Ternopil region), and montmorillonite-beidelite bentonites are distinguished.

By chemical composition, calc-alkaline (Ca-Mg with an admixture of Na, K, etc.) bentonites predominate; less common are alkaline (Na with an admixture of K, Ca, Mg) varieties (Kishtynske deposit).

The SIMR records nine deposits of bentonite clays with reserves by category A+B+C₁ of 54.1 Mt, C₂ – 1.3 Mt. Four deposits are in production where 110.2 kt were mined in 2020 (Mineral Resources of Ukraine 2021). The main companies for bentonite clay extraction are listed in Table 5.39.

Table 5.39. Main companies for bentonite mining (Mineral Resources of Ukraine 2021)

Company	Deposit	Production in 2020, kt
“Grygorivskiy Rudnik” LLC	Grygorivske	60.31
“Mineral Mining Company” LLC	Pologivske	49.9
PJSC "Dashukivski Bentonites"	Cherkaske	-
“KP Benta” LLC	Maxymove	-

The Cherkaske bentonite clay deposit in Cherkasy region is one of the largest in the world and the largest in Ukraine and Europe. It was discovered in 1954; explored in detail in 1958-1960; and developed since 1974 by PJSC "Dashukivski Bentonites". The total area of the deposit is 643.4 km². It consists of three sites: Dashukivska (under development), Ripkinska and Bosivska.

The deposit consists of five layers (0.5-15 m thick) of montmorillonite, palygorskite and polymineral clays in Lower and Middle Miocene sediments. They lie at a depth of 10-40 m; the thickness of the productive sequence varies from 0.5 to 43 m.

Reserves amount to 42.0 Mt with a total resource of 10 billion tons. The clay powder processing plant, with an annual capacity of 650 kt, was designed and built based on the total clay resource. Clays are suitable to produce expanded clay gravel, light drilling fluids, ceramics and hydraulic cement etc. Metallurgical enterprises of Ukraine use the Cherkaske bentonite clays for molding purposes, but they are not suitable to produce pellets from iron ore concentrates.

The Gorbske and Khyzhinske deposits of low-quality bentonite-like clays are in Pliocene clays in the Trans-Carpathian Depression. Alkaline bentonite clays have been found in Miocene volcanic-sedimentary piles in the Solotvynska Depression. In Fore-Carpathians and Volyn-Podillya, Miocene sediments are prospective for bentonite clays, where Berezhanske (reserves of 426 kt) and Pyzhivske (241 kt) deposits and the Zhuravne occurrence are already known.

Deposits of bentonite-like clays have been found in Miocene Meotian and Sarmatian sediments in the Fore-Black-Sea Depression (Dobrozhanivskiy, Velykomykhailivskiy, Luchynskiy, Tsezariivskiy, Severynivskiy occurrences), and Crimea (Kurtsivske and Kudrynske deposits). The Kudrynske deposit is represented by three types of bentonite: alkaline, ordinary calc-alkaline and high-Na calc-alkaline. Reserves are estimated at categories C₁ of 375 kt, C₂ – 220 kt.

In Donetsk region, the Grygorivske deposit (Bilokuzminovska Suite) with bentonite reserves of 2.9 Mt (C₁+C₂) was explored.

In Trans-Carpathians, deposits of bentonite clays are confined to horizons of

epigenetically altered Miocene and Pliocene tuffogenic-sedimentary rocks. These are the Gorbske, Ilnytske, and Kopanske deposits. Bentonites of these deposits are calc-alkaline; do not have high technological properties and cannot compete in the world market with high quality raw materials extracted in the United States, China and other countries. However, the Kishtynske deposit of alkaline, partially white-fired bentonite clays explored in the early 1980s in Trans-Carpathians meets the highest requirements of industry and can be used in various sectors of the economy.

The regional geology of *the Kishtynske deposit* comprises Neogene volcanic-sedimentary formations of the Dorobrativska, Lukivska and Almaska Suites. The bentonite clays are confined to the upper part of the Upper Dorobrativska Sub-Suite composed of alternating psammitic, siltstone and pelitic tuffs with mudstone layers. This Sub-Suite is overlain by grey and dark grey mudstones with rhyolite tuff and sandstone interbeds of the Lukivska and Almaska Suites (120-130 m). The bentonite clays occur in a 1.0-2.7 m thick (average – 1.9 m) layer gently (15-25°) inclined to the southwest, which can be traced for 1500 m along strike and for 100 m down-dip. The deposit includes 2-3 bentonite beds overlying rhyolite tuffs separated by interbeds (0.1-0.5 m thick) of dense grey mudstones that pinch out down-dip.

These bentonites are white (when dry) rocks that swell rapidly on contact with water. The primary rock is rhyolitic xenotuff, dominated by fragments of volcanic glass almost completely replaced by fine-grained aggregate of montmorillonite with or without dolomite and quartz. The bentonites are mainly alkaline, where the main components of ion exchange are sodium and potassium, which predominate over calcium and magnesium. They are characterized by high plasticity, swelling degree from 6 to 13 times, bentonite number of 65-100 and colloidal rate of 73-100. Unique, white-fired clays with high swelling (10-19 times), high bentonite number (average 100) and high colloidal rate (average 100) are found in lenticular interbeds of variable thickness in the ordinary bentonite varieties.

They are suitable to produce high-quality drilling fluids; as adsorbents; as a binder component of molding mixtures in the foundry industry; for the manufacture of fine and building ceramics. However, the volume and reserves of white clay have not been identified.

Reserves of deposit by category C₂ are 4.8 Mt with prognostic resources of 9.6 Mt. Mining conditions are difficult. The deposit can be developed by underground adits, and it is not currently being developed.

5.3.8. Feldspar Raw Materials

These are used for the manufacture of fine ceramics, glass products, and in the electroceramic industry.

World production of feldspar raw materials in recent years ranges between about 28 and 31 Mt. The largest producers are Turkey, India, China, Iran, Italy, Indonesia and Thailand, that together provide 79% of world production (Table 5.40). Iran more than doubled its annual production of feldspars between 2015 and 2019.

Table 5.40. World feldspar mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
Turkey	10,422.8	9,475.8	10,273.6	11,474.0	9,447.8	240.0
India	3,343.8	6,434.8	4,270.2	4,300.0	4,300.0	320.0
China	2,350.0	2,400.0	2,500.0	2,500.0	2,450.0	n.a.
Iran	1,003.4	1,120.5	1,128.6	1,320.5	2,415.4	630.0
Italy	2,200.0	2,200.0	2,200.0	2,200.0	2,200.0	n.a.
Indonesia	1,204.9	1,353.3	2,601.0	1,368.4	1,370.0	n.a.
Thailand	1,331.9	1,167.1	1,385.9	1,117.8	1,251.1	235.0
Brazil	456.3	295.8	290.0	300.0	632.3	150.0
Spain	558.3	634.5	819.2	616.2	620.0	n.a.
Mexico	159.4	318.2	500.7	907.8	516.2	n.a.
Other countries	5,072.1	5,464.8	5,289.9	5,085.7	4,590.8	n.a.
Total	28 102.9	30,864.8	31 259.1	31 190.4	29,793.6	1575.0

Ukraine's main feldspar deposits are in granites, pegmatites, nepheline syenites, feldspathic sands and sandstones, microgranodiorites and porcelain stones (Fig. 5.21).

The main source of feldspar is pegmatite. To date, 33 pegmatite fields with numerous pegmatite veins are known in Ukraine. The SIMR records 12 feldspar deposits including:

pegmatites – Girne and Gruzlivske in the Zhytomyr region; Balka Velykogo Taboru in the Zaporizhya region; Lozuvatske in the Kirovograd region; Bilchakivske, Bilchaky and Ustyia in Rivne region;

- microgranodiorites – Dubrynytske in the Trans-Carpathian region;
- granitoids – Maidan-Vilske in the Khmelnytskyi region;
- technogenic wastes from beneficiation of rare-metal ores – Mazurivske in the Donetsk region;
- technogenic wastes from beneficiation of apatite-ilmenite ores – Nosachivske in Cherkasy region;
- technogenic feldspar-quartz-fluorite ores – Bakhtynske in Vinnytsia region;
- alkaline kaolines, feldspar gruss and crystalline rocks (granites, migmatites, plagiogranites, pegmatoid granites) – Dubrivske deposit in the Zhytomyr region;
- rare-metal pegmatites – Shevchenkivske lithium deposit in the Donetsk region/

Total reserves of feldspar raw materials are estimated at 54.2 Mt by categories A+B+C₁ and 208.7 Mt by category C₂. Total production in 2020 was 643.7 kt (Mineral Resources of Ukraine 2021). The main companies for the extraction of feldspar raw materials are listed in Table. 5.41.

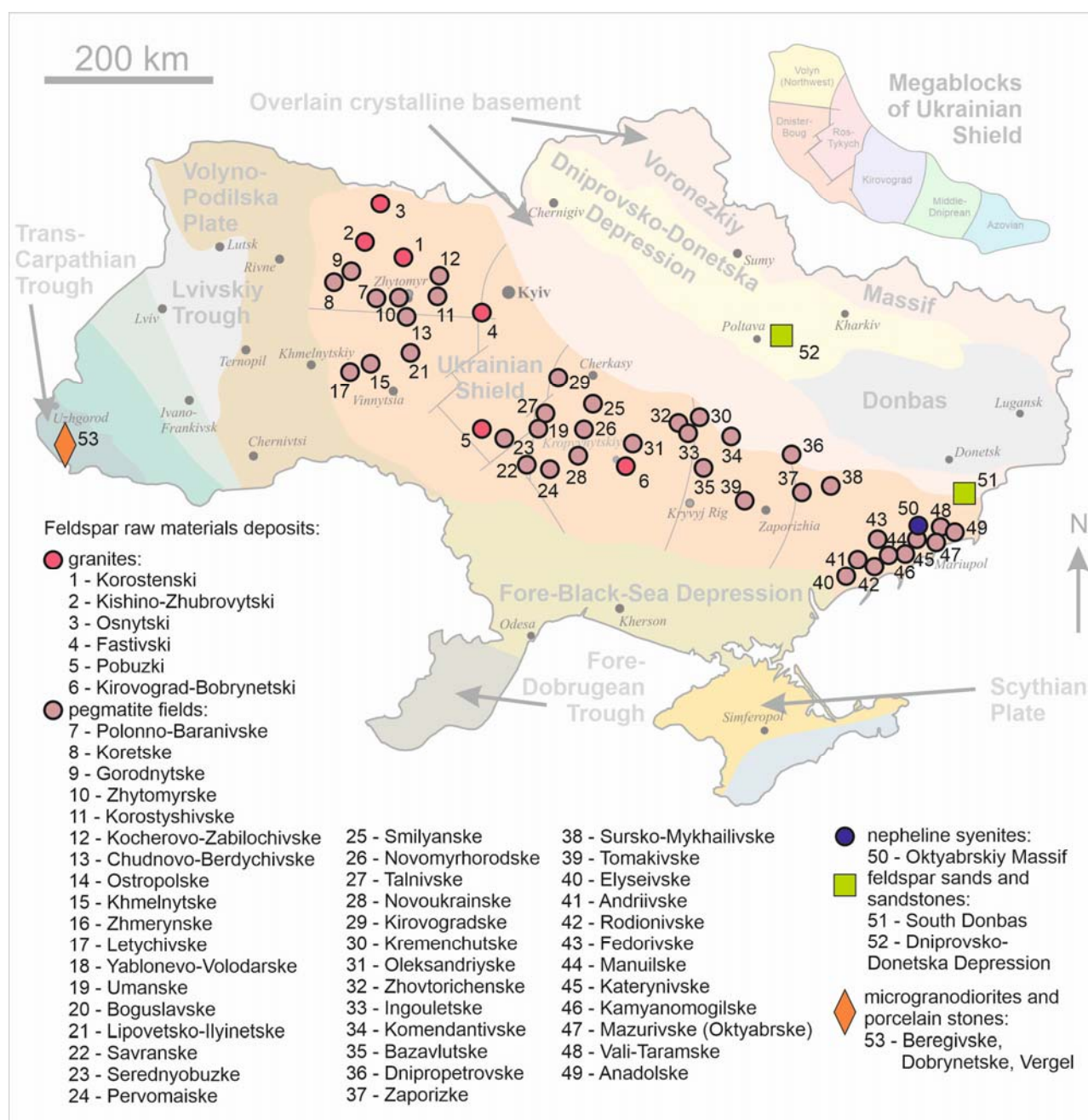


Fig. 5.21. Distribution of feldspar-yielding deposits (modified after Gurskiy et al. 2006b)

Table 5.41. Main companies for extraction of feldspar raw materials (Mineral Resources of Ukraine 2021)

Company	Deposit	Production in 2020, kt
PJSC "Maidan-Vilsky Refractory Plant"	Maidan-Vilsk, Khmelivska site	295.74
SE "Polonskiy plant Mayak"	Maidan-Vilsk, Novakivska site	284.05
SE "Shpat"	Girne	39.2
"Pyatyrychanka" LLC	Dubrivske, Pyatyrychka site	24.7
"Dovbyskiy porcelain factory Koral" LLC	Gruzlivetske, Gruzlivetska-3 site	-
"Pegmatit" LLC	Balka Velykogo Taboru	-
"Georesurs" LLC	Lozuvatske	-

The Polonno-Baranivske field in the north-western part of the Ukrainian Shield is composed of pegmatites in biotite and amphibole-biotite gneisses of the Teterivska Series. The pegmatites are pink-light-grey with pegmatoid, granitic and graphic textures. They form conformable, boudinaged seams. Vein thickness varies from tens of centimeters to 30 m (average 8.3 m). The main rock-forming minerals are (%): microcline 20-90 (average – 61), quartz 15-45 (22), and plagioclase 0-45 (14), with minor muscovite 0-5, and biotite up to 1. Accessory minerals are sericite, kaolinite, chlorite, and rare zircon grains. Contacts with the host gneisses are sharp. Light-grey to pink, fine- to medium-grained granite aplites occur along the contacts.

The Elyseivske field of Azovian region includes the Zelena Mogyla, Dalnya Kamchatka, Nyzhnya Kamchatka, Balka Glyboka, and Balka Velykogo Taboru deposits. Pegmatite and aplite veins are 90-165 m long and 17-90 m thick.

The Andriivske field includes the Kamyana Skelya and Chervona Gora deposits, which consist of pegmatite veins from 200-500 m long and from 20-60 m thick.

A license proposal is currently valid for the extraction of feldspar raw materials from tailings dumps of the Eastern section of the rare-metal **Mazurivske (Oktyabrske) deposit** (Investment Atlas of Subsurface User 2021). **The eastern part of the Mazurivske (Oktyabrske) deposit** in the Donetsk region has an area of 8.8 hectares of layered beneficiation tailing dumps of weathered rare-metal ores. The upper layer has thicknesses of 3.0-23.9 m (average 7.42 m) represented by so-called "sands", with over 80% of the grains coarser than 0.1 mm in size. The middle layer with a thickness of 0 to 15.8 m (average 3.9 m) is represented by "sandy-silty sediments", where the percentage of grains less than 0.1 mm reaches about 36%. The lower layer with an average thickness of 3.86 m is represented by "loams" composed of fine-grained material. Reserves of feldspar raw materials by category B+C₁ amount to 825.7 kt. In addition, reserves of "sandy-silty sediments" are 199.1 kt and of "loams" are 105.8 kt were calculated outside the license area by category C₂ (Investment Atlas of Subsurface User 2021).

5.3.9. Gemstone and Facing-Stone Raw Materials

Deposits of amber, marble onyx, rhodonite, and jet occur as well as diamond findings are known in Ukraine (Pavlyshyn et al. 1998) (Fig. 5.22). Gemstone raw materials are minerals and rocks, which due to their decorative properties are used to produce jewelry and art products. In Ukraine, quartz, topaz and beryl are associated with pegmatites of the Volynske deposit (described above in the subsection 'Piezo-optical raw materials').

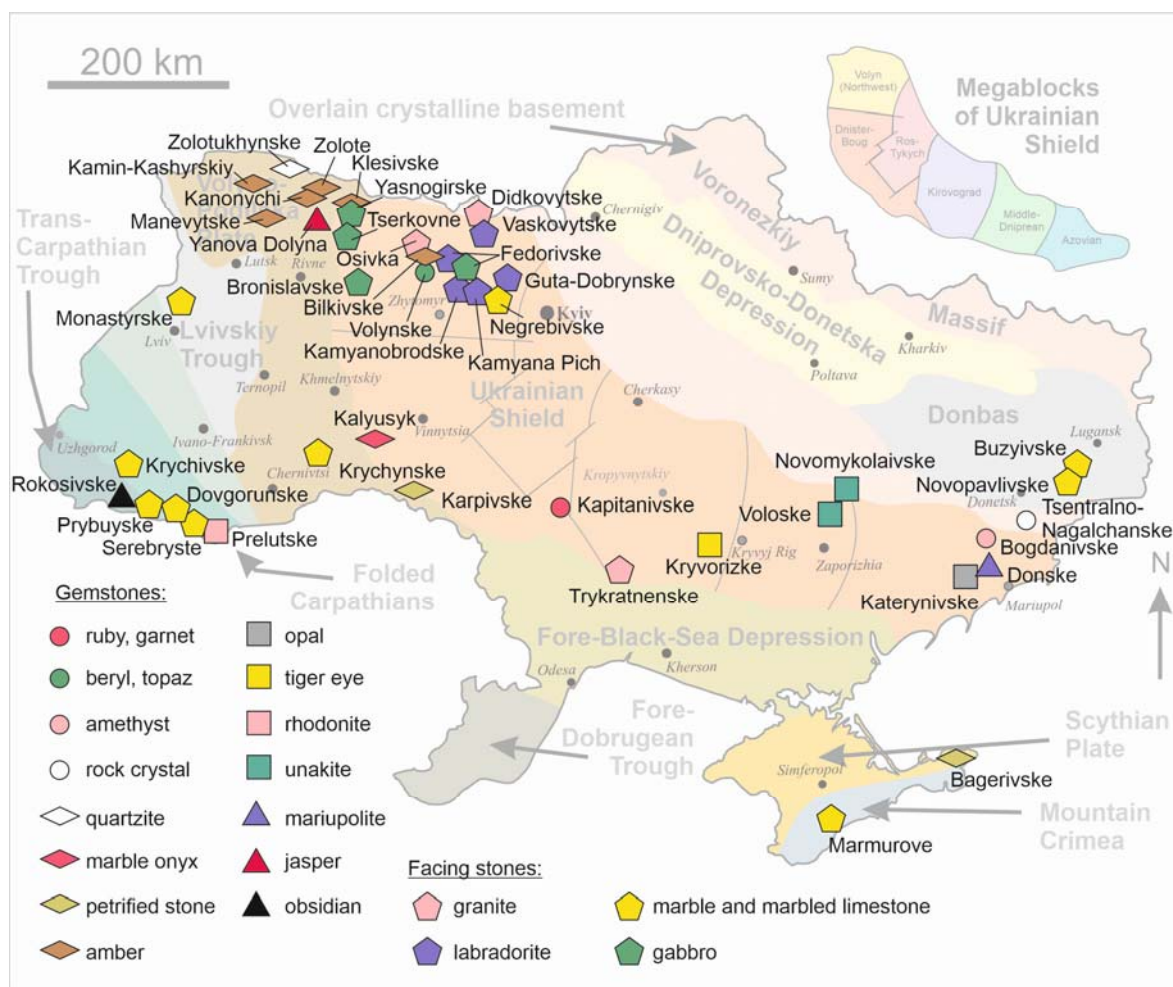


Fig. 5.22. Distribution of gemstone and facing stone deposits of Ukraine (modified after Mykhailov et al. 2008a)

5.3.9.1. Amber

It belongs to the group of precious stones of organogenic origin, used in jewelry and artistic wares. In Ukraine, large amber resources are the Prypyatskiy (Klesivsko-Perzhanska, Dubrovytsko-Volodymyretska, Manevytska, Mogylyanska, and Barashivska fields), Dnirovskiy (Verkhnyodniprovsk, Serednyodniprovsk and Nyzhnyodniprovsk fields), and Carpathian amber basins in the Baltic-Dniro amber province (Fig. 5.23).

The SIMR records amber reserves in 17 deposits; of these nine are being developed at Klesivske (Pugach (SE “Burshtyn Ukraine”) and Fedorivska (“Technobud” LLC) blocks), and at Volodymyrets Skhidniy (“Sonyachne Remeslo Center” LLC). In addition, special permits are granted for the extraction of amber from Kanonychi, Zolote, Manevytske-1 and Manevytske-2, Kamin-Kashyrske-1 and Kamin-Kashyrske-2, Bilkivske deposits. Total reserves by category C_1 are 42.3 tons, C_2 – 1,421.4 tons. Production in 2020 was 6,353.53 kg (Mineral Resources of Ukraine 2021).

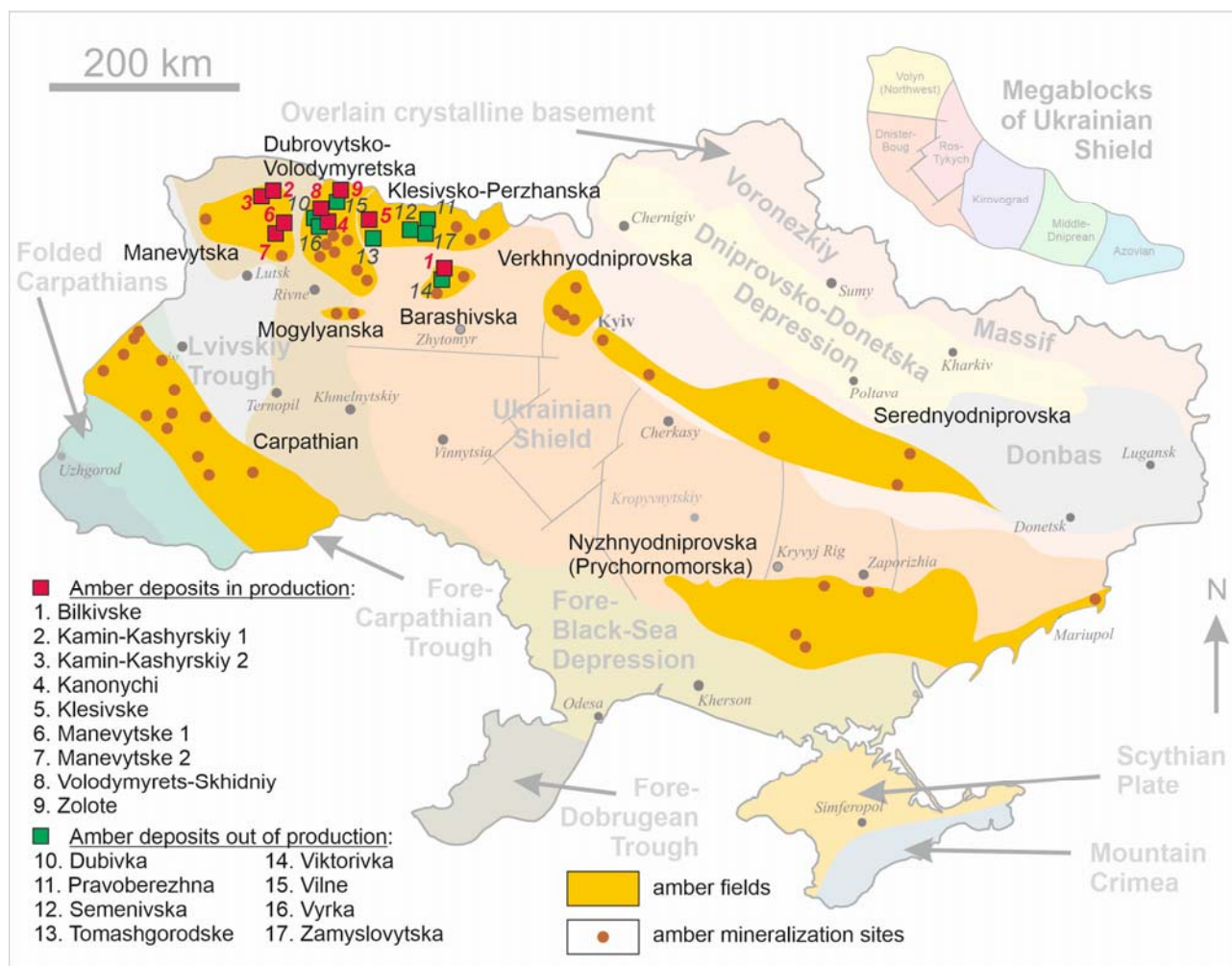


Fig. 5.23. Distribution of amber fields, deposits, amber mineralization sites and active and non active production sites of Ukraine (modified after Atlas of Geology 2001)

The amber deposits (Klesivske, Vilne, Dubivske, Viktorivske, Petrivske, Vyrka) in the **Prypyatskiy Basin** are in the Oligocene Mezhygirska Suite of the Kharkivska Series and in the Beretska Suite.

The Klesivske deposit is located approximately 90 km northeast of the city of Rivne, and is confined to coastal-marine, lagoon-delta sandy-clay sediments of the Paleogene Kharkivska and Poltavska Series. Two layers of amber-enriched sands are distinguished: the lower (1-6 m) with amber content from 1 to 420 g/m³ (average 57 g/m³) and the upper (2-3.5 m) represented by fine- and medium-grained grey and light-grey sands with an admixture containing amber from 1-2 to 20 g/m³ (average 7 g/m³) (Mykhailov et al. 2008a). This deposit includes several sites, two of which were opened by quarries No. 472 and No. 43 (Velykiy Pugach).

Quarry 472 is located 1.5-2 km south of the Klesiv railway station. The amber-bearing horizon, exposed by the side of the quarry for 700 m, lies horizontally on the weathered crust of crystalline rocks and is overlain by white quartz sands of fluvio-glacial origin. The productive horizon, 2-2.5 m thick consists of lower and upper layers. The lower layer is represented by Kharkivska Series rocks – fine-grained quartz sands mixed with unevenly distributed humus material and coalified plant

remains. Pebbles of the basement rocks and black unrounded flints occur at the bottom of the layer. The amber content in these rocks is 50 g/m^3 . The upper layer, which belongs to Poltavska Series, is distinguished by the presence of a significant amount of clayey material and lignite lenses (60-75% of the total rock) with a high content of plant detritus. In a wet state, the rock is black and viscous; when cut, it gets an earthy-peat color. The amber content in these rocks is $300\text{-}500 \text{ g/m}^3$; it is present in the form of fragments, pieces of complex morphology, rarely – rolled pebbles. At least 14 tons of amber are estimated in a productive area of 200 by 700 m^2 .

The quarry No. 43 (Velykiy Pugach) site is located 7-8 km northwest of the Klesiv railway station. The amber-bearing horizon is exposed directly above the weathering crust of crystalline rocks. It has a total thickness of 1.0-1.5 m and is formed by three sand layers (Fig. 5.24). The lower one (0.2-0.3 m) is represented by fine-grained greenish-grey quartz-glaucinite sands with an admixture of clayey material and lenticular black layers enriched with semi-coalified plant remains. Amber fragments up to 10 cm in size are found in this layer. A middle 60-cm thick layer comprises dark-grey quartz sand, depleted in amber. The upper amber layer (15-20 cm) is represented by fine-grained, brownish quartz sand with dark brown to black spots enriched with humus material. Larger rolled pebbles of amber weighting up to 400-600 g are found here. A facies change from continental flood-swamp and delta facies to marine beach facies is observed in the productive horizon from the southeast to the northwest. The productive horizon of Klesivske deposit is overlain by Quaternary fluvio-glacial, grey, fine-grained sands with cross-bedding.

The Vilne deposit is also confined to the Oligocene Mezhygirska Suite composed of greyish-green and blue-grey glauconite-quartz sands with clay interbeds. Amber is confined to the layers of clay and humused areas, with flints and grey quartz fragments, in the contact zone with underlying Kyivska Suite sands. The average thickness of the productive layers is 0.7 m. The amber content is from $1\text{-}2 \text{ g/m}^3$ to 650 g/m^3 ; the average is $44.0\text{-}63.2 \text{ g/m}^3$.

The Dniproviskiy Basin on the northeastern margin of the Ukrainian Shield has alluvial deposits of the Dnipro River and its tributaries. Two promising areas are distinguished – Dnipropetrovska and Kanivska. In the first, amber occurs in the lower part of a sand layer (0.5-15 m thick) of the Dnipro River, overlying clays and sands with glauconite. Individual pieces of amber are over 500 g in weight. In the Kanivska area, amber is found in white and yellow alluvial sands with interbeds of plant remnants and animal bones, as well as in underlying glauconite sands.

The Dnisterskiy Basin in the Fore-Carpathian Depression is composed of Miocene amber-bearing sandstones and sandy limestones, and Upper Oligocene bituminous clay shales.

Amber in the Trans-Carpathians occurs in Lower Oligocene quartz sandstones.

Absolute age, Ma	System, Division, Subdivision				Column	Thickness, m	Rock lithology	
	Modern Holocene					0.3	soil	
	Quaternary					0.3-0.6	fine-layered quartz sands	
12 30	Paleogene	Miocene	Lower	Poltavska Series		0.6-0.8	quartz sands, dark-grey clays with plant remnants, amber	
						0.6	dark-grey clays with plant remnants, sands, plant remnants, amber	
			Oligocene		Upper		0.2	quartz sand with coal lenses and fragments
							0.3	quartz sand with coal lenses and fragments, amber
		Lower			0.1	quartz sands		
					0.5	humus-bearing sands, pebble, amber		
				0.2	quartz sand with coal lenses and fragments			
70	Cretaceous					0.4	redeposited weathering crust	
						15-20	normal weathering crust	
	Proterozoic						crystalline basement	

Fig. 5.24. The lithostratigraphy of amber-bearing sediments of the Klesivske deposit exposed in the quarry No. 43 (Velykiy Pugach) (modified after Mykhailov et al. 2008a)

5.3.9.2. Marble Onyx

It is used for the manufacture of various artistic products, and as a decorative and cladding material for interior decoration.

In Ukraine, occurrences and deposits of marble onyx are known in Middle Transnistria, including the Kalyusyk deposit and the Demkivskiy, Mytsivskiy, Kravchynskiy, and Suprunkivskiy occurrences.

The Kalyusyk deposit in the Khmelnytsky region is in Lower Sarmatian shell and oolite-shell limestones with an average thickness of 9 m. Marble onyx is found in 12 large fractures, mostly striking NNE-SSW. It either forms a continuous crust on the fracture walls with a wavy surface with a thickness up to 5 cm, or in some areas it completely fills the fractures. Marble onyx is also present in the form of stalactites and stalagmites in cavities in the host limestones. Some onyx vein swelling up to 30 cm thick are also noted.

Fine-grained and coarse-grained marble onyx has been identified. The first is represented by light- and dark-brown varieties with a radial-ray structure and a persistent wavy-banded pattern. Massive, economic-grade parts of veins 1-1.5 m long are separated by the non-economic (barren) parts. The second, coarser grained variety is a uniform light-yellow onyx, sometimes with alternating honey-yellow and light-brown bands. It is less attractive than the finer grained onyx. Reported reserves of the deposit are 213 tons by category C₂ (Mineral Resources of Ukraine 2021).

Marble onyx is also known in Podilsky Tovtry at Zarichanskiy, Demykivskiy, Boryshkivetskiy and Suprunkivskiy with prognostic resources by category P₃ of 70 t (Mineral Resources of Ukraine 2021).

5.3.9.3. Rhodonite

This mineral (MnSiO₃) is a traditional decorative stone. In Ukraine, the SIMR includes the **Prelutske deposit** (Fig. 5.25) in the Trans-Carpathians. This deposit is in a Paleozoic metamorphic complex of sericite-chlorite-quartz, sericite-quartz and chlorite-sericite schists as lenticular bodies of rhodochrosite (MnCO₃) 100×60×10 m³ in size. Raspberry rhodonite forms disseminated individual, or clusters of small grains, and as veins in the rhodochrosite. Rhodonite reserves are equal to 419 tons (Mineral Resources of Ukraine 2021).

5.3.9.4. Jet

This is a jewel of organic origin; it is a black viscous variety of brown coal. In Ukraine, jet is known in Mountain Crimea, associated with Middle Jurassic Bajocian coal-bearing sediments. The **Beshuyske brown coal deposit** comprises brown coal layers interbedded with clays and sandstones. The brown coal layers can be traced along N-S strike for 1100 m, and dip to the west at an angle of 40-45°. Down-dip, they can be traced for 350-400 m. The jet in the form of lenses and small grain clusters is found in both the hanging-wall and foot-wall of individual coal (vitrain)

beds. The jet is typically dense, shiny, black with a mat sheen. Its absolute hardness is 170-177 kg/mm² with a density of 1.24 g/cm³. In thin sections it is a brown bituminous substance with an aphanitic texture and characteristic thin growth rings, sometimes with fine pyrite disseminations. The jet of Beshuyske deposit is suitable for processing and is easily polished. The products from this jet have an attractive and elegant appearance.

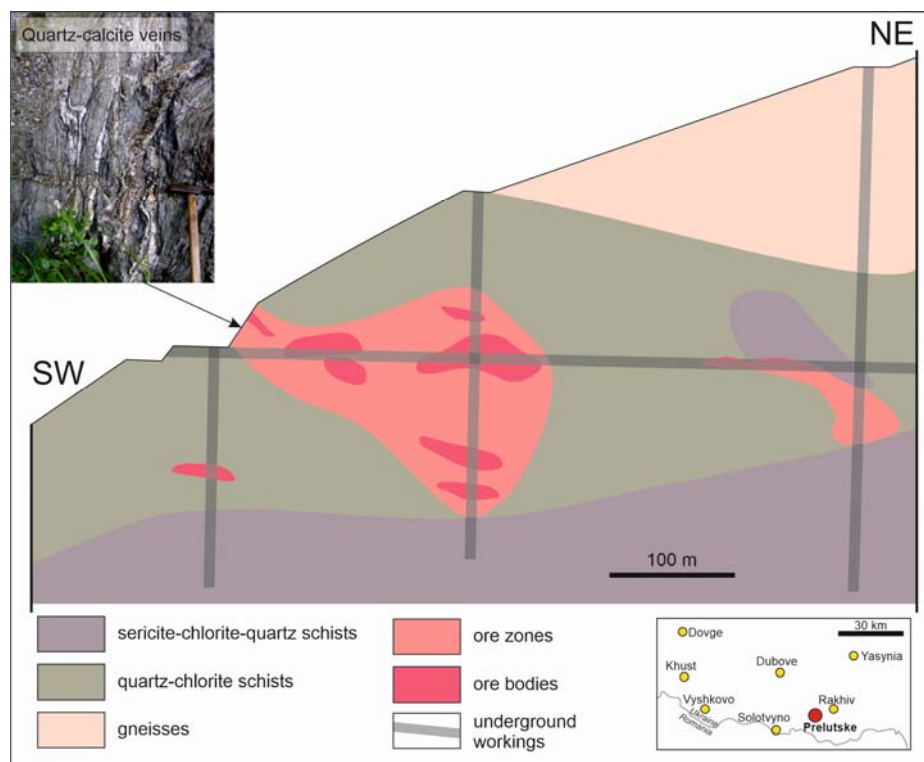


Fig. 5.25. Cross-section of the Prelutske rhodonite deposit (modified after Mykhailov et al. 2008a)

5.3.9.5. Diamond

This is a precious stone used in jewellery, but it is also used in many technical (industrial) processes; for example in cutting and abrading hard materials, as a component of drill bits, and in medical technology.

In 2019 the World production of gem quality diamonds reached about 78 million carats. The main producers are Russia, Canada, Botswana, Angola (together 89% of world production), as well as South Africa, DR Congo, and Namibia (Table 5.42). In recent years, there has been an increase in production in Canada, Botswana and Tanzania, and a decrease in South Africa and the DR Congo.

Table 5.42. World jewelry diamonds mining production (World Mining Data 2021)

Country	Production, thousand carats				
	2015	2016	2017	2018	2019
Russia	25,147.4	24,431.8	21,860.5	22,973.1	25,804.6
Canada	11,677.5	13,315.3	23,198.8	22,789.0	18,402.8
Botswana	14,576.8	14,623.7	16,058.7	17,064.6	16,580.9
Angola	8,117.0	8,119.3	8,494.9	7,567.8	8,234.8
South Africa	3,293.2	3,222.2	3,877.0	3,964.7	2,872.3
DR Congo	3,150.7	3,111.9	2,268.3	1,815.7	2,020.5
Namibia	1,676.1	1,494.4	1,713.8	1,985.7	1,722.8
Sierra Leone	420.2	418.0	165.9	402.5	433.1
Tanzania	184.0	203.9	258.8	324.1	354.2
Australia	271.2	279.2	342.7	280.2	243.1
Other countries	1,531.1	1,249.2	1,412.8	1,703.1	1,219.3
Total	70,045.2	70 468.9	79,652.2	80 870.5	77,888.4

The world's reserves of industrial diamonds are about 1,100 million carats. These are mainly found in Russia (59% of world reserves), DR Congo, Botswana, South Africa, and Australia. However, global production in recent years has decreased from 71 million carats in 2017 to 58 million carats in 2019. The main mining countries are presently Russia, Australia, DR Congo, which together provide 73% of world production. Industrial diamonds are also mined in Botswana, South Africa, Zimbabwe, Angola, Lesotho, and other countries (Table 5.43).

Table 5.43. World industrial diamonds mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, thousand carats					Reserves, million carats
	2015	2016	2017	2018	2019	
Russia	16,765.0	16,287.8	20,754.3	20,187.9	19,466.6	650
Australia	13,289.6	13,678.8	16,792.0	13,727.9	11,911.5	40
DR Congo	12,602.8	12,447.6	16,634.4	13,315.5	11,449.2	150
Botswana	6,247.2	6,267.3	6,882.3	7,313.4	7,106.1	90
South Africa	4,939.8	4,983.3	5,815.6	5,947.1	4,308.4	54
Zimbabwe	2,352.0	1,493.1	1,755.5	2,276.7	1,483.4	n.a.
Angola	901.9	902.1	943.9	840.9	915.0	n.a.
Lesotho	243.4	273.6	901.1	1,035.4	890.8	n.a.
Sierra Leone	79.9	131.6	122.4	339.1	391.4	n.a.
Brazil	21.3	123.0	170.8	168.1	108.1	n.a.
Other countries	330.3	272.8	325.4	371.3	283.2	116
Total	57,773.2	56,861.0	71,097.7	65,523.3	58,313.7	1,100

Numerous findings of small, transported (detrital) diamonds in terrigenous (mostly alluvial) deposits of different ages and lithologies are known in Ukraine. Kimberlites and lamproites, potential host rocks to diamonds, are also known in the Azovian, Volyn, and Kirovograd regions. Therefore, although diamond occurrences of economic significance have not yet been identified in Ukraine, the possibility of

finding such occurrences cannot be excluded (Gurskiy et al. 2003).

Dozens and even hundreds of small diamond grains have been found in the following sediments (Kvasnytsia et al. 2003; Prospects for diamond mineralization 2006; Yatsenko et al. 2006) (Fig. 5.26):

- Quaternary sediments of Transnistria, Pobuzhye, Middle Dniprean, Donbas, Fore-Black-Sea, and Azovian;
- Pliocene-Miocene sands of Baltska Suite in between Dnister and Southern Boug rivers;
- Miocene Sarmatian and Poltavaska Series sands of the north-eastern margin of the Ukrainian Shield;
- Lower Permian gravelites and diverse-grained sandstones of Kartamyska Suite of Donbas;
- Carboniferous Samarska, Isaivska, Avilivska, Araukaritova Suites of Donbas;
- Neoproterozoic conglomerates and sandstones of Bilokorovytska Suite of the Ukrainian Shield.



Fig. 5.26. Distribution of diamond findings and prospective sites in Ukraine (modified after Kvasnytsya, Tsymbal 1998).

There are also numerous findings of diamonds in the Neogene zircon-ilmenite placers of the Baltska Suite sediments, and in modern alluvium (in the Pobuzkiy area from Shepetivska, Berdychivsko-Vinnytska, Skvyrsk and Prydnistrovska sites). Detrital diamond findings in Quaternary and Meso-Cenozoic sediments, in zircon-

ilmenite placers (Samotkanska etc.), are known in the Middle Dniprean region. In the sedimentary cover of the Azovian megablock, isolated diamond findings are known in the alluvium of the Kamyshuvakha and Mokra Volnovakha Rivers, and in the Balka Shyroka gully (Fedoryshyn et al. 2001).

There are prospects of searching for hard-rock diamond deposits given that kimberlite fragments have been identified in heterogeneous breccias in Kukhitsko-Vilska, Serkhivska and Perekalska sites in the Volyno-Podilska Plate. The Novograd-Volynska site is promising in the Volyn megablock of the Ukrainian Shield, where diamond grains (more than 200) of 0.2-4 mm in size, mostly of kimberlite origin (75%) were encountered, as well as kimberlite indicator minerals (pyrope, chromium spinel, chromium diopside, and picroilmenite).

Kimberlites and picrite-kimberlites containing chromium spinels were found in the Kirovograd megablock of the Ukrainian Shield.

In the Azovian region, the Petrovsko-Kumachivske kimberlite field includes the Petrovske ($400 \times 200 \text{ m}^2$) intrusion, traced to a depth of 30-50 m, and composed of intensively carbonated kimberlite breccias with chromium spinels. Other kimberlites in this field include the Nadiya ($60 \times 30 \text{ m}^2$), Pivdenna ($300 \times 150 \text{ m}^2$), and Novolaspinska ($100 \times 40 \text{ m}^2$) pipes, and a number of kimberlite dykes. However, of the hundreds of microprobe analyzes of chromium spinels, only a few from Pivdenna and Novolaspinska pipes correspond to the mineral composition of diamond-bearing facies. Besides that, occurrences of lamproite magmatism are known: "Mria" pipe ($500 \times 350 \text{ m}^2$), where small diamond grains are found in weathering crust

In addition, diamond occurrences are known in Ukraine associated with impact structures, in particular with a western structure in the Vinnytsia region (Valter et al. 1999; Gurov, Gozhik 2006; Gurov et al. 1996). Impact diamonds are found in the crater rocks; the diamond-bearing rocks are outlined, but the economic feasibility of their development had not been proven due to the high cost of beneficiation.

5.4. Raw Materials with Uncertain Prospects

The types of raw materials with unclear economic potential include the following non-metallic minerals that are of strategic importance for the economy of Ukraine: barite, boron, dawsonite, bromine and iodine, mineral sorbents, high-alumina raw materials, raw materials for mineral paints, fluorine, sulphur.

5.4.1. Barite

It is used in drilling; in the manufacture of paint, rubber, paper, and glass; in chemical, construction and medical industries; as well as for radiation protection as a filler.

World reserves of barite are about 300 Mt. World production in recent years has fluctuated around 9 Mt, the largest mining countries are China, India, Morocco, which together provide 68% of world production, as well as Kazakhstan, Mexico, USA, Turkey, and other countries (Table 5.44). Note the increase in barite production in Mexico, but the decrease in Iran.

Table 5.44. World barite mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
China	2,984.0	2,771.1	3,100.0	2,900.0	2,900.0	36
India	1,252.3	1,262.5	2,050.2	2,000.0	2,000.0	51
Morocco	1,212.1	668.5	818.0	899.4	1,119.8	n.a.
Kazakhstan	752.3	612.3	569.9	773.2	530.6	85
Mexico	265.7	173.8	359.9	366.2	415.2	n.a.
USA	433.0	232.0	334.0	366.0	414.0	n.a.
Turkey	655.9	321.2	292.4	465.1	413.8	35
Iran	1,085.7	1,449.0	514.7	477.2	247.2	24
Russia	210.0	434.0	221.0	265.3	163.0	12
Pakistan	118.8	157.9	91.7	88.8	116.7	26
Other countries	765.1	660.7	602.5	549.3	494.3	31
Total	9,734.9	8,743.0	8,954.3	9 150.5	8,814.6	300

In Ukraine, barite occurrences are known in the Trans-Carpathian Depression, where the **Biganske** complex' barite-gold-polymetallic deposit is being explored. It is composed of Tortonian and Middle Sarmatian Dorobrativska Suite sediments (1200-1500 m), where secondary quartzites, beresites, propylites are common (Fig. 5.27). Barite is found in secondary quartzites, kaolinized rocks, and less often in alunite ores. It occurs as monomineral veins and disseminated grains. The largest vein-shaped barite body (7-25 m thick) is confined to the Travneva Tectonic Zone with a thickness of 10 to 100 m; a strike length of 1950 m and 500-600 m down-dip. This zone is complicated by apophyses, and smaller ore zones were discovered. A vertical ore zonation is often displayed: quartz-barite ores of the upper horizons contain 37-

40% of BaSO_4 , up to 30% of kaolinite and alunite, whereas in barite-polymetallic ores of the lower horizons BaSO_4 content is from 19 to 85%. Reserves of barite ores are 2.5 Mt by category B+C₁ and 1.0 Mt of barite, by category C₂ – 0.4 Mt of ore and 0.2 Mt of barite. Development of deposit was carried out by SE "Shtorman-Ukraine GMBH2", but in 2020 barite was not mined (Mineral Resources of Ukraine 2021).

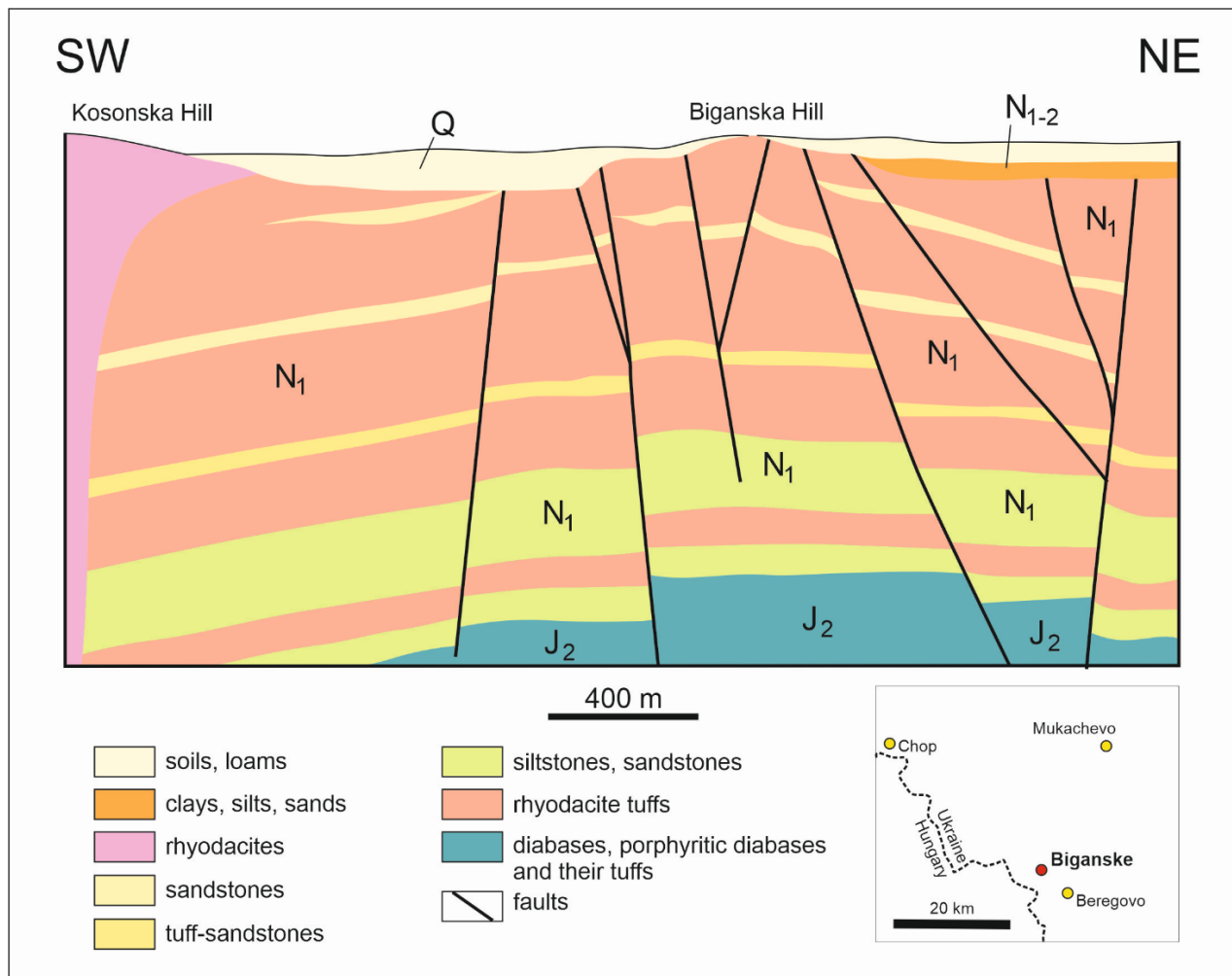


Fig. 5.27. Cross-section of the Biganske deposit (modified after Mykhailov et al. 2008a)

In the upper horizons of the **Beregivske gold-polymetallic deposit**, barite mineralization has also formed in the tuffs, tuff-lavas, and ignimbrites of the Lower Sarmatian Dorobrativska Suite, that have subsequently been intensively altered to secondary quartzites. The mineral composition of ore comprises galena, sphalerite, gold, silver, marcasite, quartz, barite, chalcedony, hydromica, kaolinite and alunite. Barite is mostly disseminated and of two morphological varieties – tabular and columnar.

Non-economic barite occurrences have also been discovered in the Ukrainian Shield, the Donbas, the DDD, and Crimea.

5.4.2. Boron

It is used in the glass and ceramic industries, in the manufacture of heat-resistant alloys, in petroleum chemistry, in the manufacture of permanent magnets, abrasives and electro chemicals, in organic synthesis, in aircraft, rocket and nuclear energy, as well as in fertilizers.

World boron production exceeds 4 Mt. The major producers are Turkey (49% of world production), the USA, Chile, China and six other countries. Of these only China has significantly increased boron production in recent years, while the USA, Chile and Argentina have reduced their production (Table 5.45).

Table 5.45. World boron mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
Turkey	1,840.0	1,831.0	2,025.0	2,432.0	2,040.0	1,100
USA	1,218.0	1,134.0	1,075.0	1,075.0	1,030.0	40
Chile	517.6	558.9	607.1	398.4	352.3	35
China	90.0	80.0	70.0	80.0	250.0	24
Bolivia	148.7	182.7	208.4	216.4	214.3	n.a.
Peru	578.9	33.8	0	100.6	111.1	4
Russia	82.0	78.8	82.5	88.0	80.4	40
Argentina	248.7	148.4	129.9	71.2	54.7	n.a.
Kazakhstan	30.0	30.0	30.0	30.0	30.0	n.a.
Iran	0.5	0	0.8	0.8	2.0	n.a.
Total	4,754.4	4,077.6	4,228.7	4 492.4	4,164.8	1,243

In Ukraine, boron occurrences are known in the DDD, on the Kerch Peninsula, in the Fore-Black-Sea Depression and in the Trans-Carpathian and Fore-Carpathian depressions.

In the DDD, the Lower Permian salt Slovyanska Suite in the Bakhmutska Dimple is boron-bearing, where borates (boronatrocalcite, probertite, kernite, hydroboracite, inyoite inderite) are found in gypsum of the leaching zone, and groundwater and brines contain up to 1.05 g/kg of boron.

On the Kerch Peninsula, the Bulganatske deposit with B_2O_3 reserves in category B+C₁ – 53.7 kt, and the Tarkhanske deposit with B_2O_3 reserves in category B – 8.7 kt, have been quantified. Economic boron concentrations (1000-1599 mg/kg) are found in chloride-bicarbonate and bicarbonate-sodium spring waters, in the liquid fraction of volcanic mud, in Neogene and Paleogene groundwater in the areas of mud volcanism and in the brines of Chokratske Lake (335 mg/kg).

In the Fore-Black-Sea Depression boron occurrences are associated with bottom sediments and brine of the lakes and the Azov Sea. The content of B_2O_3 varies from trace amounts to 0.02%. The highest concentration of B_2O_3 in groundwater is found in the Upper Cretaceous aquifer (0.665 g/kg), in Jurassic sediments at depths of 571-

1779 m where mineralization is 35-101 g/kg and B_2O_3 concentration is from 0.018 to 0.069 g/kg.

In the Trans-Carpathian Depression, groundwater with high boron content (0.01-0.209 g/kg) is widespread in the aquifer of the Novoselytski tuffs.

In the Fore-Carpathian Depression, high boron content is observed in clays, mudstones and saline breccias of the Upper Vorotyshchenska and Lower Balytska Suites, in the gypsum-clay caps of salt-bearing columns, in Miocene salt-bearing sediments (0.0025-0.25%), in natural brines and mineral springs related with these sediments (17-70 mg) and in the waters of oil fields.

5.4.3. Dawsonite

It is used in pharmacology as a raw material in the production of aluminium and soda ash.

In Ukraine, occurrences of dawsonite are found in sediments of the Solotvynska Depression, in the Folded Carpathians, and in mercury-ore fields of the Donbas, but have no industrial significance.

In the Solotvynska Depression dawsonite fills fractures and cavities in mudstones, siltstones and sandstones of the Miocene Novoselytska and Teresvynska Suites, where it forms snow-white silky clusters in the form of spherulites, globules, crusty aggregates and veins. Dawsonite is found at a depth of 123.2-464.1 m at the Bushtynska site where the average thickness of the ore bed is 21.7 m and the average content of dawsonite is 10.84%. Prognostic resources of dawsonite ores are 279 Mt and of dawsonite 30.2 Mt. The Ruske Pole deposit, the biggest in the Trans-Carpathians, contains 125 Mt of ore with the volume of dawsonite and natural soda being 7%.

In the Donbass, occurrences of dawsonite are found in the Kindrativska (Druzhkivsko-Kostyantynivska Anticline) and Slovyanska (Adamivsko-Bugaivska salt-dome structure) areas.

At the **Kindrativska site**, dawsonite is found in stratiform bodies and shear zones 7 km long by strike and up to 600 m by dip. It fills pores in sandstones, cavities of the plant root system, makes up small rosettes in cement and fills crusts and plaques on the friction planes of fractures. The content of dawsonite is 1-10%, and prognostic resources in category P_2 , with dawsonite cut-off-grade at 5% are 5.1 Mt.

At the **Slovyanska site**, soda mineralization is located in the overstock breccia, at depths of 420-940 m, in the form of a lens with an area of 0.9 km². Dawsonite occurs as micro-concretions (0.2-0.5 mm), fills fractures, and together with ankerite and calcite forms radial-ray aggregates and occurs in cement. Dawsonite distribution is uneven, the content ranging from 5 to 22% (average 11.6%). Prognostic resources in category P_1 are 3.96 Mt at a 10% cutoff-grade and 5.5 Mt at a 5% cutoff-grade.

The breccias of salt-dome structures in the DDD (Novodmytrivska, Stepkivska, Beretska, Lozivska, Nizhynska, Tvanska, Ivanogradska, Parafiiivska, Ivanytska, Synivska, etc.) are also thought to be promising for dawsonite.

5.4.4. Bromine and Iodine

These are used in medicine, photography, the chemical industry, agriculture, jet technology and in the production of high-purity metals and more.

World production of bromine is 420 kt, the main producers are Israel and Jordan, which together provide 79% of world production, in addition to that of China, Japan, Ukraine, India and Other Countries (Table 5.46).

Table 5.46. World bromine production and reserves (USGS 2020)

Country	Production, kt		Reserves, kt
	2018	2019	
Israel	175	180	Big
Jordan	100	150	Big
China	60	60	n.a.
Japan	20	20	n.a.
Ukraine	4.5	4.5	n.a.
India	2.3	2.3	n.a.
Other Countries	0.2	3.2	
Total	362	420	Big

World reserves of iodine are 6.3 Mt, the largest concentrated in Japan (79%), as well as in Chile, Azerbaijan, Russia, Indonesia and Turkmenistan. The maximum iodine mined, 28 kt to date, has mostly been produced by Chile (64% of world production) and Japan (32%), with lesser amounts from other countries as well (Table 5.47).

Table 5.47. World iodine mining production and reserves (USGS 2020)

Country	Mining production, t		Reserves, kt
	2018	2019	
Chile	18,000	18,000	610
Japan	8,800	9,000	5,000
Turkmenistan	540	600	70
Azerbaijan	200	200	170
Indonesia	38	40	100
Russia	8	10	120
USA	n.a.	n.a.	250
Total	27,586	27,850	6,320

In Ukraine, the SIMR records bromine in brines of the Syvaske deposit, which was developed by PJSC "Crimean Soda Plant", to the amount of 242 kt of bromine (A+B+C₁). In 2020 there was no mining (Mineral Resources of Ukraine 2020). An important source of bromine production is the groundwaters of the Fore-Carpathian Depression, the DDD and the Fore-Black-Sea Depression. The trapped water in oil and gas deposits are also thought to be promising.

The Syvash Lake is a shallow bay of the Azov Sea, which is characterized by the almost complete absence of constant freshwater runoff. Under such conditions, the

salt water of the Azov Sea is permanently transformed into brine – a concentrated solution of salts: $\text{Ca}(\text{HCO}_3)_2$, CaSO_4 , CaCl_2 , MgSO_4 , MgCl_2 , KCl and NaCl . Average concentrations of elemental bromine in brine are: water of Azov Sea – 12 g/m^3 , brine of Eastern Syvash – 70 g/m^3 and Middle and Western Syvash – $170\text{-}230 \text{ g/m}^3$.

Occurrences of iodine are known in the Fore-Black-Sea Depression and the DDD, and in the Fore-Carpathian and Indo-Kubanska Depressions.

Industrial iodine waters of the ***Pivnichno-Syvaske deposit*** in the Kherson region occur in the Upper Palaeocene-Middle Eocene beds of siltstones and sandstones at a depth of 1300-1600 m. The waters of the productive complex are sodium chloride with a mineralization of 26-34 g/l. Water temperature in the beds is 58-59.3°C. The average moisturized iodine content in the water intake area is 29.8 mg/l, and over the whole deposit – 30.1 mg/l.

Table 5.48. Content of useful components in industrial waters, Pivnichno-Syvaske deposit

Component	Content, mg/l
Bromine	85-86
Boron	58-64
Potassium	133-154
Lithium	0.9-1.1
Strontium	52-62

The harmful impurities content is within acceptable limits. Industrial waters of the deposit, in addition to iodine, contain other useful components (Table 5.48). Approved operational reserves of iodine waters in category A+B+C₁ are 33.6 thousand m³/day with an average iodine content in water of 29.8 mg/l. The amount of iodine in water for one year is 365 tons, and for 25 years – 9,125 tons.

5.4.5. Mineral Absorbents (Zeolite, Vermiculite)

5.4.5.1. Zeolite

It is used as a "molecular sieve" (selective absorbents) in the purification of solutions, products of chemical reactions, water, separation of gases and liquids and hydrocarbons; as ion exchangers – cationic sieves for extraction of radioactive elements from nuclear energy wastewater and processing of radioactive solutions; as catalysts for the reactions of hydrocarbons, etc. and in the cracking, isomerization, polymerization and dehydration of alcohols; as fillers in the paper industry; and as feed additives, for the vulcanization of rubber and production of hydraulic cement, etc.

World production of zeolites is 1.2 Mt, and the largest producers are China, the Republic of Korea, Indonesia and Slovakia, which together provide 60% of world production (Table 5.49).

Table 5.49. World zeolite mining production (USGS 2020)

Country	Production, kt	
	2018	2019
China	320	320
Republic of Korea	144	150
Indonesia	130	130
Slovakia	117	120

Country	Production, kt	
	2018	2019
USA	86	98
Turkey	65	65
Cuba	52	55
Russia	35	35
Jordan	10	10
Other countries	75	75
Total	1,034	1,058

In Ukraine, the SIMR records three zeolite deposits in the Trans-Carpathian region (Sokyrnytske, Sarygych, Zelenokamyane) with reserves (A+B+C₁) of 125.3 Mt, and in category C₂ – 154.9 Mt (Mineral Resources of Ukraine 2021).

The Sokyrnytske deposit is confined to zeolitized tuffs of the Late Tortonian Teresvynska Suite, represented by two layered bodies 40-60 m thick, separated by mudstone beds (16-25 m thick). The content of clinoptilolite is 30-70%. The deposit is being developed by OJSC “Zakarpaterudprom” and “Sokyrnytskiy Zeolite Plant” LLC. Zeolites are used in animal and poultry husbandry as a feed; in agriculture as ameliorants to improve crop yields and as a substrate for growing greenhouse crops; and in treatment facilities as filters for urban wastewater and drinking water. They are also used in industry for the purification of various gases from sulphur hydrogen, organosulphur compounds and carbon dioxide; for the purification of petroleum products, natural gas and hydrogen; for the release of oxygen and nitrogen from air; and in the production of building materials and detergents etc.

The Karadazke deposit in Crimea is represented by irregularly-shaped bodies (up to 160 m thick) of mordenite (20-80%), which is an alteration product of volcanic glass in the Jurassic basalt tuffs.

5.4.5.2. Vermiculite

It is used as a lightweight concrete filler, as raw material in the production of refractory heat and sound insulation, fire-retardant plasters, insulation of metallurgical furnaces, and in the production of anti-friction materials, plastics, pesticides, rubber, and paints, and in agriculture, wastewater treatment, space technology, aerospace and transport construction.

World production of vermiculite in recent years has ranged between 416 and 434 kt, the majority produced by South Africa (38% of world production) and the United States (24%), as well as by China, Brazil, Zimbabwe and Other Countries (Table 5.50).

Table 5.50. World vermiculite mining production and reserves (World Mining Data 2021; USGS 2020)

Country	Production, kt					Reserves, Mt
	2015	2016	2017	2018	2019	
South Africa	138.3	166.5	166.1	141.3	158.0	14.0
USA	100.0	100.0	100.0	100.0	100.0	25.0

China	50.0	50.0	50.0	50.0	50.0	n.a.
Brazil	54.3	53.3	50.1	50.0	47.6	6.2
Zimbabwe	30.9	29.3	23.3	33.2	26.2	n.a.
Russia	21.0	20.0	14.4	25.9	20.0	n.a.
Uganda	1.2	3.3	4.1	10.4	9.7	n.a.
India	23.3	9.0	6.1	3.0	2.8	1.6
Turkey	0.4	1.1	1.6	18.2	1.4	n.a.
Other countries	9.9	1.5	0.4	0.2	0.2	n.a.
Total	429.3	434.0	416.1	432.2	415.9	46.8

In Ukraine, more than 50 occurrences of vermiculite are known in the Ukrainian Shield, where the Kamyanomogylskiy occurrence is located in the Azovian megablock, and in the central part of the Shield where 14 promising areas with resources in categories P₁ and P₂ amounting to 32.8 Mt (Mineral Resources of Ukraine 2021).

Vermiculite occurrences in the Azovan megablock (Kamyanomogylske, Andriivske, Rodionovske) are associated with weathering crusts of gabbroids and gneisses, in weathering crusts of Precambrian metamorphic and ultramafic rocks of the Orikhovo-Pavlogradska Zone, and in the Volyn megablock (Slavgorodskiy, Lypovenkivskiy, Kolarivskiy). They have no industrial value.

The Kamyanomogylskiy occurrence is represented by weathering crust on mica-altered mafic rocks and biotite-enriched gneisses of the Manguskiy Complex. The average thickness of the productive horizon is 10.3 m, the content of hydrobiotite and vermiculite is 16.01% and the average overburden thickness is 10.3 m. The coefficient of swelling of vermiculite-hydrobiotite is 6.0-5.8 and water absorption is 107-415%. Heat-treated hydromica has a bulk density of 420 kg/m³. Vermiculite resources reach 1860 kt.

The Andriivskiy occurrence is represented by weathering crust on the ultramafic rocks and on biotite and amphibole-biotite gneisses of the Zakhidnopryazovska Series. The thickness of the ore horizon is 14.1 m and that of the overburden is 3.1 m. Vermiculite is developed mainly after biotite in the ultramafic rocks and makes up 25% of the ore. Hydrobiotite replaces biotite in the gneisses with an average content of 31.8%. The predominant size of the flakes is 0.1-0.5 mm with a density of 2.7-3.1 g/cm³. Hydro-mica resources are 848 kt.

The Rodionivskiy occurrence is represented by weathering crusts of biotite, garnet-biotite, sillimanite-biotite and muscovite-biotite schists with lenses of amphibolites, and amphibole- and chlorite-actinolite schists of the Osypenkovska Series. The thickness of the ore sequence is 12 m, and the overburden 10.1 m. The hydrobiotite content in the ore is 22.4% and vermiculite up to 1%. Other minerals in the ore include quartz and plagioclase (60%), muscovite and chlorite (11.5%), garnet (4.3%) and hornblende (2%).

The Slavgorodskiy occurrence is confined to the sequence of Archean gneisses and amphibolites of the Aulska Series together with serpentinite and biotite altered bodies of dunites and peridotites of the Devladiivskiy Complex. The maximum mica alteration of ultramafic rocks is observed at their contact with the gneisses. This zone

can be traced sub-horizontally for 1 km at a width of up to 200 m. The thickness of vermiculite-bearing layers is up to 10-30 m which can be traced to a depth of 50-70 m. The content of vermiculite and hydrobiotite in the ore bodies is up to 25%, and impurities of serpentine, tremolite and talc are also recorded. Vermiculite is partially replaced by montmorillonite near potassium feldspar veins. The bulk volume by weight of the expanded mass of enriched concentrate of hydromica is 200-340 kg/m³, and the degree of hydration and oxidation is FeO – 0,83-2,11%, Fe₂O₃ – 2.67-4.24, H₂O – 1-2%, LOI – 11.12-12.07%, and a thermal conductivity coefficient of 0.15-0.17 kcal/m·h·deg. Prognostic reserves of the deposit are 700 kt.

The Lypovenkivskiy occurrence is confined to the ultramafics of the Lypovenkivskiy Massif, where the zone of mica alteration is 250 m long and 50 m wide. Five vermiculite-bearing vein-like bodies and hydromica disseminations in fine fracture are defined in this zone. The length of the bodies is 70-160 m, the thickness is 3-8.5 m, and they can be traced to 50 m down dip. The content of hydromica is 40-80%. Bulk volume by weight of the expanded hydromica concentrate is 250-500 kg/m³. Prognostic reserves of vermiculite amount to 190 kt and hydrobiotite to 97 kt.

The Kolarivskiy occurrence is represented by vermiculite-bearing weathering crust after phlogopite lamproites of the Kolarivskiy Complex, 4-24 m thick (average 19.3 m), 4.11m of overburden and an average vermiculite content of 22.5%. Prognostic vermiculite reserves are 700 kt.

5.4.6. High-Alumina Raw Materials (Sillimanite, Disthene, Andalusite)

These are used in the production of high-quality refractories, alkali-acid-resistant products and metal ceramics.

In Ukraine, occurrences of sillimanite, disthene and andalusite are associated with Precambrian metamorphic sequences of schists and gneisses of the Ukrainian Shield in the Pobuzhye and Pryazovya (sillimanite) areas in the Kryvorizko-Kremenchutska Zone (andalusite, sillimanite) and in the Ovruchska Series of the Volyn megablock (disthene, sillimanite).

The SIMR records reserves of disthene and sillimanite in placer complex deposits – Malyshevske (under development) and Vovchanske, as well as two technogenic deposits at Balka Kruta in the Dnipropetrovsk region and at Tarasivske in the Kyiv region. Total reserves in category A+B+C₁ total 1826.7 kt. Production of disthene-sillimanite concentrate in 2020 amounted to 33.8 kt (Mineral Resources of Ukraine 2021).

Hard-rock occurrences of andalusite (the Guliaypilske iron-ore deposit) together with sillimanite (the Dragunske corundum-sillimanite deposit, the Pavlivske, Sergiivske, Novoukrainske, Korsatske, Kuksungurske and Mariupolske iron-ore deposits and the Smyrnovskiy and Andriivskiy occurrences) in Pryazovya, and sillimanite (the Kapitanivskiy and Solomiivskiy occurrences) in Pobuzhye, and disthene (the Perzhanske deposit and the Pobyhanskiy occurrence) in the Sushchano-Perzhanska Zone; are the most promising. Reserves of hard-rock deposits are small and have not been recorded in the SIMR (Fig. 5.28).

The Dragunske deposit is located in the Temryutska Suite a productive horizon, 150-300 m thick (average 220 m) and 15 km long, which includes parcels, layers, interbeds and lenses (0.2-15 m) of sillimanite, sillimanite-biotite, sillimanite-garnet-biotite, sillimanite-cordierite-biotite, spinel-sillimanite-biotite, often with corundum, gneisses and schists in migmatites and porphyritic granites. The sillimanite content is 1 to 45% (average 10-14%), and forms needle-like, prismatic crystals, sheaf-like, radiant and tangled-fibrous aggregates, inclusions in feldspars and thin intergrowths with biotite. The size of individual grains is up to 15 mm in length. Corundum content is 6-16% (average 1-5%). These high-alumina rocks contain 25-30% and up to 38% Al_2O_3 . Prognostic resources to a depth of 200 m are as follows: sillimanite (P_3) 61 kt, with an average content of 10-12%; corundum (P_2) 728 kt, with an average content of 1%; and associated abrasive garnet of more than 22 Mt.

The Smirnovskiy occurrence is similar to the Dragunske deposit, but there is no corundum-bearing material in the latter rocks. Prognostic resources (P_3) to a depth of 200 m with an average content of 20% sillimanite amount to 16 Mt.

In the **Mariupolske deposit**, the parcels (up to 28 m thick) with layers (2-12.5 m) of sillimanite-garnet-biotite, corundum-spinel-sillimanite-garnet, corundum-biotite-sillimanite and corundum-sillimanite-spinel gneisses and schists contain up to 35% sillimanite and up to 10% corundum. Prognostic resources (P_3) to a depth of 200 m total 34.1 kt sillimanite and 1.6 kt corundum.



Fig. 5.28. Distribution of sillimanite, disthene, and andalusite deposits and occurrences (modified after Gurskiy et al. 2006b)

The Kpaitanivskiy occurrence comprises a sequence of garnet-sillimanite-cordierite and garnet-sillimanite gneisses and schists 150-200 m thick and up to 1.5 km long with a sillimanite content of 1.2-4.4%.

The Solomiivskiy occurrence includes layers of sillimanite-bearing (4.7 to 34.7%) gneisses and schists 1-13 m thick and up to 1 km in length.

Table 5.51. Average chemical composition of the disthene quartzites of the Perzhanske deposit

Oxide	Wt.%
SiO ₂	70.8
TiO ₂	0.52
Al ₂ O ₃	20.8
Fe ₂ O ₃	0.71
MnO	0.02
MgO	0.11
CaO	0.58
Na ₂ O	0.26
K ₂ O	0.08
P ₂ O ₅	0.05

The Perzhanske deposit is confined to Paleoproterozoic disthene quartzites. Ore bodies include steeply-dipping layers up to 1700 m long and 35-40 m thick, and lenses up to 15 m thick. The average content of disthene is 19.5%, mica 10%, andalusite 1% and hematite, ilmenite and magnetite 4%. The average chemical composition of the disthene quartzites is shown in Table 5.51. Reserves of disthene ores to a depth of 87.5 m in category C₂ are 9.5 Mt. Estimated resources amount to 48.8 Mt (Gurskiy et al. 2006b) and with beneficiation the yield of disthene concentrate is 88-90.5%.

The Pobychanskiy occurrence has similar characteristics to the Perzhanske deposit. Prognostic resources of disthene ore are 66 Mt.

Sedimentary concentrations of sillimanite and disthene are confined to complex placer deposits (Malyshevske, Vovchanske, Zelenoyarske, Tarasivske, Selishchanske, Pravoberezhne), located in the Miocene Poltavaska Suite and Sarmatian sands. Ore fields vary in area from 1.4 to 800 km², the productive sequences having a thickness of 2-25 m. The main minerals include ilmenite, rutile, zircon, sillimanite, disthene, staurolite, garnet, andalusite, tourmaline, corundum, chromite, spinel, apatite. Disthene and sillimanite in the heavy fraction of Sarmatian sands are on average 13% and in the Poltavaska Suite from 15 to 74%. The yield of disthene-sillimanite concentrate after ore beneficiation is 17.3%.

Economic reserves of disthene and sillimanite in the Malyshevske deposit in category A+B+C₁ is 22.6 kt and in the Vovchanske deposit A+B+C₁ 901.6 kt, with a content of 41.3 kg/m³ (Gurskiy et al. 2006b). The yield of bulk concentrate is 27-153 kg/m³. The Malyshevske deposit is being developed by "Matronivskiy MBP" LLC and PJSC "United Mining-Chemical Company" which extract the concentrates of ilmenite, rutile, zircon, sillimanite, disthene, staurolite and tourmaline from the placers.

The bulk concentrate produced is granular and powdery, and of high quality that meets international standards (Table 5.52). Sillimanite and disthene are also of high quality and meet world standards. They make up 8-10% of the bulk concentrate. About 20-30 kt of disthene-sillimanite concentrate are produced annually.

Table 5.52. Bulk chemical composition of concentrate of the Malyshevske deposit

Oxide	Wt.%
TiO ₂	1.5
Al ₂ O ₃	57
Fe ₂ O ₃	0.8
MgO	0.8
CaO	0.2

5.4.7. Raw Materials for the Production of Mineral Paints

These are used in the paint, construction, engineering, printing, food, paper, rubber, porcelain, ceramics and medical industries. Coloured clays, iron and manganese ores, chalk, glauconite, vermiculite, graphite, gypsum, anhydrite, barite, cinnabar, ochre, malachite, azurite, soot, sienna, mummy, red lead, amber and other minerals are used as natural mineral pigments.

In Ukraine, more than 120 deposits and occurrences of natural mineral pigments are known in the DDD, the Ukrainian Shield, the Donbas, Crimea, and the Trans-Carpathians. The SIMR records 10 deposits with reserves in category A+B+C₁ at 13.5 Mt and in C₂ at 1.8 Mt (Mineral Resources of Ukraine 2021). Mining did not take place in 2020. The main types of mineral pigments in Ukraine are the ores of ferrous and non-ferrous metals, coloured clays and glauconite (Table 5.53).

In Ukraine five promising areas of mineral pigments have also been identified:

- Kryvorizko-Kremenchutska area where in the Kryvorizke deposit iron oxide and clay mummy have been mined together and where reserves are 888 kt;
- Pobuzka area in the Kapitanivske, Kosanivske, Antonivske, Zavallivske and other occurrences of ochre clay and graphite, and in the Vysokopilske deposit of bauxite mineral paint;
- Nikopolska area where pyrolusite manganese ores of the Nikopolske and Velyko-Tokmatske deposits are known;
- Donetsk area with deposits of Jurassic ochre clay at Sukhokamyanske and Yasnopilske, Quaternary bog iron ores at Kamyanske and cinnabar at Mykytivske;
- Trans-Carpathian area with ochre clay deposits in the weathering crusts of Neogene andesites and tuffs, at Irshavske, Novoselytske, Chernyanske and Ilnytske, with total resources of over 3 Mt, and of barite at Biganskiy and siderite at Kamyanskiy.

Table 5.53. The main types of mineral pigments in Ukraine, kt (Gurskiy et al. 2006b; Mykhailov et al. 2008a)

Deposits, manifestations	Thickness of ore bodies, m	Reserves		Prognostic resources
		A+B+C ₁	C ₂	
Ores of ferrous and non-ferrous metals				
Gigant Mine	90.0	588.7	-	-
Gigant-Drenazhna Mine	-	6,748	-	-
Saksaganska Mine	-	752	-	-
Coloured clays				
Yasnopilske	-	580.7	-	-
Ilnytske	-	335.4	-	-
Irshavske	-	445	-	-
Novoselytske	-	1,753	-	-
Chernyanske	-	96.6	-	-
Malokomyatske	-	419	-	-
Shalankivske	-	-	751	-
Sukhokamyanske	-	186.6	-	-
Glauconite				
Karachaivske	5-7	-	-	230,500
Zhvanske	-	-	5,376	37,800
Adamivske	11.5	-	2,500	-
Karpivske	4.0-19.2	-	2,007	9,204

5.4.7.1. Ores of Ferrous and Non-Ferrous Metals

These commodities as mineral pigments are known in a number of quarries in Kryvyj Rig, in particular in the Pivnichnyi quarry (Gigant Mine), where reserves of yellow ochre clay ($A+B+C_1$) are 0.8 Mt.

Until 1994, hematite and kaolin-clay ores were extracted at the Gigant-Drenazhna Mine together with iron ores. Operations there are presently suspended. Total reserves of ores are 6.7 Mt comprising 2.7 Mt of iron oxide hematite (red lead) and 4 Mt of iron oxide-clay kaolin-hematite (red mummy).

The Saksagan Mine deposit, extraction now suspended, contains reserves of iron-oxide-clay kaolin-hematite ores (red mummy). Reserves of kaolin-hematite ores ($A+B+C_1$) amounting to 0.8 Mt are recorded.

5.4.7.2. Coloured Clays

These are not mined in Ukraine, although reserves of clay pigments are recorded in the Donetsk (Yasnopilske deposit), Trans-Carpathian (Ilnytske, Irshavske, Novoselytske, Chernyanske, Malokomyatske, Shalankivske deposits), and Kharkiv regions (Sukhokamyanske deposit) and amount to more than 4.5 Mt. The content of Fe_2O_3 is from 5-7 to 45-50%.

5.4.7.3. Glauconite

It is represented by more than 80 occurrences, in the the VPP, Lvivskiy and Fore-Carpathian Troughs, at the margins of the Ukrainian Shield, in the DDD and Donbas, that are confined to Cretaceous, Paleogene and Neogene sediments. At the south-western margin of the Ukrainian Shield, Karachaivske (Khmelnysky region), Zhvanske, Adamivske, Karpivske (Vinnytsia region) deposits have been discovered, where glauconite reserves in category C_2 amount to 9.88 Mt. A number of other promising sites are those at Struzka, Tsyvkovetska, Velykooleksandrivska, Krutobrodskia and Baranivska, etc.). The total prognostic resources of glauconite of the Albian-Cenomanian glauconite formation are estimated at 277.5 Mt.

The Karachaivske deposit of glauconite sands is confined to Upper Cretaceous Lower Cenomanian sediments, the thickness of productive horizons being 5-7 m and the depth 5-15 m. Prognostic resources of sand are 388.8 Mt, of glauconite 230.5 Mt.

The Zhvanske deposit is represented by variously-grained phosphate-glauconite sands (0.9-1.5 m) with inclusions of spherical phosphorites covered with Turonian chalk-like marls. The content of glauconite in sands is 30-40%, with a P_2O_5 content of 2-9% (mostly 3-5%) and in concentrates of 14-16%. The length of the deposit is more than 10 km. Prognostic resources of quartz-glauconite sands are 37.8 Mt, and of reserves are 5.4 Mt.

In the ***Adamivske deposit*** reserves of glauconite sands in category C₂ amount to 2.5 Mt, the average content of P₂O₅ is 2.8%, and the thickness of the productive layer is on average 11.5 m.

The Karpivske deposit of phosphorite-glauconite ores is represented by Lower Cenomanian clayey and carbonate sands with a thickness of 4.0-19.2 m. Prognostic resources are 9 Mt.

5.4.8. Fluorine

It is used to produce sodium silicofluoride, sodium fluoride, potassium fluoride-tantalite and ammonium bifluoride.

In Ukraine, fluorine is found in complex ilmenite-apatite and rare-metal-apatite ores associated with massifs of mafic rocks and their weathering crusts in the Volyn and Kirovograd megablocks of the Ukrainian Shield, as well as in carbonatites and alkaline rocks of the Azovian megablock. The SIMR records two deposits of apatite-bearing ores, at Stremygorodske and Novopoltavske, where fluorine is an accompanying compound. Reserves of fluorine ores in category A+B+C₁ are 905.3 Mt (fluorine 2925.2 kt) and in category C₂ 111.4 Mt (fluorine 537.9 kt) (Mineral Resources of Ukraine 2021).

5.4.9. Sulphur

It is used in the chemical industry to produce phosphoric, hydrochloric and other acids; in agriculture – phosphorus fertilizers; in the oil industry – for the purification of kerosene and petroleum oils; and in metallurgy – for the etching of metals, as well as for the extraction of uranium ores, soap and detergents, paints and pigments.

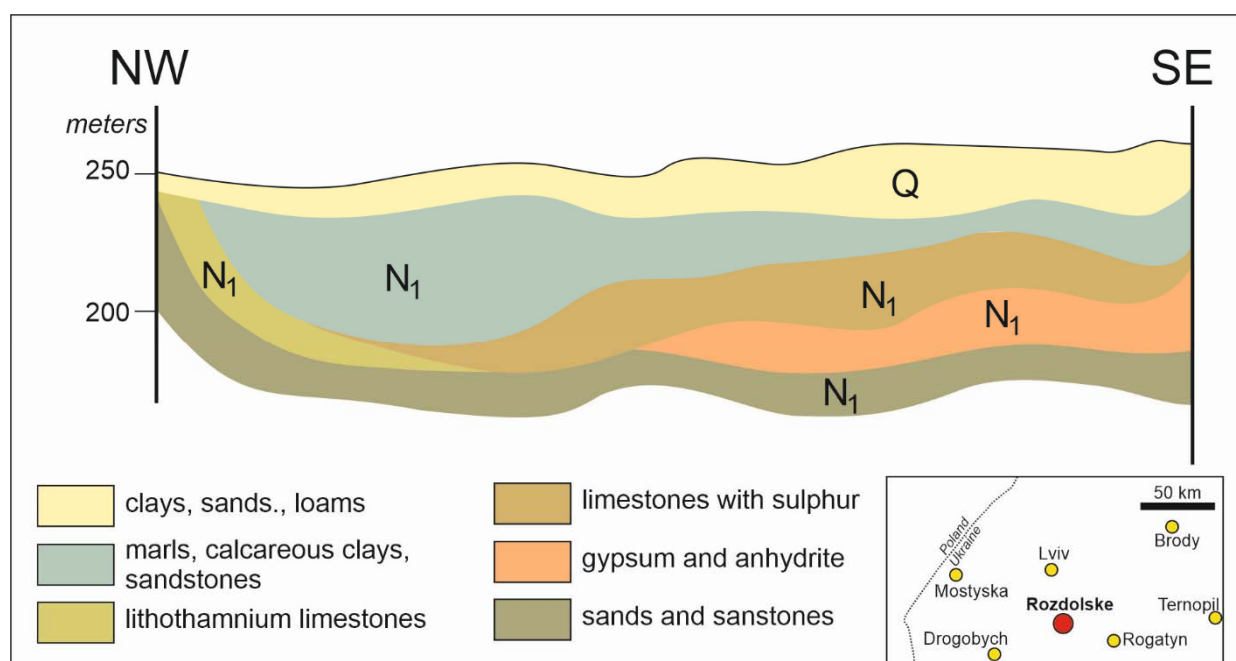
World sulphur production has gradually increased from 76.6 Mt in 2015 to 82.5 Mt in 2019. The main mining countries are China, USA, Russia, Canada, Saudi Arabia and Other Countries, with a significant growth in production in Saudi Arabia, the UAE and India (Table 5.54).

By virtue of its proven reserves of native sulphur Ukraine is ranked amongst the foremost producers in the world. The SIMR records 12 deposits with total reserves in category A+B+C₁ – 406.7 Mt of ore and 100.2 Mt of sulphur, and in C₂ – 80.0 Mt of ore and 18.5 Mt of sulphur (Mineral Resources of Ukraine 2021). Until 2000 three deposits of the Fore-Carpathian sulphur-bearing basin had been developed – the Podorozhnyanske, Yazivske, and Nemyrivske deposits – but since then all are being held on a care and maintenance basis.

Table 5.54. World sulphur mining production (World Mining Data 2021)

Country	Production, kt				
	2015	2016	2017	2018	2019
China	13,801.1	13,908.1	13,488.7	13,762.7	14,450.0
USA	9,540.0	9,740.0	9,630.0	9,670.0	8,710.0
Russia	6,720.0	6,960.0	7,000.0	7 170.0	7 175.0
Canada	5,745.0	5,381.0	5,327.0	5,333.0	6,938.0
Saudi Arabia	4,900.0	5,969.9	6,564.2	6,600.0	6,600.0
UAE	4,540.0	4,800.0	4,600.0	5,300.0	6,000.0
India	2,741.0	2,960.8	3,475.2	4,290.4	3,901.0
Kazakhstan	3 150.0	2,850.0	3,789.7	3,218.3	3,337.1
Japan	3,420.9	3,517.8	3 372.5	3,408.3	3,329.4
Iran	2,200.0	2,200.0	2,200.0	2,200.0	2,200.0
Other Countries	19,845.2	19,485.6	19,139.1	19,546.6	19,886.3
Total	76,603.2	77 773.2	78 586.4	80499.3	82,526.8

The Fore-Carpathian sulphur-bearing basin is traced in the form of a narrow strip in the territory of Lviv and the Ivano-Frankivsk regions along the south-western edge of the Eastern-European Platform. Deposits of the basin belong to the infiltration-metasomatic type in the Tortonian and Sarmatian clay-carbonate-sulphate formations, which lie on an eroded Cretaceous surface and are overlain by a thin cover of Quaternary rocks. The largest deposits in the basin are those of Rozdolske (Fig. 5.29), Yazivske (Fig. 5.30), and Truskavetske. They are associated with the Ratynski limestone layers.

**Fig. 5.29. Cross-section of the Rozdolske deposit (modified after Mykhailov et al. 2008a)**

Sulphur occurs in the form of finely scattered cryptocrystalline inclusions in pelitomorphic limestone, where cellular, oolitic, oolitoïd-banded, massive, and coarse-grained ores are found. The sulphur is represented by three varieties: 1) a fine-

grained, scattered variety with a grain size of 0.01-0.25 mm, which forms very thin intergrowths with greyish-yellow and yellow-green pleiomorphic calcite; 2) a latent-crystalline waxy yellow-brown variety, which forms various parcels and inclusions in limestones; 3) a coarse-grained light yellow variety, which forms well-faceted crystals up to 5-7 mm in size and is associated with coarse-grained secondary calcite. The first two varieties belong to the primary generation. The third variety is the result of redeposition and recrystallisation of the primary material. The total thickness of the productive sequence varies from 2 to 30 m, and the sulphur content reaches 91.4%. There are two types of ore: limestone and clay-limestone.

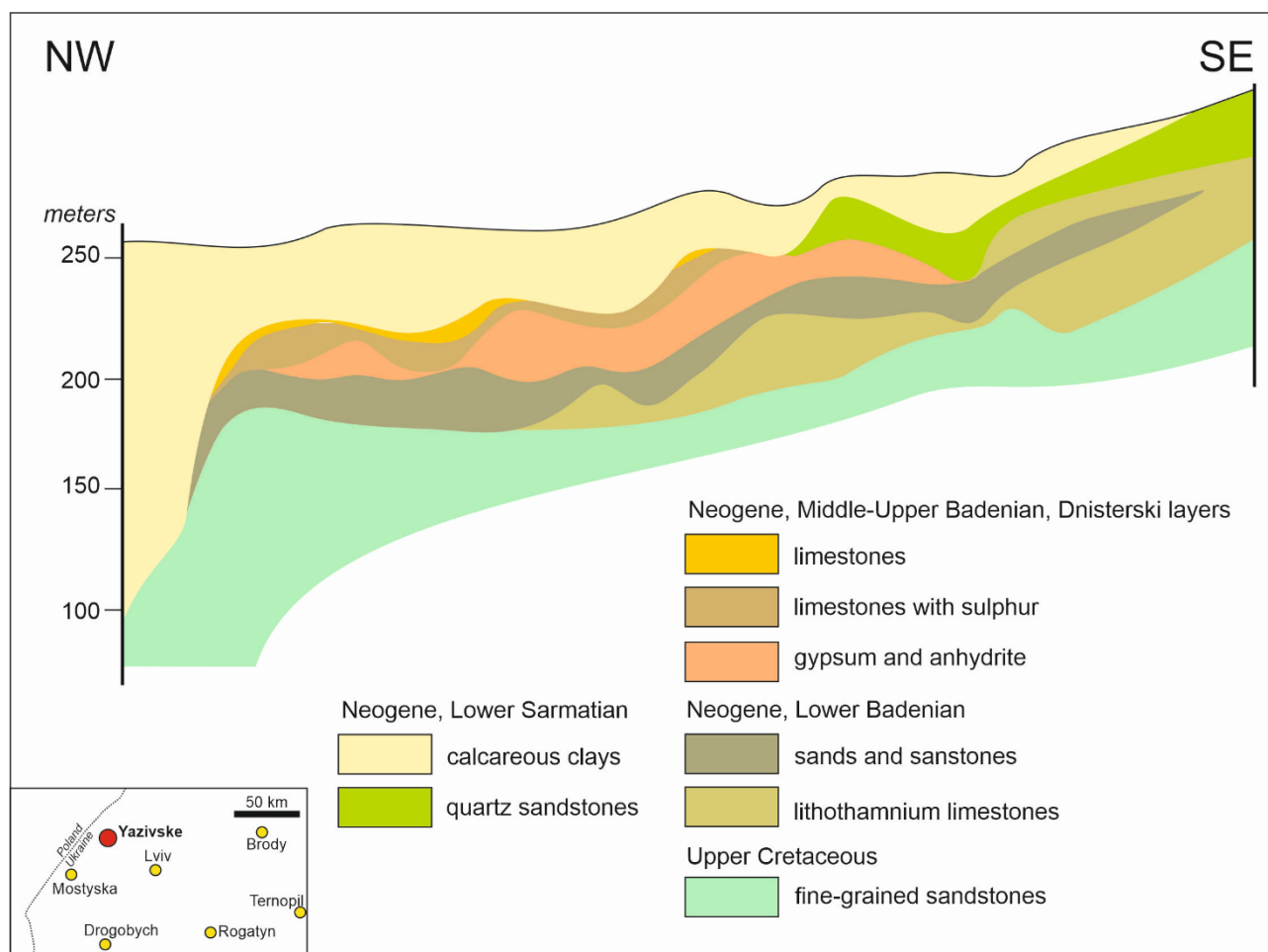


**Fig. 5.30. Cross-section of the Yazivske deposit
(modified after Mykhailov et al. 2008a)**

The Truskavetske deposit is composed of carbonate-sandy-clay rocks of the Miocene Lower Vorotyshchenska Suite. Mineralization is confined to a batch of breccia-like coarse-grained phyllite sandstones and grey clays. The "ore" horizon is underlain by a sequence of limestones and clay shales with gypsum interbeds and bunch-like accumulations of rock salt. The salty clays of the Upper Vorotyshchenska Suite with economic accumulations of potassium and rock salt lie on top. The rocks are strongly brecciated, up to the sandy-clay-salt breccias. The thickness of the mineralization zone is from 100-150 m in the central part to 20-30 m on the flanks of the deposit. The mineral composition of the rocks is diverse – native sulphur,

brookite, galena, marcasite, gypsum, calcite, anhydrite, dolomite, celestine and ozocerite.

Native sulphur occurrences are also known in the DDD (Efremivskiy, Oleksiivskiy, Petrivskiy, Beretskiy, Shyrokivskiy, Bilyaevskiy, Krasnopavlivskiy, Novodmytrivskiy and Korulskiy) and on the Kerch Peninsula, where they are associated with gypsum-limestone and clayey rocks of the Karaganskiy Horizon.

CHAPTER 6. EXPERT ASSESSMENT OF INVESTMENT ATTRACTIVENESS OF MINERAL RESOURCES OF UKRAINE

In order to conduct an expert assessment of the investment attractiveness of the MRB of Ukraine at the initial stages, a system of criteria was developed, which included the following indicators, each of which was evaluated on a 10-score scale:

1. The criticality of raw materials, the world market need and the prospects of growth in demand of that need.
2. The extent of geological and geological-economic study of deposit.
3. Geological and technological complexity of the geological structure.
4. Size of the deposit, reserves and resources.
5. The quality of raw materials (content of useful components).
6. Complexity of deposit, the presence of concomitant components.
7. Mining operating conditions.
8. Technological features of beneficiation.
9. Ecological conditions of field operation.
10. Available infrastructure.

Thus, the maximum possible score for each item is 10. The maximum sum of each of the ten criteria being 100.

Evaluation by the first criterion – the *criticality of raw materials, the world market need and the prospects of growth in demand of that need* – was based on world market trends for a particular type of product in recent years (see Table 2.5). Thus, for five years (2015-2019) the growth in production of such metals as lithium (+202.9%), rare earths (+62.3%), niobium (+54.8%), arsenic (+52.1%), tellurium (+34.5%), manganese (+33.8%), nickel (+31.4%), gallium (+31.2%), bauxite (+23.5%), and chromium (+20.1%) was particularly impressive. At the same time, the demand for germanium (-31.7%), mercury (-27.8%), bismuth (-22.5%), antimony (-16.3%), cobalt (-14.9%), beryllium (-14.2%), and uranium (-10.6%) has decreased. As for non-metallic raw materials, there was an increase in production of fluorite (+21.6%), and bentonite (+20.4%); by contrast, there was a reduction in phosphate production (-14.2%), boron (-12.4%), and asbestos (-10.3%). Such trends were taken into account when determining respective ratio.

The second criterion – the *extent of geological and geological-economic study of deposit* – is of great importance for meaningfully assessing knowledge about the deposit. Obviously, the more detailed the available information, the better the assessment of the deposit (occurrence). This assessment is carried out in accordance with domestic and international standards and in fact corresponds to the stages of geological exploration and categories of reserves and resources (A, B, C₁, C₂, P₁, P₂, P₃; whether reserves, or promising and prognostic resources, whether fully explored or preliminary explored).

The third criterion – *geological and technological complexity of the geological structure* – reflects the geometric parameters of deposit, the consistency of the ore bodies and the distribution of the components. All these characterise the complexity of a deposit and provide an invaluable indicator of its development and economic potential. Traditionally, deposits of simple, complex, very complex and extremely complex geological structure are distinguished (Korzhnev et al. 2006). As the

complexity of geological structure increases, the risks associated with its development also increase. Consequently, the score value for this parameter decreases with increasing complexity of the geological structure.

The fourth criterion – *the size of the deposit, reserves and resources* – directly affects the investment attractiveness of deposit, because these parameters determine the amount of possible profit that can be obtained during the development of deposit. Evaluation of this parameter considered the size of deposit, the scale of explored reserves, geological and economic (mining) reserves, their quantity and quality, ore concentrations in productive bodies, geometric parameters of mineralization, quantity, shape, size of ore bodies, their average thickness and continuity by strike and dip.

Equally important, is the fifth criterion – *the quality of raw materials (content of useful components)* – because this determines the costs and profitability of deposit development. Clearly, it is much more profitable to develop deposits of, for example, uranium with U_2O_3 content in ore bodies at the level of 5-10% as opposed to U_2O_3 with a content of 0.05-0.1%. This factor is why development of many uranium mines of Ukraine is unprofitable. Usually, the quality of an ore is characterised by grade i.e. high-grade, ordinary and low-grade – each determined by the ratios of different elements. The quality of the mineral, the content of the mineral component in geological reserves, the form of concomitant components (chemical element, mineral, rock mass), the presence of harmful impurities and the uniqueness of the raw material were taken into account.

The sixth criterion – *complexity of deposit, the presence of concomitant components* – can also significantly increase the investment attractiveness of deposit, as it directly affects the profitability of its development through the extraction of concomitant components. For example, in many copper-molybdenum-porphyry deposits in South America, the by-product extraction of associated gold ores becomes profitable, even at a gold grade of 0.1-0.2 g/t. This reduces the cost of extraction of the major minerals. Therefore, the presence of concomitant components is a positive factor.

The seventh criterion – *mining operating conditions* – determines the cost of mineral extraction. There are three main methods of extraction: open-cast (quarry), underground (shafts or galleries) and geotechnological (underground leaching, underground smelting and borehole hydro-extraction). Generally, open-cast quarrying, which is used under conditions of relatively shallow mineral deposits, is the most economically efficient. However, it is often the most environmentally damaging option. If the mineral deposits are deeply buried, the open-cast method becomes inefficient and mining operation is usually the preferred method for extracting the deposit.

The eighth criterion – *technological features of beneficiation* – is often crucial for evaluation of both metallic and non-metallic minerals. Thus, development of low-grade but easily beneficiated ores, can be more cost-effective due to lower consumption of energy, materials and labour during the extraction of useful components (Korzhnev et al. 2006). Therefore, to assess the investment attractiveness

of a deposit, it is important to assess the technological properties of raw the material, take optimal (in terms of quality and cost) technological solutions for processing and enrichment, depletion of ores, yield of concentration (concentrates), and amount of useful component (s) in concentrate.

The ninth criterion – *ecological conditions of operation of deposit* – has become particularly important in recent times, where special attention is paid to the preservation of the natural environment. In determining this factor, an expert assessment is made of the current state of environment, followed by an assessment of the likely environmental impact of the proposed extractive enterprise. The costs of remediation are also taken into consideration..

The tenth factor – *available infrastructure* – also significantly affects the attractiveness of the mineral extraction being considered. If an extensive infrastructure (roads, railways, power lines, local power plants, local fuel resources, water supply, manpower, etc.) is present, this greatly facilitates its development and saves investment.

Thus, the overall assessment of specific objects (deposits or occurrences of minerals) is provided by the sum of expert assessment of these ten parameters. Out of a potential 100-score, the investment attractiveness may be, in the first approximation, divided into three groups:

- objects with a high level of investment attractiveness ($\geq 70\%$), low level of investment risk ($\geq 30\%$);
- objects with an average level of investment attractiveness (50-69%), the average level of investment risk (31-50%);
- objects with a low level of investment attractiveness ($< 50\%$), high level of investment risk ($> 50\%$).

Thus, an initial assessment of the investment attractiveness of MRB can be made, suitable for preliminary identification of a number of possible licensing targets with the highest performance and the preparation of a business plan for the deposit development. In the future, to justify the feasibility and amount of investment in a project, it is advisable to conduct an in-depth geological and economic assessment of planned targets, taking into account a number of economic factors such as:

- assumed costs for deposit development,
- capital investments (buildings, roads, mine workings, concentrator, reclamation of disturbed lands, housing construction, etc.),
- operating costs, decommissioning costs,
- payment for special use of subsurface,
- deductions for the repair and maintenance of roads,
- contributions to the innovation fund,
- depreciation of fixed assets, etc.,
- annual production capacity, life of mine, ore mining,
- annual, gross and net profit,
- profitability of the project,
- payback period of investments,
- product liquidity,
- social and economic viability of projects,
- investment risk assessment, etc.

6.1. Metallic Minerals

Based on the above criteria, an expert assessment of the investment attractiveness of metallic minerals of Ukraine was conducted (Table 6.1).

It should be noted at once that the evaluation of such minerals as iron, manganese and uranium ores is not included, despite there being sufficient localities to warrant it. The fact is that this group of minerals is traditional for the mining complex of Ukraine; the best deposits with a high level of mineral resources (potentially for tens or even hundreds of years) have long been distributed among financial and industrial groups. Therefore, investment can be made through these already established financial and industrial groups.

However, an assessment was made for complex titanium-zircon ores – mainly of placer genesis – as there are many license proposals for this group of minerals occurring as relatively small bodies of placer origin, in hard-rock deposits and occurrences that have not been previously developed.

Of course, the ranking provided is subjective and those or other parameters of ore objects may be assessed differently by different researchers. Nevertheless, the overall ratio, in our opinion, should be maintained. Therefore, despite a degree of subjectivity in the assessment of individual parameters, we consider the overall assessment of deposits and occurrences is relatively objective, and can be used effectively when choosing investment opportunities at the initial stage.

Table 6.1. Expert assessment of investment attractiveness of metallic minerals of Ukraine

Metal	Deposits (occurrences)	Criteria and scores										
		1	2	3	4	5	6	7	8	9	10	Σ
Ti, Zr	Stremygorodske (Ti+P ₂ O ₅ +Sc+V+F+kaolin)	6	4	5	7	4	10	3	6	4	7	56
	Fedorivske (Ti+P ₂ O ₅)	6	3	4	5	6	7	4	6	4	6	51
	Nosachivske (Ti+P ₂ O ₅ + plagio-feldspars)	6	3	4	6	5	8	3	6	4	7	52
	Tarasivske (Ti+Zr+Sc+dis*+sil+st)	6	7	8	5	6	9	9	8	9	8	75
	Yuriivsko-Koziivska (Ti+Zr)	6	2	8	4	5	6	9	7	8	9	64
	Bilovodska (Ti+Zr)	6	2	4	3	4	6	8	5	7	8	53
	Korchakivska (Ti+Zr)	6	2	4	3	4	6	8	5	7	8	53
	Khrapivshchyna (Ti+Zr)	6	2	4	3	4	6	8	5	7	8	53
	Gaydarivska (Ti+Zr)	6	2	4	3	4	6	8	5	7	8	53
	Malyshevske (NW section) (Ti+Zr+dis+sil+st)	6	7	8	7	8	10	9	8	9	9	81
	Vovchanske (Ti+Zr)	6	3	7	4	5	6	9	6	7	8	61
	Krasnokutske (Ti+Zr)	6	2	6	3	5	7	8	6	7	7	57
	Zelenoyarske (Ti+Zr)	6	3	5	2	6	8	7	5	6	6	54
	Mokro-Yalinske (Ti+Zr)	6	2	4	2	2	4	5	6	7	6	44
	Yastrubetske (Zr+TR)	6	4	3	7	6	5	2	3	5	6	47
TR	Novopoltavske (TR+Nb+Ta+P ₂ O ₅)	10	9	6	8	7	10	6	7	8	9	80
	Anadolske (TR)	10	6	7	7	6	5	2	7	6	8	64
	Azovske (TR+Zr)	10	7	6	8	7	9	6	3	7	8	71

Metal	Deposits (occurrences)	Criteria and scores										Σ
		1	2	3	4	5	6	7	8	9	10	
	Balka Korabelna (TR)	10	3	4	2	4	5	6	4	6	8	52
	Petrovo-Gnutivskiy (TR)	10	7	8	2	9	4	7	8	7	8	70
	Mazurivske (TR+Zr+Ta+Nb)	10	8	7	9	6	10	7	8	6	8	79
	Uspenivskiy (TR)	10	2	4	3	3	2	5	2	6	7	44
	Khashchuvatske (Fe+Mn+TR)	10	5	7	2	3	7	8	4	6	8	60
Li	Shevchenkivske (Li+Ta+Nb+Be+Q+mica)	10	7	6	8	9	7	4	5	6	8	70
	Polokhivske (Li)	10	8	5	9	5	2	5	6	7	8	65
	Stankuvatske (Li+Rb+Cs+Ta+Nb+Be+Sn)	10	8	6	9	8	9	4	6	6	8	74
	Kruta Balka (Li+Ta+Nb+Cs+Rb)	10	5	6	3	4	9	4	5	6	7	59
Sc	Zhovtorichenske (Fe+U+V+Sc)	10	9	5	8	6	10	7	6	4	9	74
Ge	Coal of Donbas	8	10	9	10	8	9	8	9	5	10	86
	Malobiganske	8	6	7	2	5	8	7	8	5	7	63
Ni, Co	Tarnuvatske (Ni+Co)	7	5	4	6	5	4	6	4	5	8	54
	Devladivske (Ni+Co+Fe+refractory clays)	7	4	5	5	6	7	5	5	4	6	54
	West-Lashchivska (Co+Ni)	7	3	4	4	5	4	5	3	6	7	48
	Sukhokhutorska (talc magnesite +Ni+Co)	6	3	5	6	5	8	4	6	7	4	54
Cr	Kapitanivske (Cr+Ni)	6	7	5	7	8	6	4	5	6	7	61
	Lypovenkivske (Cr+Ni+Co)	7	7	5	7	8	7	5	8	5	6	65
Al	Vysokopilske (bauxite)	5	7	4	2	4	3	8	7	4	7	51
	South-Nikopolske (bauxite)	5	4	4	2	3	3	7	7	5	6	46
	Biganske (alunites+barite+Pb+Zn)	5	3	4	2	3	5	6	4	4	5	41
Cu	Zhyrychi (Cu)	6	6	5	2	4	3	4	6	5	5	46
	Rafalivske (Cu)	6	6	4	1	2	3	3	2	4	6	37
	Prutivskiy (Cu + Ni + Co)	6	2	4	2	5	6	3	4	5	4	41
	Zheleznyaky (Cu+Ni+Co)	6	2	4	2	5	7	4	3	5	6	44
Be	Perzhanske (Be)	8	6	5	7	6	3	5	6	6	7	59
Au	Sergiivske (Au, Mo)	9	5	4	5	6	6	4	5	4	6	54
	Balka Zolota	9	4	5	3	5	2	5	4	5	6	48
	Balka Shyroka	9	7	4	5	6	5	4	5	6	5	56
	Surozke	9	3	5	4	5	3	5	6	5	4	49
	Klyntsivske	9	5	4	6	6	3	4	5	4	6	52
	Yuriivske	9	6	5	4	6	3	3	6	5	5	52
	Maiske	9	7	5	6	6	2	4	6	5	4	54
	Kvitkivska	9	4	4	3	3	2	4	4	5	4	42
	Muzhyivske	9	8	2	3	4	6	4	2	4	8	50
	Beregivske	9	4	2	2	4	5	3	4	4	5	42
	Saulyak	9	4	7	6	7	4	5	7	3	4	56
	Bobrykivske	9	2	4	4	5	7	6	5	5	6	53
	Mykhailivskiy	9	2	3	2	3	2	4	3	4	5	37

* dis – disthene; sil – sillimanite; st – staurolite; deposits (occurrences) for which licensing proposals are open are marked in **bold**.

As can be seen from Table 6.1, deposits assessed as having a high level of investment attractiveness ($\geq 70\%$) and low level of investment risk ($\geq 30\%$) include:

- placer titanium-zirconium deposits – the **Tarasivske occurrence** in the Kyiv region, where reserves of scandium, distene, sillimanite, staurolite are recorded in addition to titanium and zircon (cumulative score 75)
- the north-western part of the **Malyshevske** deposit at the border of Kirovograd and Dnipropetrovsk regions, where reserves of disthene, sillimanite, and staurolite are recorded in addition to titanium and zircon (cumulative score 81). Extraction and development license proposals have been opened for both deposits.

Occurrences assessed as the most promising for rare-earth mineralization include:

- The **Novopoltavske** complex rare earth-niobium-tantalum-apatite deposit in the Zaporozhye region (cumulative score 80)
- The **Mazurivske** complex rare earth-zirconium-tantalum-niobium deposit in Donetsk region (cumulative score 79)
- The **Azovske** complex rare earth-zirconium deposit in Donetsk region (cumulative score 71)
- The **Petrovo-Gnutivskiy** rare-earth occurrence in the Donetsk region (cumulative score 70).

Of these, license proposals are only open for the Azovske deposit.

Regarding lithium, this category includes the **Stankuvatske** occurrence (lithium, rubidium, cesium, tantalum, niobium, beryllium, tin) in the Kirovograd region (cumulative score 74) and the **Shevchenkivske** occurrence (lithium, tantalum, niobium, beryllium, quartz, mica) in the Donetsk region (cumulative score 70). License proposals have been opened for both deposits.

Regarding scandium, the iron-uranium-vanadium-scandium complex of the **Zhovtorichenske** deposit (with a cumulative score of 74) is one of the most promising.

Regarding germanium, the **Coal of Donbas** was highly rated (cumulative score 86).

This list highlights those metallic mineral occurrences assessed as highly promising for investment opportunities. That said, there are a number of other promising occurrences listed in Table. 6.1. It should be noted that none of the Ukrainian gold deposits (occurrences) appears in the list of highly promising targets; this absence may be due to a low level of study or lack of objective information. It is also necessary to note the low assessment score of copper ore mineralization, which is primarily caused (as shown above) by the biased assessment of copper occurrences during exploration

6.2. Non-Metallic Minerals

The results of expert assessment of MRB of non-metallic minerals of Ukraine are given in Table 6.2.

Table 6.2. Expert assessment of investment attractiveness of non-metallic minerals of Ukraine

Types of raw materials	Deposits (occurrences)	Criteria and scores										
		1	2	3	4	5	6	7	8	9	10	Σ
Kaolin	Glukhovetske *	5	9	8	9	9	2	8	9	5	10	74
	Turbivske *	5	8	9	7	8	2	9	8	6	9	71
	Velykogadomynetske *	5	9	8	8	9	2	9	8	5	9	72
	Zhezhelivske *	5	10	9	8	9	2	8	9	6	9	75
	Novoselytske *	5	3	6	3	4	2	6	7	4	4	44
	Kirovogradske	5	4	5	2	5	2	5	6	5	4	43
	Pologivske *	5	3	4	3	4	2	4	4	5	3	37
	Volodymyrivske	5	2	3	2	4	2	4	4	5	3	34
	Murzynske *	5	4	5	7	8	2	7	8	5	4	55
Facing stones	Slipchyske (Labradorite) *	4	9	8	10	10	2	9	8	6	10	76
	Golovynske (Labradorite) *	4	9	8	10	10	2	9	8	6	10	76
	Omelyanivske (granite) *	4	9	8	9	9	2	9	8	7	9	74
	Lyznytske (granite) *	4	9	8	10	7	2	8	9	6	8	71
	Kornynske (granite) *	4	9	8	9	6	2	8	8	7	10	71
	Tokivske (granite) *	4	9	8	10	7	2	8	9	7	9	73
	Kapustyanske (granite)	4	9	8	9	8	2	8	9	7	9	73
	Velykokaminetske (marbled limestone)	4	7	6	7	7	2	8	8	6	7	62
	Velykokuzhelivske (travertine)	4	4	5	3	4	2	6	4	5	3	40
	Beretyanske (tuffs)	4	3	4	3	5	2	5	3	4	4	37
Refractory clay	Chasiv-Yarske (+ foundry sands) *	5	9	8	10	9	8	9	8	7	9	82
	Novorayske *	5	9	8	9	9	5	9	8	7	9	78
	Veselivske	5	6	7	6	7	4	8	6	6	5	60
	Pologivske *	5	8	8	6	9	5	8	7	6	8	70
	Volodymyrivske *	5	9	7	6	9	5	9	8	5	8	71
Graphite	Zavallivske (+ garnet) *	8	9	8	10	10	9	7	9	7	10	87
	Petrivske	8	6	7	6	7	5	6	7	6	5	63
	Balakhivske	8	7	7	8	8	5	6	7	6	6	68
	Burtynske (Khmelivska site)	8	6	8	9	8	5	6	8	7	6	71
	Troitske	8	5	6	6	6	5	6	7	6	5	60
	Mariupolske	8	4	5	5	4	4	5	6	6	4	51
Potassium salts	Stebnytske *	4	8	7	8	9	6	7	8	4	8	69
	Kalush-Golynske *	4	8	7	8	9	6	7	8	4	8	69
Garnet	Slobidske *	5	8	8	9	8	7	8	8	6	9	76
	Ivanivske *	5	8	8	9	8	7	8	8	6	9	76
	Loznenske	5	7	7	8	7	6	8	7	5	7	67
Quartz raw	Gusarivske (+ foundry sands) *	4	9	8	9	8	9	9	8	5	9	78
	Avdiivske	4	6	8	7	7	5	7	7	5	6	62

Types of raw materials material	Deposits (occurrences)	Criteria and scores										
		1	2	3	4	5	6	7	8	9	10	Σ
	Velykoglibovetske *	4	7	8	8	8	5	8	8	5	9	70
	Ardyvske (perlite)	4	6	7	9	7	8	8	9	4	5	67
Piezoquartz	Volynske (+ gemstone)	8	9	8	9	9	8	6	8	7	9	81
Phosphorites	Ratnivske (Postupelska site)	4	7	7	8	8	5	8	7	6	6	66
	Osykivske	4	6	7	7	7	4	8	7	6	5	61
	Zhvanske	4	8	7	9	8	5	8	8	6	7	70
Fluorite	Bakhtynske	6	7	6	7	6	8	7	8	6	7	68
	Pokrovo-Kyreivske	6	7	6	7	7	5	7	7	6	5	63
	Vyshcheolchedaivskiy occurrence	6	5	6	4	5	4	6	6	5	5	52
	Tsentrallyy occurrence	6	4	6	7	8	9	7	7	6	6	66
	Yastrubetskiy occurrence	6	4	5	6	6	9	7	8	5	5	61
	Bobrynetskiy occurrence	6	5	6	7	5	7	6	7	6	4	59
	Petrovo-Gnutivskiy	6	4	6	4	7	8	5	6	5	4	55
Limestones for sugar industry	Zamok*	5	9	8	9	8	6	9	8	6	10	78
	Lysogirka *	5	9	8	9	8	6	9	8	6	10	78
Bentonite	Cherkaske *	7	9	8	10	9	5	8	8	6	10	80
	Kishtynske	7	5	6	7	6	5	6	6	5	4	57

* – Deposit is under development. Targets where tenders are open are marked in **bold**.

As can be seen from Table 6.2, the highest cumulative scores given to occurrences of **kaolin** were: Zhezhelivske (75), Glukhovetske (74), Turbivske (71) and Velykogadomynetske (72). For **facing stones**: Slipchytske (76) and Golovynske (76) both labradorite occurrences, Omelyanivske (74), Tokivske (73), Kapustyanske (73), Lyznytske (71) and Kornynske (71) all granite occurrences. For **refractory clays**: Chasiv-Yarske (82), Novorayske (78), Volodymyrivske (71) and Pologivske (70). For **graphite**: Zavallivske (87) and Burtynske (the Khmelivska site) (71). For **garnet**: Slobidske (76) and Ivanivske (76). For **quartz raw materials**: Gusarivske (78), and Velykoglibovetske (70). For **piezoquartz**: Volynske (with gemstone occurrences) (81). For **phosphorites**: Zhvanske (70). For **limestones for the sugar industry**: Zamok(78) and Lysogirka (78). Finally, for **bentonite**: Cherkaske (80).

Notwithstanding these high cumulative scores, it is the case that the most of these deposits have a long history of industrial development and are already intensively developed by various financial and industrial groups. Therefore, only the Khmelivska site of Burtynske graphite deposit in the Khmelnytsky region can be realistically considered as a target for possible investment. The last field here was intensively developed in Soviet times, but its operation has long been suspended.

CHAPTER 7. CRITICAL RAW MATERIALS – THE GLOBAL CONTEXT

Chapter 1 was devoted to the general issues of the EU-Ukraine interaction in the context of mineral resources, with a special emphasis on critical raw materials (CRM). In this chapter, CRM issues are described in the world context, leading to consideration of the implications that changing global demand for minerals may have on Ukraine.

7.1. Overview

Like it or not, minerals are an integral part of our lives, with importance which only grows with the development of industrial production, new technologies and the need to introduce "green energy". As the saying goes: *"if we can't grow it, we have to mine it"*.

Some minerals and chemical elements have always been considered vital strategic inputs to industry, but in recent years the increasing sophistication of consumer, industrial, agricultural and defence technologies and the urgent need to move to clean energy have hugely increased the number of elements which are essential in manufacturing. The production, refining or processing of many of these elements has become very highly concentrated. For example, a 2021 report by the International Energy Agency shows that more than half of global supplies of five key clean energy elements derive from just one country. China has become especially dominant in many supply chains.

Consumer countries and economic blocs have woken up to the risks of such high dependency and most have now developed Critical Raw Materials (CRM) policies aimed at reducing these risks. Definitions and lists of CRM vary somewhat between markets, but there is general agreement that they are those raw materials which are economically and strategically important but have a high supply side risk. CRM are not necessarily rare or scarce, but:

- They are vital or important for key sectors of the economy, such as consumer electronics, agricultural and environmental technologies, automotive, aerospace, defence, health and steel;
- They have a high supply risk due to very high import dependence and concentration of production, refining or processing in particular countries; and
- There are no viable substitutes, due to the unique and reliable properties of these materials.

In the first approximation, the whole range of raw materials can be divided into three groups according to the degree of criticality (Table 7.1).

Table 7.1. Degree of criticality of raw materials (Critical commodities for a high-tech world 2013)

High	Average	Low
Rare Earth Elements	Selenium	Mercury
Gallium	Titanium	Thorium
Indium	Strontium	Arsenic
Tungsten	Graphite	Lead
PGMs	Tin	Barium
Cobalt	Germanium	Silver
Niobium	Beryllium	Cadmium
Magnesium	Zirconium	Copper
Molybdenum	Bismuth	Aluminium
Trumpet	Fluorine	Rhenium
Lithium	Zinc	Gold
Vanadium		Uranium
Nickel		Diamonds
Tantalum		Iron
Tellurium		
Chrome		
Manganese		

According to the World Bank, demand for metals and minerals will increase rapidly. The OECD predict that demand for industrial metals will increase from 8 billion tons in 2020 to 20 billion tons in 2060. Demand for the metals used in electric batteries is forecast to increase by more than 1000% to 2050. This will hugely increase the pressure on the mineral resource base of our planet (Communication from the Commission 2020).

As we have seen, critical minerals are those that, on the one hand are necessary to ensure the economic and national security of a country, and on the other hand are supplied entirely or significantly by imports from third countries (Bartekova, Kemp 2016; Blengini et al. 2020; European Commission 2020c; The methodology to identify CRM 2020; Haumann 2018). Dependence on imports brings risks due to the rarity of deposits of certain elements; the degree of geopolitical stability of supplier countries; the concentration of resources, production or processing in certain countries or companies; trade policy; competition arising from increasing demand; difficulties in production, and more.

Modern high-tech industries rely to a great extent on CRM, notably clean energy technologies (solar and wind energy, electric vehicles, etc.); the aerospace and

defence industries; battery manufacture; electronics and agricultural inputs. In fact, CRM are essential for nearly all our electronic, life-saving and green technologies. Consider now some important applications of CRM.

7.1.1. Lithium-Ion Batteries

Demand for lithium-ion batteries is growing rapidly. From initial uses in consumer electronics, their application has mushroomed into electric vehicles (EVs) and utility-scale battery storage (BS). The EU has published a list of the mineral content of the ‘average 2020 battery’, ie the weighted average of battery chemistries on the market in 2020. The cells in the average battery with a 60 kilowatt-hour (kWh) capacity contained **185 kilograms** of minerals, excluding materials used for the electrolyte, binder, separator, and battery pack casing (Table 7.2).

Table 7.2. Breakdown of the cells in the average battery

Mineral	Cell Part	kg	%
Graphite	Anode	52kg	28.1%
Aluminum	Cathode, Casing, Current collectors	35kg	18.9%
Nickel	Cathode	29kg	15.7%
Copper	Current collectors	20kg	10.8%
Steel	Casing	20kg	10.8%
Manganese	Cathode	10kg	5.4%
Cobalt	Cathode	8kg	4.3%
Lithium	Cathode	6kg	3.2%
Iron	Cathode	5kg	2.7%
Total	N/A	185kg	100%

The IEA report on clean energy (IEA 2021) shows that:

- 87% of raw lithium minerals come from Australia, Chile and China
- 96% of processed lithium comes from China, Chile and Argentina
- 82% of raw graphite comes from China, Mozambique and Brazil
- 70% of raw cobalt minerals come from DRC
- 64% of refined cobalt comes from China
- 56% of nickel comes from Indonesia, Philippines or Russia
- 48% of copper comes from Chile, Peru and China

The risk of reliance on this list of just 10 countries is evident, the more so as some suffer political instability, international sanctions or have shown preference to supply domestic industries to the detriment of exports. Engineers are working on substitutions, for example replacing cobalt by nickel alloys and graphite by titanium, but there is no guarantee of success, especially as the market also

demands ever more power per kg and every faster recharge times. Moreover, the market for these batteries is forecast to grow at a compound annual growth rate (CAGR) of 35% during the period 2022-2030, and beyond.

7.1.2. Electric Vehicles (EVs)

In order to achieve global climate goals, EV's share of all vehicle sales needs to climb rapidly from around 3% today to around 40% by 2030, alongside the rapid electrification of light commercial vehicles, buses and freight trucks. As EVs use around six times more non-ferrous minerals than conventional vehicles, this will require huge expansion of production and refining. In addition to the metals in their batteries as outlined above, the permanent-magnet electric motors used in most EVs require 0.25-0.50 kg/vehicle of the rare earth element neodymium, 0.06-0.35 kg of other REEs, 3-6 kg of copper, 0.9-2 kg of iron and 0.01-0.03 kg of boron (IEA 2021). Induction motors, which are cheaper but less efficient and less widely used, use far smaller quantities of REEs but require 11-24 kg copper per vehicle for the rotor cage and copper stator.

Neodymium allows the permanent magnets to be made smaller and stronger, while dysprosium (and to a lesser extent, terbium) increases the magnets' ability to maintain magnetization at high temperatures. China totally dominates the REE market, producing 60% of raw REEs and providing 96% of global REE refining capacity. In 2010, China temporarily limited REE exports – an alarm bell for countries that rely on imports. Prices leapt temporarily, more than 10-fold for some key REEs, although they subsequently declined again.

According to the International Energy Agency, neodymium demand will rise from 582 to 1,162 tons in 2017 to 20,000 to 40,000 tons by 2030, and the expected increase in EV production is forecast to boost dysprosium demand from between 180 and 360 tons in 2017 to 6,000 to 13,000 tons by the same date.

The copper market is expected to record a CAGR between 5% and 6% or even more, during the period 2022-30.

7.1.3. Clean Energy: Solar Photovoltaic Panels, Wind Turbines and Hydrogen

To achieve global climate goals, expanding clean energy generation will require huge expansion of solar panels and wind turbines, and probably also development of hydrogen production.

Worldwide solar photovoltaic (PV) capacity has increased by almost 20 times over the past decade, spurred by declining costs and strong policy support in key regions (IEA 2020a). Reduced costs and improving efficiency over the past decade, means that solar PV now offers some of the lowest electricity costs in most

countries, cheaper than new coal- or gas-fired power plants.

Two main types of photovoltaic cells are used for solar energy: crystalline siliceous and thin-film solar cells. Crystalline silicon (c-Si) modules have become the dominant PV technology, followed by the “thin-film” cells: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and amorphous silicon (a-Si). Typical c-Si PV panels contain about 5% silicon by weight, 1% copper and less than 0.1% silver and other metals. Thin-film technologies require less minerals overall, but more specialised CRM.

Global installed capacity of wind power has nearly quadrupled over the past decade, spurred by falling costs and policy support in more than 130 countries. Wind power is set for strong growth, both offshore and onshore, on the back of technology improvements and low-cost financing. New capacity installations are expected to more than double by 2040 to 160 GW/yr (IEA 2021).

Wind power employs between 10 and 12 tonnes of non-ferrous metals per megawatt, dominantly copper and zinc, but also manganese, chromium, nickel and molybdenum. As with electric motors, the generator magnets require significant amounts of the rare earths neodymium, dysprosium, terbium and praseodymium.

Distributed clean energy power generation will also require huge expansion of electricity grids, which will consume large amounts of minerals and metals. Copper and aluminium are the two main materials in wires, cables and transformers.

Hydrogen is expected to find increasing application in steelmaking, automotive uses and perhaps domestic heating. Currently the clean hydrogen market is immature, with most hydrogen still being produced from natural gas. Existing technologies for clean hydrogen production use significant quantities of CRM, especially nickel and zirconium. Some methods also use the light rare earths lanthanum and yttrium while others use PGMs. Fuel cells to generate electric power from hydrogen, for example in trucks and buses, also use significant quantities of PGMs.

7.1.4. Consumer Electronics

A typical modern smartphone is said to use 70 to 75 of the 98 naturally occurring elements of the periodic table, including more than 60 metals. They include indium and tin in the touchscreen; REEs in the LED screen, microphone and speaker; tantalum in capacitors; gold, silver, copper, lead, bismuth, and tin in the circuitry; silicon, antimony, arsenic, gallium and phosphorous in the microchips; and magnesium and nickel in the casing, as well as the various elements used in the battery, as discussed above.

Electronics have become a vital part of almost every modern consumer product,

from personal computers and phones to vehicles and white goods. Domestic products such as washing machines and air conditioners also contain electric motors, transformers, switches and other circuitry which all use CRM.

7.1.5. Some Other CRM and Their Applications

Antimony is used in fire retardant treatments, some types of battery, plastics manufacture, semiconductors and specialised metallurgical products. It has the smallest ratio of known resources to annual consumption of any metal.

Beryllium is used in the automotive, aerospace, defence, consumer electronics, electrical engineering, medical equipment and other industry sectors. Just one mine in the USA which holds 100+ years of reserves, supplies over 65% of global demand.

Bismuth is mostly obtained as a by-product of lead and tungsten refining. Considered to be eco-friendly and non-toxic, it is often used in pharmaceuticals or cosmetics and as a substitute for lead in solder. Supply is dominated by China, which is responsible for 82% of global production of refined bismuth.

Metallurgical or coking coal is one of the key inputs to the production of steel, although efforts are underway to replace it by hydrogen to reduce carbon emissions. China and Australia together produce 70% of the world's coking coal.

Phosphorus is an essential element for life and cannot be replaced. Phosphate rock is mined for its phosphorus content, to produce fertilizer, feed, food and pharmaceutical products. Phosphate is one of the three key plant nutrients and many modern farming methods exhaust soil of its phosphate content, meaning it must be replaced from artificial fertilisers. Globally, phosphate is not scarce, but reserves of high grade rock are depleting and are held by four or five big suppliers outside Europe.

Scandium is used in small amounts to add strength to lightweight aluminium alloys, for aerospace and other applications. Production is concentrated in China, followed by Russia, Ukraine and Kazakhstan.

Tungsten has the highest melting point of all metals and is alloyed with other metals to strengthen them. Tungsten and its alloys are used in many high-temperature applications, such as arc-welding electrodes and heating elements in high-temperature furnaces. Tungsten carbide is immensely hard and makes excellent cutting and drilling tools, tungsten alloys and some tungsten compounds. It cannot be substituted in many important applications and China, the world's largest supplier of tungsten ores, concentrates and intermediates, has placed restrictions on exports.

7.2. Critical Raw Materials Policies of Selected Economies

It is clear that the list of CRM may be different in different countries, depending on the needs of their industries and the extent of their reliance on imports. CRM policies and lists have been developed in the EU, USA, Canada, Australia, Great Britain, Japan, and South Korea. Below we consider some of these.

7.2.1. European Union

Risks associated with CRM supplies are especially important for the countries of the European Union (EU), which have many high-tech industries but have become heavily dependent on imports of raw materials from third countries. Thus, China supplies 98% of rare earth elements (REE) to the EU; Turkey supplies 98% of boron; Kazakhstan, 71% of phosphorites; USA, 88% of beryllium; Chile, 78% of lithium; and South Africa, up to 93% of PGM.

Thus, access to resources is a strategic security issue for Europe to implement new technologies, including green energy. That is why since 2011 the European Commission has been compiling and systematically reviewing its list of CRM. In 2011 the list included 14 types of raw materials, in 2014 it was increased to 20, in 2017 to 27, and in 2020 to 30 materials required to ensure the functioning of key industries in Europe, especially high-tech industries. For the EU, the main parameters for determining the criticality of raw materials are the economic importance of raw materials and the risk of its supply by third countries. The list includes metallic and non-metallic minerals, and a single biological material (Table 7.3):

Table 7.3. The EU Critical Raw Materials (Communication from the Commission 2020)

Antimony Sb	Germanium Ge	PGMs [Pd, Pt, Rh, Ir, Os, Ru]
Baryte (Ba)	Hafnium Hf	Phosphate ore (P)
Bauxite (Al)	Heavy REE [Tb, Dy, Ho, Er, Tm, Yb, Lu, Y]	Phosphorus P
Beryllium Be	Light REE [La, Ce, Pr, Nd, Pm, Sm, Eu, Gd]	Scandium Sc
Bismuth Bi	Lithium Li	Silicon metal Si
Borate (B)	Indium In	Strontium Sr
Cobalt Co	Magnesium Mg	Tantalum Ta
Coking coal (C)	Natural graphite (C)	Titanium Ti
Fluorite (F)	Natural rubber	Tungsten W
Gallium Ga	Niobium Nb	Vanadium V

The dependence of the EU on imports of mineral resources and the main areas

of their use in the EU are given in Table 7.4. This shows that Europe is completely dependent on supplies from third countries of many raw materials essential for EU industries.

Table 7.4. The EU dependence on mineral imports (Communication from the Commission 2020)

Raw	Major global suppliers,%	Main suppliers to the EU (%)	Dependence on imports,%	The main areas of use
Antimony	China (74) Tajikistan (8) Russia (4)	Turkey (62) Bolivia (20) Guatemala (7)	100	Flame retardants Protective equipment Lead-acid batteries
Barytes	China (38) India (12) Morocco (10)	China (38) Morocco (28) Germany (10) Norway (1) Other EU countries (15)	70	Medical supplies Radiation protection Chemistry
Bauxite	Australia (28) China (20) Brazil (13)	Guinea (64) Greece (12) Brazil (10) France (1)	87	Aluminium production
Beryllium	USA (88) China (8) Madagascar (2)	n / a	n / a	Electronic and communication equipment Automotive, aerospace and safety components
Bismuth	China (85) Laos (7) Mexico (4)	China (93)	100	Pharmaceutical industry and production of animal feed Medical equipment Low-temperature alloys
Borates	Turkey (42) USA (24) Chile (11)	Turkey (98)	100	Special glass Fertilizers Permanent magnets
Cobalt	Congo DR (59) China (7) Canada (5)	Congo DR (68) Finland (14) French Guiana (5)	86	Batteries Superalloys Catalysts Magnets
Coking coal	China (55) Australia (16) Russia (7)	Australia (24) Poland (23) USA (21) Czech Republic (8) Germany (8)	62	Coke for steel Hydrocarbon fibres Battery electrodes

Raw	Major global suppliers,%	Main suppliers to the EU (%)	Dependence on imports,%	The main areas of use
Fluorite	China (65) Mexico (15) Mongolia (5)	Mexico (25) Spain (14) South Africa (12) Bulgaria (10) Germany (6)	66	Production of steel and cast iron Refrigeration equipment and air conditioning Aluminium production and other metallurgy
Gallium	China (80) Germany (8) Ukraine (5%)	Germany (35) United Kingdom (28) China (27) Hungary (2)	31	Semiconductors Photovoltaic cells
Germanium	China (80%) Finland (10) Russia (5)	Finland (51) China (17) United Kingdom (11)	31	Optical fibers and infrared optics Satellite solar panels Polymerization catalysts
Hafnium	France (49) USA (44) Russia (3)	France (84) USA (5) United Kingdom (4)	0	Superalloys Nuclear control rods Fire-resistant ceramics
Indium	China (48) Republic of Korea (21) Japan (8)	France (28) Belgium (23) United Kingdom (12) Germany (10) Italy (5)	0	Flat displays Photovoltaic cells and photonics Solders
Lithium	Chile (44) China (39) Argentina (13)	Chile (78) USA (8) Russia (4)	100	Batteries Glass and ceramics Metallurgy of steel and aluminium
Magnesium	China (89) USA (4)	China (93)	100	Light alloys for automobiles, electronics, packaging and construction Sulfur extraction in steel smelting
Natural graphite	China (69) India (12) Brazil (8)	China (47) Brazil (12) Norway (8) Romania (2)	98	Batteries Refractory materials for steelmaking
Natural rubber	Thailand (33) Indonesia (24) Vietnam (7)	Indonesia (31) Thailand (18) Malaysia (16)	100	Tyres Rubber parts for machines and household goods
Niobium	Brazil (92) Canada (8)	Brazil (85) Canada (13)	100	High-strength steel and superalloys for transport and infrastructure High-tech products (capacitors, superconducting magnets, etc.)

Raw	Major global suppliers,%	Main suppliers to the EU (%)	Dependence on imports,%	The main areas of use
Phosphate ore	China (48) Morocco (11) USA (10)	Morocco (24) Russia (20) Finland (16)	84	Mineral fertilizers Phosphorus compounds
Phosphorus	China (74) Kazakhstan (9) Vietnam (9)	Kazakhstan (71) Vietnam (18) China (9)	100	Chemical compounds Protective equipment
Scandium	China (66) Russia (26) Ukraine (7)	United Kingdom (98) Russia (1)	100	Solid oxide fuel cells Light alloys
Silicon metal	China (66) USA (8) Norway (6) France (4)	Norway (30) France (20) China (11) Germany (6) Spain (6)	63	Semiconductors Photovoltaics Electronic components Silicone products
Strontium	Spain (31) Iran (30) China (19)	Spain (100)	0	Ceramic magnets Aluminium alloys Medical devices Pyrotechnics
Tantalum	DR Congo (33) Rwanda (28) Brazil (9)	DR Congo (36) Rwanda (30) Brazil (13)	99	Capacitors for electronic devices Superalloys
Titanium	China (45) Russia (22) Japan (22)	n / a	100	Lightweight high-strength alloys for aviation, space, defense, etc. Medical devices
Tungsten	China (69) Vietnam (7) USA (6) Austria (1) Germany (1)	n / a	n / a	Alloys for aeronautics, space, defense, electrical engineering, etc. Milling, cutting and mining tools
Vanadium	China (55) South Africa (22) Russia (19)	n / a	n / a	High-strength low-alloy alloys for aviation, space, nuclear reactors, etc. Chemical catalysts
PGM	South Africa (84) (iridium, platinum, rhodium, ruthenium) Russia (40) (palladium)	n / a	100	Chemical and automotive catalysts Fuel cells Electronic devices

Raw	Major global suppliers, %	Main suppliers to the EU (%)	Dependence on imports, %	The main areas of use
Heavy REE	China (86) Australia (6) USA (2)	China (98) Other non-EU countries (1) United Kingdom (1)	100	Permanent magnets for electric motors and generators Phosphors for lighting Catalysts Batteries Glass and ceramics
Light REE	China (86) Australia (6) USA (2)	China (99) United Kingdom (1)	100	Lasers, catalysts superconductors sensors flat panel displays fibre optics

Of particular concern is Europe's significant dependence on supplies from China (barite, bismuth, gallium, germanium, magnesium, graphite, phosphorus, REE), Guinea (bauxite), DR Congo (cobalt, tantalum), Chile (lithium, tantalum), Russia (lithium, lithium, phosphate ore, scandium), Kazakhstan (phosphorus), and Rwanda (tantalum).

In its 2020 report to the EU policy and law-making organs, the European Commission urges the EU to act urgently to ensure a secure, sustainable supply of raw materials, pooling the efforts of companies, sub-national and national authorities as well as the EU institutions, and recommends an EU action plan for critical raw materials which should:

- develop resilient value chains for EU industrial ecosystems;
- reduce dependency on primary critical raw materials through circular use of resources, sustainable products and innovation;
- strengthen the sustainable and responsible domestic sourcing and processing of raw materials in the European Union, and
- diversify supply with sustainable and responsible sourcing from third countries, strengthening rules-based open trade in raw materials and removing distortions to international trade.

The Commission proposes 10 action points to address these four objectives. Regarding development of domestic resources, it notes that although Europe has a long history of mining, it has been less successful in developing projects to source critical raw materials, even though there is significant potential for these. The obstructions are multi-faceted: lack of investment in exploration and mining, diverse and lengthy national permitting procedures and low levels of public acceptance of mining.

7.2.2. United States of America

The US Energy Act of 2020 defines a “critical mineral” as a non-fuel mineral or mineral material essential to the economic or national security of the U.S. and which has a supply chain vulnerable to disruption. Critical minerals are also characterized as serving an essential function in the manufacturing of a product, the absence of which would have significant consequences for the economy or national security. The Act requires the Department of the Interior to review and update the list of critical minerals at least every three years.

In 2018, the US published a list of 35 critical minerals prepared by the US Geological Survey based on indicators such as supply risk (concentration of production); production growth (change in market size and geological resources); market dynamics (price change); the ratio of import-export operations; analysis of supply chains, their role in the development of new technologies and so on (US Policy; Critical and Strategic) (Table 7.5). The 2022 revision included 50 elements, most of the increase resulting from listing rare earth and platinum group elements individually rather than as “mineral groups.” In addition, the 2022 list adds nickel and zinc while removing helium, potash, rhenium and strontium.

The "skew" that has developed in the world with the extraction of critical minerals has been identified and poses a threat to the national security of the United States. Thus, the leading position is occupied by China, which produces the lion's share of yttrium (99%), gallium (94%), magnesium (87%), tungsten (82%), bismuth (80%), REEs (80%), as well as a significant proportions (60% or more) of graphite, germanium, tellurium, fluorspar.

The southern part of Africa is the main region of the world for the extraction of chromium, manganese, PGM, tantalum, cobalt. 88% of niobium is produced in Brazil and 58% of lithium derives from Australia.

The United States themselves produce significant quantities of helium and REE, and smaller quantities of antimony, cobalt, gallium, germanium, lithium, magnesium, palladium, rhenium, tellurium, titanium. Recycling in the US generates domestic supplies of aluminum, chromium, cobalt, gallium, indium, magnesium, PGM, tin, and titanium.

Table 7.5. US Critical Minerals (US Critical Minerals Policy 2019)

Mineral	Global production			Leading manufacturers (2017,%)
	2000	2010	2017	
Aluminum (bauxite), million tons	135	209	309	Australia (28.5), China (22.6), Brazil (12.5), Guinea (15), others (21.4)

Mineral	Global production			Leading manufacturers (2017,%)
	2000	2010	2017	
Antimony, thousand tons	118	167	137	China (72), others (28)
Arsenic, thousand tons	33.9	52.8	34.6	China (69), others (31)
Barite, million tons	6.2	7.85	8.7	China (37), India (18), Others (45)
Beryllium, t	280	205	210	USA (71), others (29)
Bismuth, t	5,880	8900	17100	China (73), others (27)
Caesium	n.a.	n.a.	n.a.	n.a.
Chrome, million tons	14.4	23.7	30.2	South Africa (46.2), Kazakhstan (12.9), others (40.9)
Cobalt, thousand tons	33 300	89,500	120,000	DRC (61), others (39)
Fluorspar, million tons	4.5	6.0	5.7	China (61), Mexico (18), others (21)
Gallium, t	100	182	320	China (94), others (6)
Germany, vol	71	118	106	China (57), others (43)
Graphite, thousand tons	571	925	897	PRC (75), Brazil (10), Others (15)
Hafnium	n.a.	n.a.	n.a.	n.a.
Helium, million m ³	986.	75	160	USA (57), Qatar (28), Algeria (8.7), others (6.3)
India, t	335	609	714	China (40), Republic of Korea (31.5), others (27.5)
Lithium, thousand tons	14	28.1	38	Australia (58), Chile (21), China (9.8), Argentina (8.3), others (2.9)
Magnesium, thousand tons	368	757	1100	China (89), others (11)
Manganese, million tons	7.28	13.9	17.3	South Africa (31), Australia (16), Gabon (12.7), China (9.8), others (30.5)
Niobium, thousand tons	32.6	62.9	69.1	Brazil (88), others (12)
Platinum, vol	155	192	199	South Africa (72), Russia (11)
Potassium salt, million tons	25.3	33.7	41.4	Canada (29), Russia (17.6), China (13), others (40.4)
REE, thousand tons	83.5	133	132	PRC (80), Australia (14), Others (6)
Rhenium, t	28.4	47.2	51.6	PRC (55), Poland (19), USA (17), Others (9)
Rubidium	n.a.	n.a.	n.a.	n.a.
Scandium	n.a.	n.a.	n.a.	n.a.
Strontium, thousand tons	520	405	255	Spain (35.3), Mexico (28), China (19.6), Iran (15.7)
Tantalum, t	836	681	1810	DRC (42), Rwanda (24), Nigeria (8.5), Others (25.5)
Tellurium, vol	125	n.a.	470	China (68), Japan (12), Russia (12), others

Mineral	Global production			Leading manufacturers (2017,%)
	2000	2010	2017	
				(9.2)
Tin, thousand tons	238	256	313	China (29.7), Indonesia (26.5), Burma (15), others (28.8)
Titanium, million tons	4.3	6.4	5.5	South Africa (18), China (15), Canada (16), Australia (13)
Tungsten, thousand tons	37.4	68.8	82.1	China (82), others (18)
Uranium, vol	n.a.	1,506	1 021	Kazakhstan (39), Canada (22.5), Australia (10)
Vanadium, thousand tons	43.0	57.6	71.2	China (56), Russia (25), South Africa (11.2)
Zirconium, million tons	1.04	1.25	1.55	Australia (32.5), South Africa (24.3), China (9), others (34.2)

Summaries of world reserves and resources of critical raw materials are given in Table. 7.6. It should be noted that China is a world leader in the resources and supply of antimony, REE, strontium, tellurium, tin, tungsten, vanadium, as well as barite, fluorspar, graphite, magnesium and titanium.

Table 7.6. World resources and reserves of critical minerals (US Critical Minerals Policy 2019)

Mineral	Resource	Stocks	Leading countries (%)
Aluminum (bauxite), billion tons	Very significant	30	Guinea (24.6), Australia (20.6), Vietnam (12.3), Brazil (8.6), Jamaica (6.6)
Antimony, billion tons	The main resources in Australia, Bolivia, China, Mexico	1.5	China (32), Russia (23), Bolivia (21)
Arsenic	Unknown	n.a.	n.a.
Barite, million tons	2 billion tons	320	Kazakhstan (26.5), India (16), China (11), Turkey (11), others (35.5)
Beryllium	60% of the world's resources (100 million tons) are concentrated in the United States	n.a.	n.a.
Bismuth	n.a.	n.a.	n.a.
Cesium, thousand tons	unknown	90	Zimbabwe (67), Namibia (33)
Chrome, million tons	Significant	560	Kazakhstan (41), South Africa (35.7), India (17.8), others (5.5)
Cobalt, billion tons	25 (land), 120 (including sea)	6.9	DRC (49), Australia (17.4), Cuba (7.2), Others (26.4)

Mineral	Resource	Stocks	Leading countries (%)
Fluorspar, million tons	500 million tons	310	Mexico (21.9), China (13.5), South Africa (13.2), others (51.4)
Gallium	Significant	n.a.	unknown
Germanium	Not defined	n.a.	unknown
Graphite, million tons	> 800 million tons	300	Turkey (30), China (24.3), Brazil (24), Others (21.7)
Hafnium	n.a.	n.a.	n.a.
Helium, million m ³	USA – 20.6	n.a.	USA, Algeria, Russia
India	n.a.	n.a.	n.a.
Lithium, million tons	47	14	Chile (57), Australia (19.3), Argentina (14.3) China (7), others (2.4)
Magnesium, billion tons	Many billion tons	8.5	Russia (27), North Korea (27), China (11.8), others (34.2)
Manganese, million tons		760	South Africa (30.2), Ukraine (18.4), Brazil (14.5), Australia (13), others (23.9)
Niobium, million tons	Great	9.1	Brazil (80), Canada (17.6), Others (2.4)
PGM, thousand tons	100 thousand tons	69	South Africa (91)
Potassium salt, billion tons	250	n.a.	Canada, Belarus, Russia
REE, million tons	Significant	120	China (37), Brazil (18), Russia (15), India (5.8), Australia (2.8)
Rhenium, thousand tons	Significant	2.4	Chile (54), USA (16.6), Russia (12.9), others (16.5)
Rubidium, thousand tons	Significant	90	Namibia (55), Zimbabwe (33), Others (12)
Scandium	Great		unknown
Strontium, billion tons	1 billion tons	6.8	PRC
Tantalum, thousand tons	n.a.	110	Australia (70), Brazil (30)
Tellurium, thousand tons	n.a.	31	China (21.3), USA (11.3), others (67.4)
Tin, million tons	Great	4.7	China (23.4), Indonesia 17), Brazil (15), others (44.6)
Titanium, million tons	2000	880	Australia (28.4), China (26.1), India (9.7), others (35.8)
Tungsten, million tons	Great	3.2	PRC (57.5), others (42.5)
Uranium, million tons	7.6	4.4	Australia (26), Canada (11) Kazakhstan (8.2), Niger (7.2), Namibia (6.8), Russia (6.2)

Mineral	Resource	Stocks	Leading countries (%)
Vanadium, million tons	63	20	China (47.5), Russia (25), South Africa (17.5), others (10)
Zirconium, million tons	Significant	73	Australia (57.5), South Africa (19), others (23.5)

The United States has limited reserves of critical minerals, with the exception of helium and beryllium, although there are significant resources of tungsten, lithium, vanadium, uranium, REE and some resources of cesium, manganese and niobium, as well as cobalt, germanium, tellurium and rhenium, copper, zinc and bauxite.

Exploration expenditure in the USA, mostly by companies, accounted for around 8% of the global total over the past decade, rising to 11% by 2020 as exploration increasingly focussed on lower risk jurisdictions. However, the majority of this investment was for gold, copper and silver, with relatively little for critical minerals.

The US government, along with many other countries with a mature mining industry, such as Canada, Australia, South Africa, and much of Europe, provide national geoscience information freely, to support and incentivise exploration by private companies. In the last few years this government funded mapping has become increasingly focussed on CRM. In the US, the Earth Mapping Resources Initiative, a partnership between the USGS, State Geological Surveys, and industry, aims to acquire new geoscientific data to understand better the geologic framework of areas with potential for hosting CRM.

The US remains 100% dependent on imports for arsenic, cesium, fluorspar, gallium, graphite, indium, manganese, niobium, REEs, rubidium, scandium, strontium, tantalum, vanadium and more than 50% import dependant for aluminum, antimony, barite, bismuth, chromium, cobalt, germanium, lithium, magnesium, PGM, potassium salt, rhenium, tellurium, tin, titanium, tungsten, uranium (Table 7.7).

Table 7.7. US Dependence on Mineral Imports (US Critical Minerals Policy 2019)

Raw	Major suppliers to the United States (%)	Dependence on imports, %	The main areas of use
Aluminum (bauxite)	Jamaica (46), Brazil (25), Guinea (15), Others (14)	>75	Transport, construction, electricity, packaging materials
Trumpet	China (61), Others (39)	85	Products from ceramics, glass and rubber, flame retardant
Arsenic	China (91)	100	Lead batteries, herbicides, insecticides,
Barytes	China (63), India (14), Others (23)	86	Filler, paint and varnish industry, production of plastics and rubber

Raw	Major suppliers to the United States (%)	Dependence on imports, %	The main areas of use
Beryllium	Kazakhstan (44), Japan (14), others (42)	17	Car and consumer electronics, security systems
Bismuth	China (80), Other (20)	97	Additives for lead-free fittings
Cesium	Canada	100	Photovoltaic cells, energy
Chrome	South Africa (97)	71	Transport, packaging, construction, electricity
Cobalt	Norway (18), China (12), Japan (12), Others (58)	71	Superalloys, aircraft engines, batteries, permanent magnets
Fluorite	Mexico (69), Vietnam (10), South Africa (8), others (13)	100	Processing of aluminum and uranium
Gallium	China (32), United Kingdom (28), Germany (15), Ukraine (14), Others (11)	100	High-tech equipment, LEDs, solar panels
Germanium	China (58), Belgium (26), Others (14)	>50	Fiber and infrared optics, solar cells
Graphite	China (37), Mexico (29), Canada (17), Others (17)	100	Steel smelting, refractory products, foundry production, brake pads
Hafnium	Germany, France, Great Britain	n.a.	Superalloys
Helium	-	-	Gas lifting, laboratory use, MRI, welding
India	China (27), Canada (22), Others (51)	100	Electronics, liquid crystal displays, solar cells, photovoltaics
Lithium	Argentina (51), Chile (44), Others (4)	>50	Batteries, ceramics, glass, chemical compounds
Magnesium	China (57), Canada (22), Others (21)	51	Agriculture, chemical and other industries, construction
Manganese	Gabon (74), South Africa (13), Australia (8), others (5)	100	Production of steel and metals
Niobium	Brazil (72), Canada (18), Others (10)	100	Production of steel and superalloys
PGM	South Africa (44), Germany (15), United Kingdom (10), Others (31)	71	Car catalysts, fuel cells, jewelry
Potassium salt	Canada (84), Others (16)	92	Fertilizers, chemical industry
RE	China (80), Other (20)	100	Permanent magnets, oil refining, glass, lasers, steel alloys, fluorescent lighting

Raw	Major suppliers to the United States (%)	Dependence on imports, %	The main areas of use
Rhenium	Kazakhstan (34), Canada (19), Republic of Korea (13), Germany (10), others (24)	81	Superalloys for high-temperature turbine engines, catalysts for oil reform
Rubidium	Canada	100	Biomedical research, electronics, special glass
Scandium	China, EU, Japan, Russia	100	Ceramics, electronics, lasers, radioactive isotopes, lighting
Strontium	Mexico (52), Germany (39), Others (9)	100	Additives to drilling fluids
Tantalum	Brazil (35), Rwanda (31), Australia (15), Others (19)	100	Capacitors for electronic devices
Tellurium	Canada (66), China (27), Others (7)	>75	Photovoltaic panels, solar cells, thermoelectric devices
Tin	Indonesia (23), Malaysia (23), Peru (22), Bolivia (17), Others (15)	76	Chemicals, tin, solder, alloys
Titanium	South Africa (35), Australia (27), Canada (12), Mozambique (11), Others (15)	92	Aerospace vehicles
Tungsten	China (32), Germany (9), Bolivia (9), Canada (8), Others (42)	>50	Cutting tools, wear-resistant materials, construction, metalworking
Uranus	Canada, Australia, Russia	93	Fuel for nuclear reactors
Vanadium	South Africa (46), Russia (18), Brazil (13), China (10), Others (13)	100	Steel production, aerospace application
Zirconium	South Africa (59), Australia (22), Senegal (14)	-	Ceramics, foundry sand, refractory materials, abrasive materials

Of particular concern is the significant dependence of the United States on supplies from China (antimony, arsenic, barite, bismuth, cobalt, gallium, germanium, graphite, indium, magnesium, REE, scandium, tellurium, tungsten, vanadium); Guinea (bauxite); Kazakhstan (beryllium, rhenium); Ukraine (gallium); Gabon (manganese); Russia (scandium, uranium, vanadium); Rwanda (tantalum), Mozambique (titanium); and Senegal (zirconium).

That is why the United States has developed a number of pieces of legislation to promote the development of its own MRB and encourage producers to extract and process important minerals for the country's economy. Mining in the United States

is regulated by the Mining Act, which was passed in 1872, and has the main purpose of encouraging the exploration and development of minerals. It provides an opportunity for individuals and businesses to search for minerals in the federal states with the preemptive right to further develop them, and it does not set time limits for the start of their extraction.

The provisions of the federal law of 1872 are supplemented by a number of federal acts, which include environmental issues, financial justification of projects, subsoil permits, requirements for project management, responsibility of project owners, public participation and so on. In particular, the laws of the 60's and 70's of the last century, such as the Law on Sustainable Reusable Income, the Law on Wildlife, the National Law on Forest Management, the National Law on Environmental Policy, the Federal Law on Land Management politics. The most important laws regarding critical minerals include (US Critical Minerals Policy 2019):

- National Law on Mining of Strategic and Critical Minerals (HR 2531) for 2019;
- State Defense Act (HR 2500) for 2020;
- Mineral Safety Act (p. 1317) for 2019;
- National Law on Mining of Strategic and Critical Minerals (520) for 2017;
- National Defense Approval Act (HR 5515) for 2019;
- Law on Energy and Natural Resources (1460) for 2017;
- National Law on the Production of Strategic and Critical Minerals (HR 761) for 2013
- National Law on the Production of Strategic and Critical Minerals (p. 145) for 2017
- Critical Minerals Policy Act (1600) of 2013

7.2.3. Canada

Canada has developed a list of critical minerals important to the sustainable economic development of Canada and its allies that can be mined in Canada, are important to domestic industry and security, and can be supplied to other countries, which includes (Table 7.8).

Table 7.8. Critical Minerals of Canada (Canada releases list of critical minerals 2021; Canada's list of critical minerals 2021)

Aluminum	Potassium salts	REEs
Antimony	Helium	Scandium
Bismuth	Indium	Tantalum
Cesium	Lithium	Tellurium
Chrome	Magnesium	Tin
Cobalt	Manganese	Titanium
Copper	Molybdenum	Tungsten
Fluorite	Nickel	Uranium
Gallium	Niobium	Vanadium

Germanium Graphite	PGMs	Zinc

As one of the world's great mining countries, Canada is the only Western country to have large resources of cobalt, graphite, lithium and nickel needed in the production of batteries for electric vehicles; it is the world's second largest producer of niobium for the aerospace industry, the fourth largest producer of indium, a key metal of semiconductors, and so on (Canada releases list of critical minerals 2021).

7.2.4. Australia

Australia is one of the world's leading producers of minerals, including the world's leading supplier of iron ore, coal, gold, bauxite, copper, zinc, lead, manganese and more. Australia's resource potential is one of the highest in the world. In addition, ores of copper, lead and zinc, nickel, gold and others. can serve as a source of such critical elements as PGM, rare earth elements, chromium, tungsten, cobalt, cadmium, germanium, selenium, tellurium, rhenium. Therefore, the issue of critical minerals for Australia is not as acute as for other industrialized countries.

Australia has a high resource potential for chromium, cobalt, copper, nickel, PGM, REE, zirconium; medium and high – antimony, beryllium, bismuth, graphite, helium, indium, lithium, manganese, molybdenum, niobium, tantalum, thorium, tin, titanium, tungsten (Critical Minerals 2022; Critical commodities for a high-tech world 2013). Of these 22 elements, 13 are among the most critical (important) in the EU, USA, Japan, South Korea, and the United Kingdom. Some of these metals (antimony, indium, gallium, germanium, cadmium tellurium, selenium) are related components in the deposits of polymetals, copper, gold, nickel and aluminum, widely distributed in Australia. This determines the high potential of this country to provide critical minerals to the world commodity market.

Given the origin and connection with certain rock complexes, Australia's critical minerals can be grouped into three main mineral systems:

- associated with basic-ultrabasic igneous rocks of predominantly mantle origin: Nickel, PGM, chromium, cobalt;
- associated with granitoid and subalkaline intrusions: REE, tungsten, niobium, tantalum, molybdenum, beryllium, tin, bismuth;
- associated with heavy mineral sands: zirconium, titanium, REE, thorium.

A special role in the MRB of Australia is played by lithium, associated mainly with Archean pegmatites and salt lakes.

7.2.5. Ukraine: a CRM Review

The concept of critical raw materials is relatively new for Ukraine. The draft law of Ukraine "On Amendments to the National Program of Development of Mineral Resources of Ukraine until 2030" (Law 2021b) includes the following minerals as CRM: natural gas, oil, uranium, coking and anthracite coal, aluminum ore, tungsten, copper, lead, zinc, nickel, lithium, tantalum, niobium, chromium, cobalt, magnesium, PGM (Decree 2021). CRM are defined as "strategic raw materials that are not produced in the country or are produced in limited quantities, but are consumed in large quantities and have a high potential risk of limiting its imports, which may lead to the cessation of relevant industrial production" (Draft Code on Subsurface 2021). It is clear that the list of critical raw materials may change over time depending on world conditions, demand, changes in technology and so on.

A slightly different definition of critical raw materials is provided in the Draft Subsurface Code (Draft Code on Subsurface 2021).

The list of critical minerals in this document is much broader and includes: diamonds, barite, beryllium, bismuth, bauxite, borates, vanadium, tungsten, gallium, hafnium, graphite, gold, indium, potassium salts, cobalt, anthracite coal, crystalline raw materials (piezo-quartz), coking coal, lithium, magnesium, manganese, metallic silicon, PGM, copper, molybdenum, oil, nickel, niobium, drinking groundwater, natural gas, REE, aluminum, iron, phosphate raw materials (apatite and phosphorite), lead, scandium, antimony, tantalum, titanium, fluorite, phosphorus, zinc, and zirconium.

The first scientific publication in Ukraine devoted to the issue of its critical mineral raw materials was an article by G.I. Rudko and G.R. Bala (2021), which provides an overview of the concept of "critical raw materials", which in Ukraine, according to the authors, include: rare metals (vanadium, beryllium, lithium, germanium, hafnium, tantalum and niobium, scandium, strontium, REE), non-ferrous metals (titanium, antimony, cobalt, nickel, tungsten), PGM, and a wide range of non-metallic minerals: graphite, barite ores, boron, fluorspar, phosphorite ores, silicon (Rudko, Bala 2021).

If we analyze the lists of CRM from different countries and by different authors, we see a general list of 53 minerals that are most needed by modern industry, with some variation between different countries. This list includes combustible minerals, ferrous, light, non-ferrous, precious, radioactive and rare and rare earth metals, non-ferrous, mining-chemical, mining (mining) raw materials, as well as

helium and natural rubber. Table 7.9 below shows which minerals are included in the CRM lists of the EU, USA, Canada and Australia and the three lists for Ukraine described above. Any analysis of opportunities strategic raw materials of Ukraine should be carried out taking into account this list.

Table 7.9. Comparative characteristics of critical minerals in different countries

Mineral	EU	US	CA	AU	UA1	UA2	UA3
Combustible minerals							
Natural gas					+	+	
Oil					+	+	
Coking and anthracite coal	+				+	+	
Metallic minerals							
Ferrous metals							
Iron						+	
Manganese		+	+	+		+	
Chrome		+	+	+	+		
Titanium	+	+	+	+		+	+
Vanadium	+	+	+			+	+
Light metals							
Aluminum (bauxite)	+	+	+	+	+	+	
Magnesium	+	+	+		+	+	
Non-ferrous metals							
Copper			+	+	+	+	
Lead					+	+	
Zinc			+		+	+	
Nickel			+	+	+	+	+
Cobalt	+	+	+	+	+	+	+
Molybdenum			+	+		+	
Tungsten	+	+	+	+	+	+	+
Tin		+	+	+			
Antimony	+	+	+	+		+	+
Arsenic		+					
Bismuth	+	+	+	+		+	
Precious metals							
Gold						+	
PGMs	+	+	+	+	+	+	+
Radioactive metals							
Uranium		+	+				
Thorium				+			
Rare and rare earth metals							
Beryllium	+	+		+		+	+
Lithium	+	+	+	+	+	+	+
Rubidium		+					
Cesium		+	+				

Mineral	EU	US	CA	AU	UA1	UA2	UA3
Germanium	+	+	+				+
Gallium	+	+	+			+	
Tantalum	+	+	+	+	+	+	+
Niobium	+	+	+	+	+	+	+
Zirconium		+		+		+	
Hafnium	+	+				+	+
Scandium	+	+	+			+	+
Strontium	+	+					+
Indium	+	+	+	+		+	
REEs	+	+	+	+		+	+
Rhenium		+					
Tellurium		+	+				
Non-metallic minerals							
Diamond							
Diamond						+	
Chemical raw materials							
Phosphorite	+					+	+
Phosphate ore (apatite)	+					+	
Barytes	+	+				+	+
Potassium salts		+	+			+	
Boron	+					+	+
Fluorite (fluorspar)	+	+	+			+	+
Other non-metallic minerals							
Graphite	+	+	+	+		+	+
Piezo-optical raw materials (piezoquartz)						+	
Silicon metal	+					+	+
Other							
Helium		+	+	+			
Natural rubber	+						

Sources: EU (Communication from the Commission 2020); USA (US Critical Minerals Policy 2019); Canada (Canada releases list of critical minerals 2021; Canada's list of critical minerals 2021); Australia (Critical commodities for a high-tech world 2013; Critical Minerals 2022); UA1 – Ukraine: (Law 2021b), UA2 – Ukraine (Draft Code on Subsurface 2021), UA3 – Ukraine (Rudko, Bala 2021)

CONCLUSIONS

This publication investigates the possibilities and preconditions for attracting investments in the development of domestic RMB, both in the developed fields for the renewal of existing funds, reproduction of their reserves, and for facilities at the stage of exploration and design. RMB of Ukraine now includes numerous mineral deposits that have been explored and applied to industrial development, as well as a myriad of other possible investment opportunities. Extraction and processing of mineral deposits are traditionally capital-intensive industries, which involves the creation and operation of valuable infrastructures and the purchase of mining and transport equipment and so on. Investments in these areas are usually large-scale projects with significant time to develop mineral deposits, which entails many investment risks. These factors determine the relevance of investment assessment of domestic RMB at different levels; local, for individual mineral deposits, and regional and state with the definition of the most strategically important types of minerals.

In terms of investment attractiveness, four groups of strategic minerals of Ukraine have been identified, namely:

- 1) **Traditional raw materials**, existing intensively developed resources in Ukraine, with significant proven reserves, contributing to the State budget, and characterised by a high level of investment attractiveness ($\geq 70\%$), low risk of investment ($\leq 30\%$), but high competition: iron, manganese, titanium, uranium, kaolin, foundry sands, building and facing stones, refractory clay;
- 2) **Highly promising types of raw materials**, known deposits in Ukraine, with significant reserves (resources), but not yet developed or developed in small quantities; they have a high level of investment attractiveness ($\geq 70\%$), low investment risk ($\leq 30\%$), and are characterised by medium level of competition: rare earths, zirconium and hafnium, lithium, scandium, germanium, graphite, potassium salts, garnet, quartz raw materials, piezoquartz;
- 3) **Promising types of raw materials**, deposits in Ukraine where reserves (resources) are not reliably established, so the prospects for their development are not definitively determined; they are characterised by an average level of investment attractiveness (50-69%), average investment risk (31-50%), low competition : nickel and cobalt, chromium, aluminum, copper, tantalum and niobium, beryllium, gold, phosphorites, apatite, fluorite, glauconite, flux limestones and dolomites, limestones for the sugar industry, bentonite clays, feldspar raw materials;
- 4) **Types of raw materials with unclear prospects**, localised deposits which are known in Ukraine, where their scale does not indicate significant resources; they are characterised by low level of investment attractiveness ($< 50\%$), high investment risks ($> 50\%$), lack of competition: vanadium, lead and zinc, tungsten, molybdenum, platinum group minerals, strontium, magnesium, arsenic, rubidium and cesium, barite, boron, dawsonite, bromine and iodine, mineral sorbents, high alumina raw materials, diamond, raw materials for mineral paints, fluorine, sulphur.

The selection of priority facilities for capital investment in mineral extraction should be based on the results of the relevant assessment of investment attractiveness, involving the establishment of absolute and relative criteria and ranking of facilities.

The evaluation methodology depends on the purpose, such as:

- 1) assessment of the feasibility of capital investment in the expansion and technical re-equipment of existing mining enterprises;
- 2) selection of alternative subsoil use facilities for investment, including those deposits that have not yet been developed;
- 3) purchase of securities of individual mining companies.

The list of evaluation criteria for preliminary assessment of investment prospects in the domestic mineral complex is determined. This list is based on qualitative and quantitative parameters of mineral deposits, geological, mining, technological prerequisites for development, and includes basic technical and economic indicators. A system of criteria for assessing the investment attractiveness of MRB of metallic and non-metallic minerals of Ukraine has been developed, which includes the following indicators:

- criticality of raw materials, its need on the world market;
- degree of geological and geological-economic study of the deposit;
- geological-industrial type, complexity of geological structure;
- field size, reserves and resources;
- quality of raw materials (content of useful components);
- complexity of the field, the presence of related useful components;
- mining operating conditions;
- technological features of enrichment;
- ecological conditions of field operation;
- available infrastructure.

Domestic MRB can be ranked by the level of investment attractiveness and risk of investment in industrial development for the main groups of metallic, and non-metallic minerals.

Based on the expert assessment of the investment attractiveness of metallic and non-metallic mineral deposits of Ukraine, the following targets have been identified as the most promising:

- **titanium-zirconium** : Tarasivske deposit and north-western part of Malyshevske deposit;
- **rare lands** : Novopoltavske, Mazurivske, Azovske deposits and Petrovo-Gnutivskiy occurrence;
- **lithium** : Stankuvatske and Shevchenkivske deposits;
- **scandium** : Zhovtorichenske deposit;
- **germanium** : coal of Donbas;
- **chromium, nickel, cobalt** : Lipovenkivske deposit;
- **kaolin** : Zhezhelevske, Glukhovetske, Turbivske, Velykogadomynetske deposits;
- **facial stones** : Slipchyske and Golovynske labradorite deposits; Omelyanivske, Tokivske, Kapustyanske, Lyznytske and Kornynske granite deposits;
- **refractory clays** : Chasiv-Yarske, Novoraiske, Volodymyrivske, Pologivske deposits;
- **graphite** : Zavallivske, Burtynske (Khmelivska site) deposits;
- **garnet** : Slobidske, Ivanivske deposits;
- **quartz raw materials** : Gusarivske, Velykoglibovetske deposits;
- **piezoquartz** : Volynske deposit (with occurrences of stone-colored raw materials);
- **phosphorites** : Zhvanske deposit;
- **limestones for the sugar industry** : Zamok, Lysogirsk deposits;
- **bentonite** : Cherkaske deposit.

Prospects for further development of the mineral complex of Ukraine are associated, first of all, with iron, manganese, uranium, zirconium and titanium ores, which are traditionally extracted from the rocks of Ukraine; with involvement in the industrial development of complex rare and rare earth ores (Perzhanske, Mazurivske, Novopoltavske, Azovske deposits); exploration and evaluation of deposits of non-ferrous and precious metals, non-metallic minerals. Common problems that need to be addressed in the coming years are the search for deposits of new geological and industrial types, solving technological problems of complex extraction of useful components, geological and economic assessment of objects taking into account the requirements of a market economy. The problems of ensuring the rational use of nature and minimizing the negative environmental consequences of field development are also very important.

The following types of raw materials can be recommended as priority targets of investment in the mineral resource base of Ukraine: the metallic minerals of titanium and zirconium deposits, rare earth elements, lithium, scandium, germanium, and the non-metallic - minerals such as kaolin, graphite, facing stone graphite, granite quartz, etc.

Determination of the prospects for investment and the degree of investment risk for specific SME facilities is necessary, including:

- analysis of the dynamics of the world market for a particular type of raw material in recent years to determine trends in its further development;
- identification of objects of possible licensing;
- analysis of primary exploration materials in order to determine the objectivity of the assessment of the industrial potential of the deposit;
- preliminary geological and economic assessment of the feasibility and profitability of development of facilities (capital investments, operating costs, income from sales, etc.).

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