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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

PETROLOGY AND POTENTIAL MINERALIZATION OF THE UPPER JURASSIC AGE GRANITOIDS OF THE GEDABEK ORE DISTRICT (IN THE REPRESENTATION OF THE GADIR DEPOSIT)

Speciality: 2515.01 – Petrology, volcanology

Field of science: Earth sciences

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Baku - 2025

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INTRODUCTION

The relevance of the work. The Gedabek ore district is located within the Lesser Caucasus segment of the Tethys metallogenic belt, forming part of the Lok-Qarabağ island arc, which was created during the Mesozoic era as a result of the subduction of the Tethys Ocean beneath the Eurasian plate. The multiphase nature of the intrusive massifs observed in the ore district and the formation of the gabbro-tonalite rocks during the Upper Jurassic to Lower Cretaceous period have been confirmed through geochronological studies. However, understanding the petrographic-mineralogical and petrogeochemical characteristics of the widely developed volcanogenic and plutonogenic rock formations in the ore district, as well as determining the geodynamic conditions under which these magmatic rocks were formed, remains an urgent issue for petrologists. Clarifying how these rocks were formed during the evolution of the island arc is important for understanding the broader context of the region's magmatic activity.

Studying the geochemical properties of compatible and incompatible elements in the chemical composition of the intrusive rock formations widely present in the ore district provides insights into the processes of crystallization differentiation, fractionation, assimilation, and contamination of these rocks. Based on the results of these studies, it is possible to develop geological-genetic models of the petrogeochemical and ore-forming systems that characterize the magmatic evolution stages of the region. This can contribute to significant advancements in understanding the magmatic and ore-forming processes in the ore district and provide a valuable database for future scientific research.

The primary focus of this research is to investigate the multiphase Gedabek intrusive rock formation, which is known for its potential ore-forming capabilities, as well as the gold, silver, copper, and polymetallic mineralization potential in the western flank of the formation. A particularly important research topic is determining the spatial or indirect genetic link between the Gedabek granitoids and the

Gadir area, discovered in 2012, located 370 meters northwest of the Gedabek deposit in the central part of the Gedabek-Bittibulag ore belt. Furthermore, exploring the potential ore-forming capabilities of this intrusive formation, the lithological-structural conditions of the Gadir deposit, the morphological features of hidden ore bodies, the influence of various geological-tectonic settings on ore formation, the mineralogical-geochemical zonality, and the physico-chemical conditions of mineral formation remain pressing research issues. Finally, refining the geological-genetic criteria for the Gedabek ore district continues to be one of the crucial challenges in this field.

The object and subject of the research. The object of the research consists of the Upper Jurassic granitoid intrusive massifs located in the ore district, with a primary focus on the multiphase Gedabek intrusive rock formation and the Gadir Au-Ag-Cu-Zn deposit, which plays a significant role in ore formation and concentration. The research also covers the Yoğundağ epithermal area. The main subject of the research is the evaluation of the petrographic, mineralogical, and geochemical characteristics of ore formation processes, which are spatially or genetically related to the petrological and petrogeochemical features of the geological objects being studied.

The purpose of the research. The main purpose of the research is to study the petrological and geochemical characteristics of the Upper Jurassic granitoids observed in the Gedabek ore district and to determine their potential role in ore formation, thereby contributing to the development of new exploration criteria.

The following objectives are outlined for the research:

– Detailed study of the stratigraphic and metallogenic features of the tectono-magmatic and geological structure of the Gedabek ore district.

– Investigate the petrogeochemical characteristics of the volcanic-plutonic rocks in the district and assess the ore-forming potential of the granitoid intrusive rock formations.

– Analyze the petrographic, mineralogical, and geochemical characteristics of the volcanic-plutonic rock formations in the

Yoğundağ epithermal-porphyry type mineralization area and determine their significant role in the ore-forming process.

– Study the morphological features of deep ore bodies in the Gadir deposit, along with the internal structure of the ore masses and hydrothermal alterations, investigate the physico-chemical conditions of ore formation, the mineralization stages, the material composition of mineral associations, and their textural-structural features. Develop exploration criteria for the deposit and assess the potential prospects of gold, silver, copper, and zinc mineralization.

– Based on the results, perform a comparative analysis of the geological-genetic characteristics of the Gedabek and Gadir deposits. Forecast the potential prospectivity of gold-copper porphyry mineralization in the flanks and depth horizons of these deposits and determine the role of the multiphase Gedabek intrusive rock formation in the ore-forming processes.

Research methods. The dissertation is based on the author's personal observations during 12 years (2011-2023) of scientific research and exploration activities in the Gedabek ore district, as well as on the analysis of laboratory results from volcanic and intrusive rock, ore, and non-ore mineral samples collected during field geological exploration. For petrographic, mineralogical, petrological, and geochemical research, data from more than 140 oxide analyses, 30 thermobarometric measurements, over 1,000 quantitative analyses of 36 chemical elements, more than 15 U-Th-Pb, Sm-Nd, and Rb-Sr isotope analyses, and about 100 descriptions of transparent and polished thin sections and polished mounts were used.

The analytical studies were carried out in several prestigious laboratories, including: Cardiff University (Wales, UK) central laboratory, using Scanning Electron Microscopy (SEM) and Reflected Light Microscopy methods; The General Directorate of Mineral Research and Exploration (Ankara, Türkiye), for X-ray Diffraction (XRD) analyses; The "SÜKOP Precious Stone Workshop" at Konya Technical University (Konya, Türkiye) for polished thin section samples; The Environmental Isotope Laboratory at the University of Arizona (USA), for sulfur isotope analysis of sulfides using the

ThermoQuest Finnigan Delta PlusXL method; The Geological Institute of the Kola Science Center of the Russian Academy of Sciences, for Sm/Nd and Rb/Sr isotope analyses; The Research and Development Center of the All-Russian Geological Institute (St. Petersburg, Russia), for SHRIMP II ion microanalyses of U-Pb isotopes. Additionally, around 320 core samples from the Gadir area were analyzed for 36 elements using the ME-ICP41 and LA-ICP-MS methods at the "Izmir – Geochemistry ALS" laboratory (Australian Laboratory Services) in the Gaziemir district of Izmir, Türkiye. In the preparation of graphical materials, the author used software programs such as MapInfo, ArcGIS, QGIS, GCDkit, Google Earth Pro, Datamine, and Leapfrog Geo.

The main provisions defended:

1. The investigation of the petrogeochemical characteristics of major and trace elements in the formation of the Gedabek ore district's gabbro-tonalite formation, dating to the Upper Jurassic-Lower Cretaceous period (159±1 - 144±1 million years);
2. The development of a petrogeochemical model of the ore district based on the geodynamic conditions and the petrological-geochemical properties of the magmatic sources responsible for the formation of the gabbro-tonalite formation;
3. The classification of the Gadir Au-Ag-Cu-Zn deposit as a low-sulfidation epithermal deposit, with a scientifically substantiated explanation of the significant role played by the Upper Jurassic-aged Gedabek intrusive granitoid rocks in the genesis of the deposit.

Scientific novelty of the research:

1. Based on U-Th-Pb, Sm-Nd, and Rb-Sr geochronological isotope studies, it has been established that the formation age of the gabbro-tonalite rocks corresponds to the Oxfordian-Berriasian stages of the Upper Jurassic-Lower Cretaceous period (159±1 to 144±1 million years).

2. It has been determined that the granitoids of the Gedabek intrusive complex belong to I-type magnesium-rich granitoids formed in a subduction environment, characteristic of islands arc.

3. A petrogeochemical model of the gabbro-tonalite formation process has been developed by synthesizing geochemical, isotope-geochemical, and geochronological data.

4. The ore formation process in the Gadir deposit has been identified as multi-stage, based on the study of the morphological features, spatial conditions, internal structure, and material composition of hidden ore bodies. The distribution patterns of gold and other ore elements have been examined, revealing the structural-tectonic and mineralogical-geochemical factors contributing to ore zonation.

5. Geothermometric and isotope-geochemical studies suggest that the ore formation process occurred at temperatures between 100-300°C, leading to the development of epithermal mineralization.

6. For the first time, siliceous tuff layers ("silica sinter" and "lacustrine siliceous deposit") and a hydrothermal explosion breccia pipe (or crater), which are key lithological indicators for epithermal systems, have been discovered in the upper horizons of the Gadir deposit in the northwestern flanks of the Gedabek deposit. Based on these and other geological factors, the deposit has been classified as belonging to a low-sulfidation epithermal system. Regional and local factors controlling the mineralization have been studied, and a geological-genetic and volumetric model of the deposit's formation has been developed.

7. It has been determined that the Upper Jurassic-aged Gedabek granitoids played a significant direct and indirect role in the formation of the Gadir and Gedabek deposits.

Practical significance of the work. The conducted research enhances the theoretical foundation for understanding the genesis and differentiation processes of island arc magmatism formed in subduction environments, particularly in the study of geochemical characteristics of island arc magmatism in the region. The developed petrogeochemical models can be applied to the study of the features of Upper Jurassic-Lower Cretaceous intrusions within the Lok-Qarabağ structural-formational zone of the Lesser Caucasus, as well as the Central Tethys metallogenic belt.

The granitoid phase of the multiphase Gedabek intrusion, dating to the Upper Jurassic-Lower Cretaceous period, played a significant spatial and genetic role in the formation of various ore deposits within its boundaries. In this context, the recently discovered Gadir (2012), Ugur (2016), Gilar (2020), and Zafer (2020) gold, copper, and polymetallic deposits highlight the importance of these geological objects. The obtained results can serve as benchmarks for the practical exploration and discovery of concealed ore bodies at depth, contributing to a better understanding of the region’s metallogenic characteristics.

The geological-genetic criteria derived from comprehensive geological-petrological research can be used in the search and exploration of low-sulfidation epithermal deposits. These findings offer significant contributions toward the discovery of new ore deposits and the assessment of the region's ore potential.

Approbation of the research and publication. The main findings and propositions of the dissertation were presented at various international and national scientific conferences, including the I, VI, and VII conferences of young researchers and students (Baku, 2014, 2015, 2018), scientific conferences dedicated to the 90th, 91st, and 92nd anniversaries of the National Leader of the Azerbaijani People, Heydar Aliyev, and the liberated territories' mineral resources (Baku, 2013, 2014, 2015, 2021), as well as at the international conference on "New Findings on the Regional Geology, Geodynamics, and Metallogeny of the Lesser Caucasus" (Tbilisi, 2013). Presentations were also made at the VIII International Symposium on the Geology of the Eastern Mediterranean (Muğla, 2014, Türkiye), the International Multidisciplinary Forum dedicated to the 70th anniversary of the Azerbaijan National Academy of Sciences (Baku, 2015), the international scientific-practical conference dedicated to the 75th anniversary of the K.I. Satpayev Institute of Geological Sciences (Almaty, 2015, Kazakhstan), the international conference on "Tethys Tectonics and Metallogeny" (Çeşme-Izmir, 2016, Türkiye), the Society of Economic Geologists (SEG) conference on "Ore Deposits of Asia: China and Beyond" (Beijing, 2017, China), the XXVIII All-

Russian Youth Conference (Irkutsk, 2019, Russia), the VI International Congress of Natural and Health Sciences (Konya, 2020, Türkiye), and at the NASCO XXV conference for doctoral students and young researchers (Baku, 2022). Further presentations were made at the international scientific conference of the Society of Economic Geologists (SEG) on "Gold: Responsible Discovery and Mining in the 21^{st} Century: Resourcing the Green Transition" (London, 2023, UK), and the Republican scientific conference "Geology: Unity of Theory and Practice" dedicated to the 85^{th} anniversary of academician Vasif Baba-zadeh (Baku, 2023), conference materials and abstracts were published.

The results of the scientific research carried out for the dissertation have been published in 19 articles (including 2 in journals indexed in Clarivate Analytics' Web of Science database, 2 in Crossref, 1 in Springer, and 5 in journals indexed in the Russian Science Citation Index (RSCI, ISI)). Additionally, 4 conference materials, 20 posters, and abstracts (15 of which were presented at international conferences and symposiums) have also been published.

The name of the organization where the dissertation work was performed. The work was performed at the Department of "Geology and Exploitation of Mineral Deposits" of the Azerbaijan State Oil and Industry University of the Ministry of Science and Education of the Republic of Azerbaijan.

During the research process, the author expresses deep gratitude to the academic staff, particularly to the head of the Department of "Mineral Deposits" at Baku State University (BSU), academician Vasif Baba-zadeh, the dean of ASOIU's Faculty of Geological Exploration, associate professor N.V. Pashayev, the former head of the Department of "Geology and Exploitation of Mineral Deposits", associate professor R.T. Ismayilova, the current head of the department, professor Z.C. Afandiyeva, and associate professor A.M. Agayev, a PhD in Chemistry and the director of the Mineralogy Museum, who also served as the author's scientific supervisor.

The author extends sincere appreciation to the staff of the Anglo Asian Mining Company, led by the company's president and CEO, Reza Vaziri, with special thanks to the vice president Farhang Hedjazi, mining operations manager Mehman Talibov, exploration geology director, PhD in Earth sciences Anar Valiyev, chief geologist for exploration Shakir Qadimov, mining operations manager, PhD in Earth sciences Samir Mursalov, and PhD in Earth sciences Rashad Asgarov, as well as other geologists, for their valuable advice and guidance.

In addition, the author respectfully remembers the first scientific advisor, prof. M.N. Mammadov, a Doctor of geological and mineralogical sciences, for his direct involvement and contributions to the research process, though he passed away before its completion.

Scope and structure of the work. The dissertation consists of an introduction, five chapters, a conclusion, a bibliography with 126 references, 24 tables, and 116 figures, totaling 231 printed pages. The content of the dissertation, excluding figures, tables, and the bibliography, comprises 116 pages, with a total of 210,485 characters. The breakdown of the character count is as follows: Introduction: 13,953 characters, Chapter I: 30,271 characters, Chapter II: 33,805 characters, Chapter III: 21,668 characters, Chapter IV: 46,683 characters, Chapter V: 58,515 characters, Conclusion: 2,889 characters.

GENERAL CHARACTERISTICS OF THE WORK

CHAPTER I. MAGMATISM AND METALLOGENY OF THE LOK-QARABAĞ STRUCTURE-FORMATION ZONE OF THE LESSER CAUCASUS

The Lesser Caucasus mega-anticlinorium is part of the Tethys metallogenic belt, one of the world's most significant industrial raw material bases for noble, non-ferrous, ferrous metals, and other ore deposits. This mega-anticlinorium is located in the continental collision zone between the Eurasian and African-Arabian tectonic plates. The formation of various types of ore deposits in the Lesser Caucasus corresponds to three main tectonic stages associated with the closure of the Tethys Ocean[1]: (1) subduction of the Tethys Ocean during the Middle Jurassic - Early Cretaceous period; (2) a collision stage during the Late Cretaceous period related to the closure of the Tethys Ocean, and (3) various post-collision processes associated with the Cenozoic era[2].

The Lok-Qarabağ structure-formation zone, considered the primary metallogenic-geological object of the Lesser Caucasus, is regarded as an analogue of islands arc formed on mature continental crust. It borders the Goycha-Hakari zone to the southwest and the Kura intermountain depression to the northeast. The multiphase intrusions of the Kimmerian period (gabbro, quartz diorite, granodiorite, plagiogranite) played a crucial role in the formation of the main ore deposits of the Lok-Qarabağ island arc. These intrusions acted as a hydrothermal-magmatic source, facilitating the development of ore deposits[3]. The most significant group of ore deposits is concentrated in the Alaverdi-Kirovakan (Alaverdi, Shamlyk, Akhtala, and Tehut), Dashkasan-Gedabek, Murovdag, and Kafan ore districts.

The granitoid intrusions of the Lok-Qarabağ zone are mainly aligned with anticlinoriums and are less commonly found in synclinal folds. In the Shamkir anticlinorium, the largest quantity of granitoid massifs is concentrated in the dome parts of structures formed from Middle Jurassic volcanic layers. These granitoids consist of the Shamkir group, Ashagi Chaykend-Yukhari Chaykend, Jayir, Qabaqtapa, and Dashbulag granodiorite and quartz diorite intrusions. In the Dashkasan synclinorium, the Dashkasan-Zurnabad multiphase

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[1] Geology of Azerbaijan: [in 10 volumes] / Edited by Academician A.A. Alizadeh. – Baku: Nafta-Press, – vol. 4: Tectonics. – 2005. – 505 pages. (in Russian)

[2] Moritz, R. Metallogeny of the Lesser Caucasus: from arc construction to postcollision evolution / R.Moritz, D.Selby, N.Popkhadze [et al.] // Society of Economic Geologists, Inc. Spesial Publication, – 2016. vol. 19, – p. 157-192.

[3] Mesozoic magmatic formations of the Lesser Caucasus and related endogenous mineralization / R.N.Abdullaev, G.V.Mustafaev, M.A.Mustafaev [et al.], edited by E.Sh.Shikhalibeyli. – Baku: Elm, – 1988. – 160 pages. (in Russian)

intrusion, consisting of gabbro-granite, has developed. These intrusions belong to the Late Jurassic period and include the Shamkir, Dashkasan-Gedabek, Uchtepe-Qizilqaya, and Mehmana granitoid formations. Their absolute ages have been determined to be 134, 144, 141, and 136 million years, respectively (see fig. 1)[4].

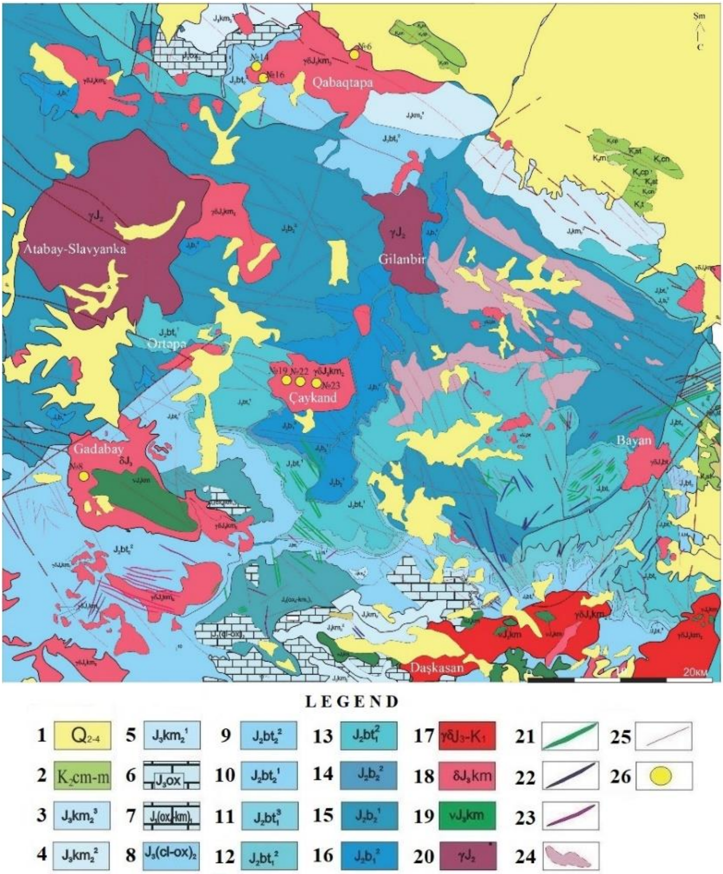

Figure 1. Regional geological map of Gedabek and Dashkasan ore districts. Scale 1:2 000 000[1,3,4]. Legends: 1-Quaternary alluvial, deluvial

[4] Kerimov, G.I. Petrology and ore-bearing potential of the Gedabek ore belt (Lesser Caucasus): [in 2 volumes] / G.I.Kerimov. – Baku: Academy of Sciences of the Azerbaijan SSR, – vol. 2. – 1963. – 223 pages. (in Russian)

and proluvial sediments; 2-Upper Cretaceous (Cenomanian-Maastrichtian) sediments: Limestones, marbles, sandstones, clays, gravels, tuffaceous sandstones; 3-Tuff-breccias, tuff-conglomerates and tuffs; 4-Basalts, andesibasalts and their tuffs; 5-Tuff-breccias, tuff-conglomerates, tuff-aleurolites, tuff-sandstones, tuffs; 6-Limestones; 7-Calcareous tuff-conglomerates, calcareous sandstones, limestones; 8-Tuffs; 9-13-Alternation of Bathonian aged tuff-breccias, tuff-conglomerates, tuff-aleurolites, tuff-sandstones, and volcanoclastic sediments; 14-Lava facies of rhyolites and dacites; 15-Plagiorhyolites, rhyolites, dacites and their tuffs, tuff-breccias; 16-Basalts, andesites, tuffs and their tuff breccias; Intrusive rocks: 17-Granodiorites, granites; 18-Diorites and quartz diorites; 19-Gabbros, gabbro-diorites, norites, diorites; 20-Plagiogranites; Dikes and veins: 21-Dolerite; 22-Barite; 23-Quartz; Others: 24-Metasomatites; 25-Faults; 26-Locations of U-Pb analyzed sample collection points

The Gedabek ore district, located north of Lake Goycha in the central zone of the Lok-Qarabağ island arc, is considered one of the regions where the country's largest epithermal-porphyry type deposits are concentrated[5]. This area is rich in Cu-porphyry deposits (Khar-Khar, Qaradağ, Jayir), associated with Upper Bajocian-Kimmerian volcanism. Additionally, exploration continues over epithermal and epithermal-porphyry type deposits such as Bittibulag, Gedabek, Ugur, Gadir, Zafer, Gilar, and others, with search efforts ongoing in some areas. The study and exploitation of these deposits enhance the region's economic and industrial potential[6].

CHAPTER II. PETROGRAPHY OF THE MAGMATIC ROCKS OF THE GEDABEK ORE DISTRICT

Several Azerbaijani scientists, including Abdullayev R.N., Akhundov F.A., Allahverdiyev Sh.I., Baba-zadeh V.M., Aliyev V.I.,

[5] Gold of Azerbaijan / V.M.Baba-zadeh, Sh.D.Musayev, T.N.Nasibov [et al.]. – Baku: Azerbaijan National Encyclopedia, – 2003. – 424 pages. (in Russian)

[6] Veliyev, A.A. Geological setting and ore perspective of the new discovered Gadir low sulfidation epithermal deposit, Gedabek NW flank, Lesser Caucasus, Azerbaijan / A.A.Veliyev, A.A.Bayramov, J.R.Ibrahimov [et al.] // Universal Journal of Geoscience, – 2018. vol. 6 (3), – p. 78-101.

Azizbeyov Sh.A., Bektashi S.A., Gashgay M.A., Kerimov H.I., Ismayilzade A.J., Mammadov A.I., Mustafayev M.A., Mammadov M.N., Rustamov M.I., Mustafayev H.V., Shikhalibeyli A.Sh., Abdullayev Z.B., Musayev Sh.J., Hasanov R.K., Hajiyev T.Q., Imamverdiyev N.A., and others have studied the magmatic formations of the Lesser Caucasus at various times. Previous research led to the classification of these magmatic formations, and a map of magmatic formations was compiled based on the collected data. In this and subsequent chapters, the description of the magmatic formations in the Gedabek ore district will focus on solving petrological and geochemical issues, primarily based on archive materials and recent research conducted by the author.

During Jurassic magmatism, the basalt-rhyolite formation, which constitutes a bimodal association, developed in depressions and uplifts within the Gedabek ore district[7]. The rocks of this formation exhibit contrasting chemical compositions: mafic rocks contain an average of 55.54% SiO_2, while felsic rocks have 70.27% SiO_2.

These rocks occur in amygdaloidal and massive forms and exhibit porphyritic and aphanitic textures. In the porphyritic textures of mafic rocks, phenocrysts are mainly represented by olivine, clinopyroxene, plagioclase, and sometimes orthopyroxene and hornblende. The groundmass consists of clinopyroxene, plagioclase, magnetite, titanomagnetite microlites, and volcanic glass. In felsic rocks, phenocrysts include plagioclase, K-Na feldspars, quartz, amphibole, and biotite. Accessory minerals commonly found in these rocks are magnetite, apatite, ilmenite, orthite, and zircon.

The Gedabek, Qabaqtapa, and Chaykend gabbro-tonalite and granitoid formations observed in the Gedabek ore district are comagmatic with the basalt-rhyolite formation. The primary indicator rocks of these formations are gabbro-norite, gabbro, gabbro-diorite, diorite, quartz diorite, tonalite, and granodiorite. The primary rock-

[7] Imamverdiev, N. Petro-geochemical features of the Bajocian island-arc volcanism in the Lesser Caucasus (Azerbaijan) / N.Imamverdiev, A.Orudzhov, A.Valiyev [et al.] // Journal of Geology, Geography and Geoecology, – 2022. vol. 31 (2), – p. 280-292.

forming minerals in these rocks are quartz, potassium feldspar, plagioclase, pyroxene, biotite, and hornblende.

One of the distinguishing features of these formations is the widespread presence of accessory minerals. The most common accessory minerals include magnetite, pyrite, ilmenite, zircon, and apatite. Rarer minerals such as tourmaline, garnet, and occasionally sphalerite, chalcopyrite, and cassiterite are also observed. The diversity and abundance of these minerals reflect the complexity of magmatic processes in the region and the geochemical composition of ore deposits formed as a result of these processes.

CHAPTER III. PETROGEOCHEMISTRY OF THE MAGMATIC ROCKS OF THE GEDABEK ORE DISTRICT

The chemical composition of the volcanic rock formations in the Gedabek ore district varies widely. The SiO_2 content in these rocks ranges from 50.19% to 79.72%. The Bajocian-aged basalt-rhyolite formation rocks are characterized by low magnesium content (MgO ranging from 0.85% to 4.53%, sometimes as low as 0.24%), calcium-rich composition (CaO ranging from 1.13% to 9.34%, occasionally reaching 11.01%), and titanium-rich levels (TiO_2 content varying from 0.28% to 1.18%). During the Lower Bajocian period, volcanic activity was associated with the tholeiitic series, which later transitioned to the calcium-alkaline series during the Upper Bajocian.

The plutonic rock formations in the district, according to the SiO_2-(Na_2O+K_2O) classification, belong to the normal calcium-alkaline series. In these rocks, SiO_2 content varies from 48.64% to 76.75%, with most rocks falling within the 51-69% range. On the SiO_2-K_2O and AFM (Na_2O+K_2O-FeO-MgO)* diagrams, the points for gabbro-tonalite formation rocks are classified under the calcium-alkaline series, though some are attributed to the tholeiitic series. A clear trend of magmatic differentiation is observed, ranging from gabbroids to granitoids.

Based on petrogeochemical characteristics, the gabbro-gabbro-diorites of the first phase and the diorite-quartz diorite-granodiorites of the second phase crystallized sequentially from the same magmatic source. Despite this sequence, all rocks of the gabbro-tonalite formation are considered as distinct and unified series. These processes are key indicators that deepen the understanding of the magmatic history and geochemical evolution of rock composition in the Gedabek ore district.

Rare Earth Elements (REEs). The distribution of rare earth elements in the second-phase rocks generally aligns with the spectra of gabbro, gabbro-norite, and gabbro-diorite rocks. The REE and trace element spectra, normalized to primitive mantle, N-MORB, and chondrite, reveal negative Ta-Nb-Ti anomalies and positive Pb anomalies, typical of islands arc settings (see fig. 2)[8].

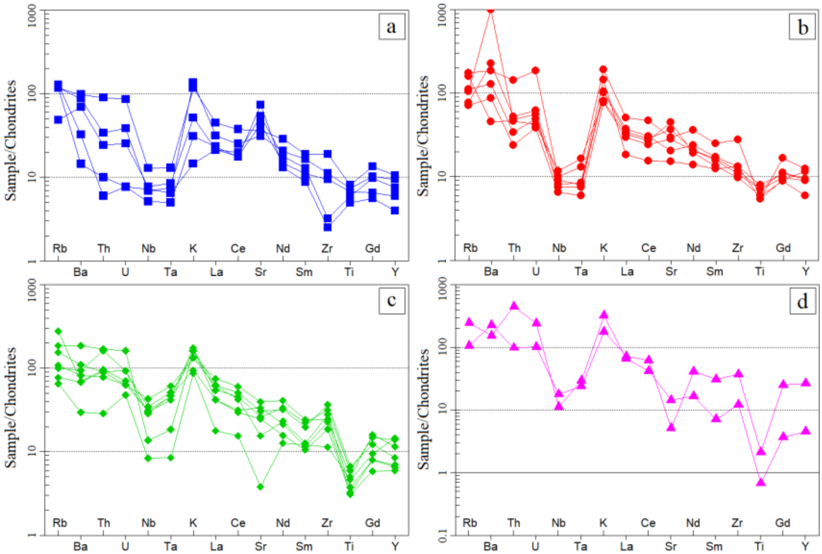

Figure 2. Chondrite-normalized diagrams: a) gabbroids; b) diorite-monsodiorite-quartz diorites; c) tonalite-granodiorites; d) granite-aplites[9]

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[8] Stern, R.J. Subduction initiation: spontaneous and induced // Earth and Planetary Science Letters, – 2004. vol. 226, – p. 275-292.

[9] Sun, S.S. Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs // Philosophic Transactions of the Royal Society, – 1980. vol. 297 (1431), – p. 409-425.

The REE results of the formation rocks, particularly the LREE enrichment and negative Eu anomaly, are characteristic of rocks formed in subduction zones. In such zones, partial melting processes often lead to magmas enriched in LREEs and with low concentrations of HREEs, resulting in magmas that are enriched in the continental crust. These geochemical features reflect the evolutionary processes of I-type granitoids, which are typically associated with subduction and continental rifting zones. Additionally, the dominant presence of plagioclase and magnetite among the primary mineral phases serves as further petrogenetic evidence supporting the presence of I-type granitoids.

CHAPTER IV. GEODYNAMIC EVOLUTION AND MAGMATIC SOURCES OF THE GEDABEK ORE DISTRICT'S MAGMATIC ROCKS

Geodynamic evolution and magmatic sources of volcanic rock formations. The basalt-rhyolite formations exhibit low values of TiO_2/Yb and Nb/Yb ratios, characteristic of tholeiitic series oceanic islands arc basalts. Based on the constructed diagrams, the trend of the formation rocks indicates an increasing influence of crustal components and subduction enrichment on the composition of the melts.

The geodynamic evolution and magmatic sources of intrusive rock formations.

Geochronological (U-Th-Pb, SHRIMP II) and isotope-geochemical (Sm-Nd and Rb-Sr) research results. The existing views on the formation age of the gabbro-tonalite rocks in the Gedabek ore district are based on the results of U-Th-Pb geochronological studies. Using the SIMS and SHRIMP II methods[10], rock samples taken from the Gedabek, Chaykend, and Qabaqtapa intrusive massifs

[10] Sadikhov, E.A. Isotopic-geochemical characteristics (Sm-Nd, Rb-Sr, S) and U-Pb SHRIMP II age of the Gedabek intrusive (Azerbaijan) / E.A.Sadikhov, A.A.Veliyev, A.A.Bayramov [et al.] // Regional Geology and Metallogeny, – Saint Petersburg: – 2018, vol. 76, – p. 83-94. (in Russian)

have been dated to between 159±1 and 144±1 million years, corresponding to the Upper Jurassic and Lower Cretaceous periods (see fig. 3).

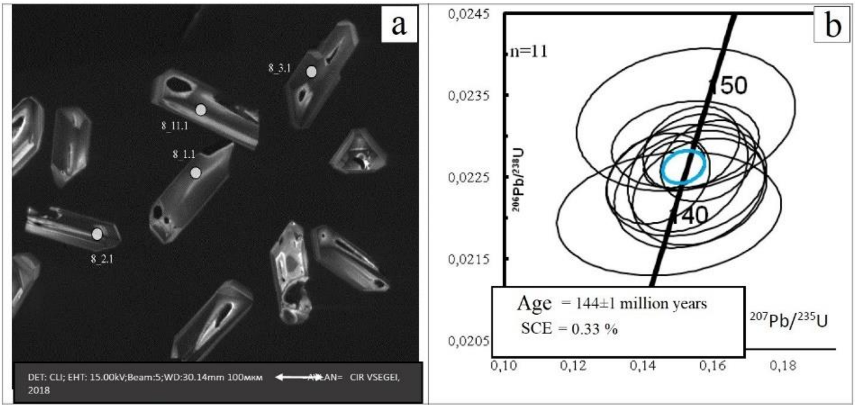

Figure 3. Catadeluminescence images of zircon in quartz diorite (a) and concordia diagram for $^{206}Pb/^{238}U$ - $^{207}Pb/^{235}U$ (b)[10]. Note: SCE - standard calibration error

Isotope-geochemical (Sm-Nd and Rb-Sr) studies. The Assimilation-Contamination-Fractional Crystallization model (AFC process).

According to modern concepts, the main source of magmatic rocks formed in subduction zones is considered to be the mantle wedge, which isotopically corresponds to a depleted mantle. However, for these rock formations, the εNd(t) values differ from the depleted mantle's εNd values by 4-5 units. This difference is most likely related to contamination by the continental crust. The $^{87}Sr/^{86}Sr$ ratios of the rocks range between 0.70402 and 0.70595, and these results also indicate that the source is depleted[11]. The $^{87}Rb/^{86}Sr$ ratios, however, display a wider range (0.16321–0.52943), which increases the likelihood of continental crust contamination during the initial stages

[11] Zindler, A. Chemical geodynamics / A.Zindler, S.Hart // Annual Review of Earth and Planetary Sciences. – 1986. vol. 14. – p. 493–571.

of the melting process. These indicators highlight the influence of both mantle and continental crust components in the petrogenesis of magmatic rocks and demonstrate that geochemical enrichments occurred during subduction processes.

Crystallization temperature results.

Modern geothermometric calculations based on magnetite-ilmenite equilibrium indicate that the derivatives of the quartz diorite phase crystallized within a temperature range of approximately 700-770°C and under relatively high partial pressure of oxygen ($lgf(O_2)$ $=10^{-15.0}$ to $10^{-13.2}$). Based on the obtained results, the upper crystallization temperature of quartz monzonites was approximately 770°C, which characterizes their formation conditions as occurring at higher temperatures and in an environment with relative oxygen enrichment[12].

Results of oxygen fugacity.

Based on the analysis of oxygen fugacity values, the aforementioned factors indicate that the formation causes of the Gedabek intrusive formation depended on mantle-derived magmas and geotectonic processes under subduction conditions. As a result, the granitoids described in this study crystallized from oxidized magma at significantly different pressures (4.2±1.1 - 6.6±1.0 kbar) and at temperatures that were relatively uniform (700±50 - 770±50°C).

Geodynamic conditions for the formation of the gabbro-tonalite formation.

The figurative points of the formation rocks in the Nb/Zr-Zr, Zr/Nb-Nb/Th, Y-Nb, Zr-Zr/Y, Y+Nb-Rb, Ta+Yb-Rb, and Ta-Yb discriminant diagrams correspond to the granite area of island arcs formed under subduction conditions (see fig. 4).

Magmatic sources for the formation of intrusive rock formations.

The diagrams of ratios of conservative elements with different

[12] Mammadov, M.N. Petrological factors of formation of Central Lok-Garabakh zone intrusion complexes of Upper Jurassic-Early Cretaceous age / M.N.Mammadov, G.J.Babaeva, A.A.Veliyev [et al.] // ANAS Transactions, Earth Sciences, – Baku: – 2021. No. 2, – p. 3-15.

distribution coefficients (Nb/Y, Nb/Ta, Ta/Yb, Ba/Nb, Th/Yb, Ba-Nb/Y, Ba/Th-Th/Yb, etc.) clearly illustrate the trend of enrichment of the gabbro-tonalite formation rocks with subduction components (see fig. 5).

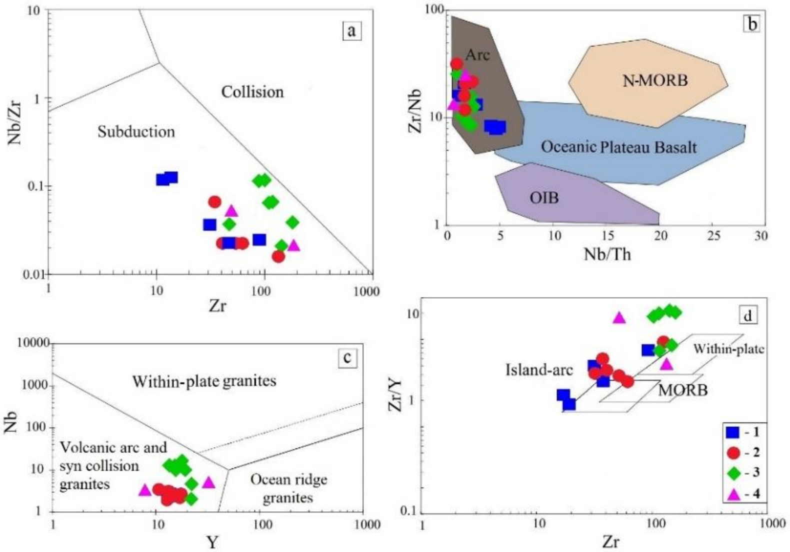

Figure 4. The position of figurative points of the gabbro-tonalite formation rocks in tectonism diagrams: a) Zr-Nb/Zr[13]; b) Zr/Nb-Nb/Th[14]; c) Y-Nb[15]; d) Zr-Zr/Y[16]. Abbreviations: Basalt fields: NMORB – normal mid-ocean ridge basalts; OIB - ocean island basalts. Legend: 1 - gabbroids; 2 - diorites, quartz monzonites, monzodiorites, quartz diorites; 3 - tonalites,

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[13] Thieblemont, D. and Tegyey, M. Geochemical discrimination of differentiated magmatic rocks attesting for the variable origin and tectonic setting of calc-alkaline magmas // Comptes Rendus De L Academie Des Sciences Serie II, – 1994. vol. 319 (1), – p. 87-94.

[14] Condie, K.C. High field strength element ratios in Archean basalts: a window to evolving sources of mantle plumes? // Lithos, – 2005. vol. 79, – p. 491-504.

[15] Pearce, J.A., Harris, N.B.W., Tindle, A.J. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks // Journal of Petrology, – 1984. vol. 25, – p. 956-983.

[16] Pearce, J.A., Norry, N.J. Petrogenetic implications of Ti, Zr, Y and Nd variations in volcanic rocks // Contributions to Mineralogy and Petrology, – 1979. vol. 69, – p. 33-47.

granodiorites; 4 - granites-aplites.

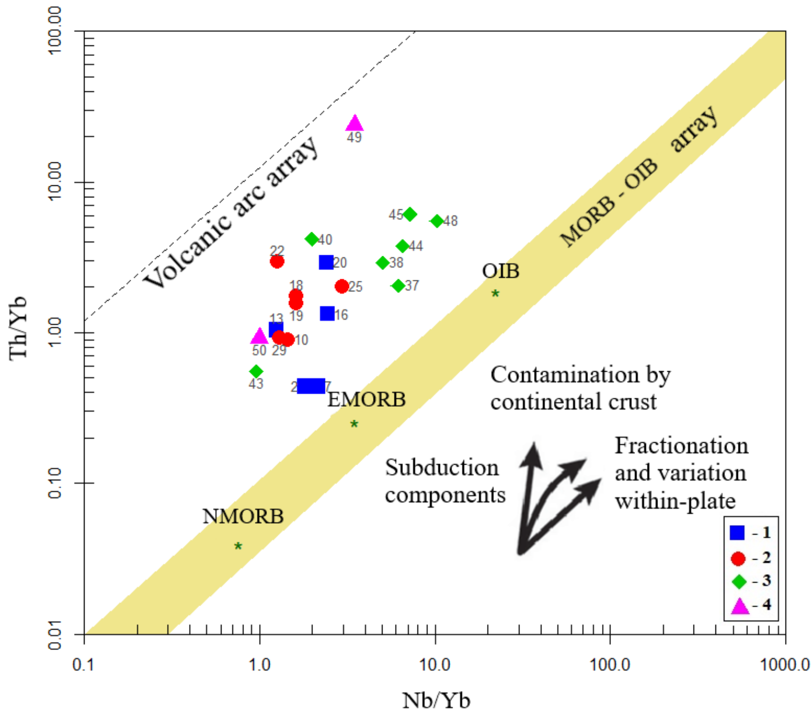

Figure 5. The position of the figurative points of the gabbro-tonalite formation rocks in the Th/Yb-Nb/Yb diagram[17]. Abbreviations: NMORB - normal mid-ocean ridge basalts; EMORB - enriched mid-ocean ridge basalts; OIB - ocean island basalts. Legend: as in Fig. 4.

Based on the analysis of the La/Sm-La and La/Yb-Sm/Yb diagrams, the figurative points of the gabbro-tonalite formation rocks are positioned along the trend of a garnet lherzolite melt, lying on an enriched mantle line. Such a magmatic source could result from partial melting of the lithospheric mantle due to its components during the subduction phase that occurred in the study area during the Jurassic

[17] Pearce, J.A. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust // Lithos, – 2008. vol. 100 (1), – p. 14-48.

period.

The dependence diagram of Rb/Sr and Sr/Ba ratios shows a slight decrease in the Sr/Ba ratio and a rapid increase in the Rb/Sr ratio from lower to higher silicon members. Such observations indicate the fractional crystallization of plagioclase and potassium feldspar as significant stages in the magmatic evolution of I-type granitoids.

The correlation of the tetrad effect ($TE_{1,3}$) with Sr/Eu, Eu/Eu*, Y/Ho, and Zr/Hf ratios proves that the figurative points of the Gedabek granitoid phase rocks lie below the minimum threshold value of $TE_{1,3}$. This result indicates that the rocks formed from a mantle-derived magmatic source under specific melting conditions and are consistent with I-type granitoids.

According to the tectonic discriminant diagram based on FeO*/(FeO*+MgO)-SiO_2, the formation rocks transitioning from diorite to quartz diorite, monzodiorite, tonalite to granodiorite, and granite-aplite are classified as magnesium-rich I-type granitoids, indicating their magmatic origin and formation through deep magmatic processes.

The Nb/La-La/Yb diagram indicates enrichment with incompatible elements, suggesting that the magma formed from the initial melt originated from the lithospheric mantle enriched with other incompatible elements.

Petrogeochemical model.

The petrogeochemical model for the formation of gabbro-tonalite rocks in the Gedabek ore district of the Lok-Qarabağ island arc indicates that they originate from the same mantle source but are characterized by varying degrees of partial melting and fractional crystallization (see fig. 6)[18]. The enrichment of incompatible elements, depletion of LREE and Ta-Nb-Ti, high Sr/Y ratios, enrichment of LILEs, and depletion of heavy metal isotopes are indicators of mantle metasomatism in subduction zones.

[18] Tornos, F. The role of the subducting slab and melt crystallization in the formation of magnetite-(apatite) systems, Coastal Cordillera of Chile / F.Tornos, J.M.Hanchar, R.Munizaga [et al.] // Mineralium Deposita, – 2021. vol. 56, – p. 253-278.

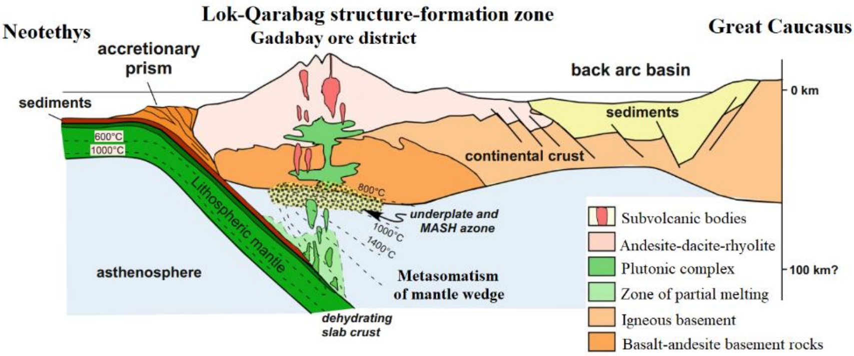

Figure 6. The petrogeochemical model for the mature development of the Lok-Qarabağ island arc[18]. Abbreviation: MASH (Melting, Assimilation, Storage, and Homogenization) - a zone where melting, assimilation, storage, and homogenization occur.

CHAPTER V. POTENTIAL MINERALIZATION OF UPPER JURASSIC GRANITOIDS

The Gadir deposit, discovered in 2012 by the exploration geology team of AIMC Ltd., is located 370 meters northwest of the Gedabek high-sulfidized epithermal-porphyry type gold-copper-polymetallic deposit in the Shamkir uplift of the Lok-Qarabağ structural-formation zone within the Lesser Caucasus mega-anticlinorium[19,20]. The Gadir deposit is influenced by the Gedabek-Bittibulag deep fault, which plays a significant tectonic role in the deposit's location. The geological structure of the deposit consists of veins from the diorite-granodiorite, which is the second phase of the multiphase Gedabek intrusive rock formation, and volcanic rocks from

[19] Babazadeh, V.M. New perspective Gadir mineralization field in Gedabey ore region / V.M.Babazadeh, A.A.Veliyev, A.A.Bayramov [et al.] // – Baku: The reports of National Academy of Sciences of Azerbaijan, – 2015. vol. 71 (2), – p. 74-79
[20] Novruzov, N.A. Mineral composition and paragenesis of altered and mineralized zones in the Gadir low sulfidation epithermal deposit (Lesser Caucasus, Azerbaijan) / N.A.Novruzov, A.A.Valiyev, A.A.Bayramov [et al.] // Islamic Azad University Mashhad Branch, Iranian Journal of Earth Sciences, – 2019. vol. 11, – p. 14-29.

the Middle-Upper Jurassic that are complicated by fracture structures, as well as subvolcanic masses composed of dacite-rhyodacite-rhyolite.

Morphology and internal structure of the ore bodies.

The morphology of the Gadir ore body is adapted to the subvolcanic form of the erupted quartzites that manifest in the deposit. There are three main zones, each composed of similar mineral associations. The predominant ore and non-ore minerals include pyrite, chalcopyrite, sphalerite, and quartz, while secondary and rare minerals consist of tetrahedrite, galena, magnetite, hematite, free gold, tellurides, barite, and others.

Physico-chemical conditions of mineralization.

In the Gadir area, the sulfur isotopic values vary as follows: for chalcopyrite, 2.1‰<$\delta^{34}S$<3.5‰; for sphalerite, 1.4‰<$\delta^{34}S$<5.1‰; and for pyrite, 2.7‰<$\delta^{34}S$<3.5‰. In contrast, the sulfur isotopic values in the Gedabek deposit range as follows: for chalcopyrite, -2.5‰< $\delta^{34}S$<2.8‰; for sphalerite, -0.23‰<$\delta^{34}S$<4.1‰; and for pyrite, -1.24 ‰<$\delta^{34}S$<4.0‰ (see fig. 7)[21].

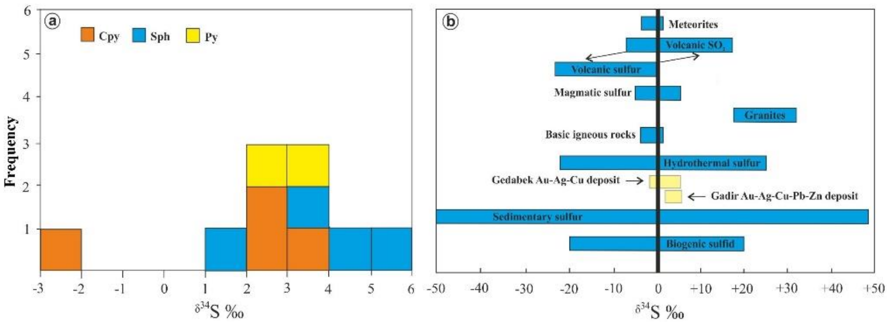

Figure 7. Sulfur isotope compositions of sulfide mineral samples from Gadir and Gedabek ore bodies[21]: a) frequency histogram showing the distribution of $\delta^{34}S$ values for chalcopyrite (Cpy), sphalerite (Sph), and pyrite (Py) sulfide minerals; b) comparison of the genesis of deposits based on the results of $\delta^{34}S$ sulfur isotopic values.

[21] Ismayil, C. Geochemical, mineralogical and sulfur isotopic evidence on the genesis of the Gadir Au-Ag-Cu-Pb-Zn deposit (NW Azerbaijan) in the Lesser Caucasus / C.Ismayil, F.Arik, A.Bayramov [et al.] // Arabian Journal of Geosciences, – 2021. vol. 14 (1298), – p. 1-20.

As indicated by the results of the analyses, while it is assumed that the mineralization in the Gedabek and Gadir deposits originates from the same magmatic source or solution, the formation of the Gedabek deposit plays a significant role directly linked to the multiphase Gedabek intrusion. In contrast, the Gadir deposit can be interpreted as having formed as a result of geothermal processes that are genetically related to that intrusion (see fig. 8).

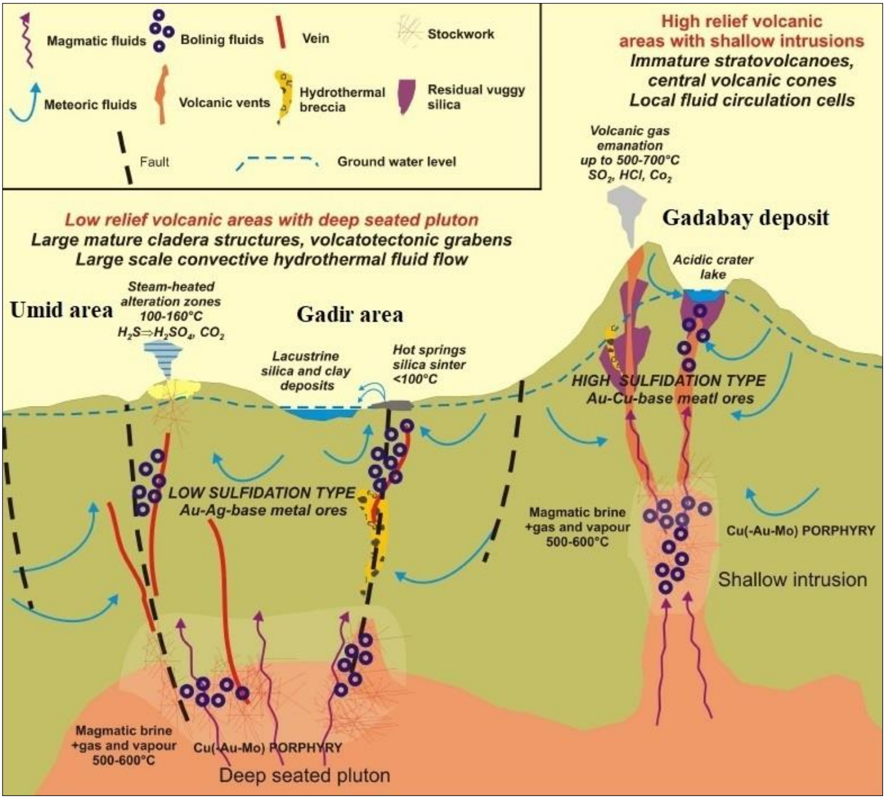

Figure 8. 2D geological-genetic model of the formation mechanism of the eastern flanks of the Yoğundağ epithermal system (developed based on

the ore formation model of deposits similar to the porphyry-epithermal systems of the Tokaj Mountains in Hungary)[22]. Note: Gadabay or Gedabek

Sulfur isotope geothermometric analysis.

To determine the equilibrium isotopic temperatures of the ores in the Gadir Au-Ag-Cu-Zn deposit, research was conducted using the sulfide-sulfide (chalcopyrite-sphalerite) pair analysis method. The temperature indicator was determined to be in the range of 100-300°C. For the sphalerite-chalcopyrite pair of the Gedabek ore bodies, the temperature indicator varies between 250-500°C[21].

For the Gadir deposit, the Au mineralization resources have been calculated at 4,226.8 kg of gold and 9,967 kg of silver for 767,097.8 tons of ore in the C_1+C_2 and P_1 categories (see fig. 9).

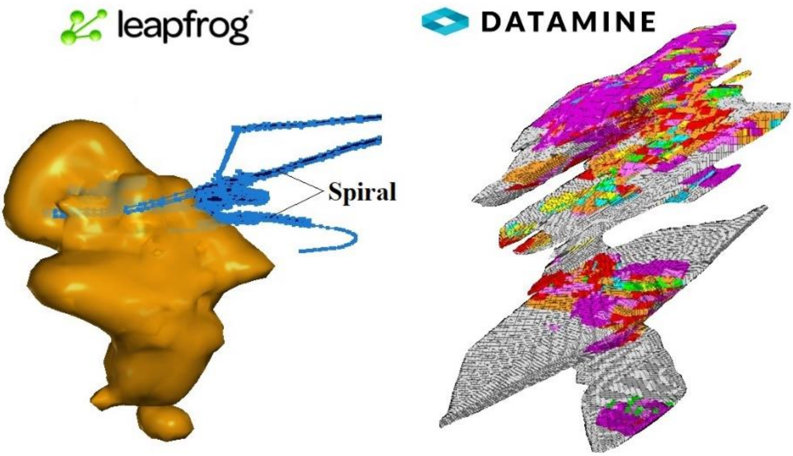

Figure 9. 3D model of the Gadir ore body created using Leapfrog and Datamine computer graphics software

During geological exploration and research work in the Gadir area, including the study of the sulfide/hydrothermal alteration systems

[22] Molnár, F., Zelenka, T., Pécskay, Z., Gatter, I., Bernadett, B. Metallogeny of Paleogene and Neogene volcanic belts in Hungary // Mineral exploration and sustainable development, Conference: 7th Biannual SGA Meeting, – Rotterdam: Millpress, – August 11-13, – 2003, – p. 1205-1208.

at the Yoğundağ site, the developed geological-genetic model can contribute to the discovery of hidden mineralization areas in covered regions.

Based on the obtained results, figure 10 presents the petrogeochemical model of the formation of the Mesozoic-age Lok-Qarabağ island arc, formed as a result of the subduction of the Tethys Ocean beneath the Eurasian margin in the part of the Lesser Caucasus meganticlinorium of the Tethys metallogenic belt.

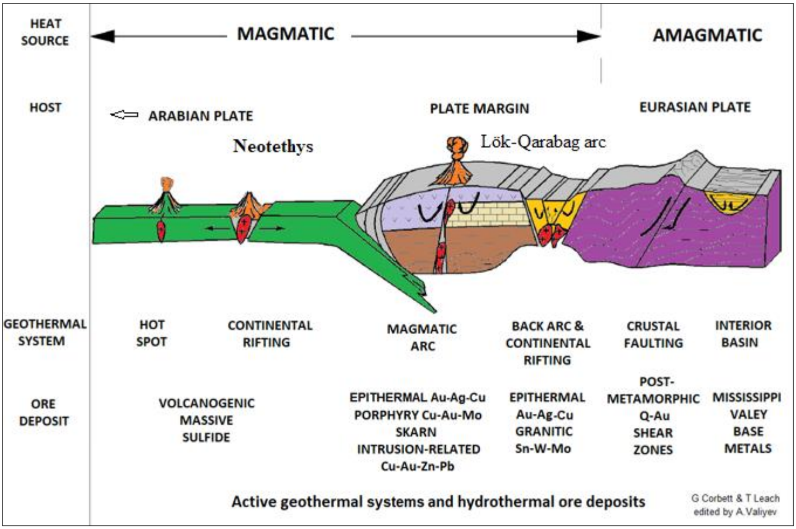

Figure 10. The petrogeochemical model of the formation of the Lok-Qarabağ island arc[23]

The study of various compiled petrogeochemical models is essential for understanding the evolution of continental margins and

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[23] Valiyev, A.A., Westhead, St.J., Bayramov, A.A., Ibrahimov, J.R., Mammadov, S.M., Gadimov, Sh.M., Talibov, M.A., Mursalov, S.S., Asgarov, R.G., Hasanov, F.A., Imamverdiyev, N.A. Ore deposits discovered in Azerbaijan in recent years (on the example of Gadabay mineralisation district) // Abstracts of the reports of the Republican scientific conference dedicated to the 85th anniversary of Academician Vasif Babazadeh on "Geology: Unity of Theory and Practice", – Baku: Baku University, – 2024, – p. 65-75.

the formation of mineral deposits. For instance, gabbroid rocks are often associated with nickel, copper, and chromium deposits, while granitoid rocks are linked to gold, silver, and molybdenum deposits. By understanding the processes that form and differentiate the gabbro-tonalite formation, researchers or geologists can better target their exploration efforts.

In conclusion, it can be noted that the analysis of the results from the comprehensive studies discussed above will be beneficial for the identification of foundational elements in future field geological research and exploration activities.

CONCLUSIONS AND SUGGESTION

As a result of the conducted research and comprehensive analysis of petrographic-geochemical, isotopic-geochemical, geochronological, and mineralogical data, the following conclusions have been drawn:

1. The gabbro-tonalite formation rocks of the Gedabek ore district have been determined to belong to low-potassium tholeiitic and calc-alkaline series. The crystallization differentiation processes, associated with the fractionation of dark minerals and plagioclase, play a significant role in the formation of these rocks, scientifically substantiating their formation from the same geochemical parent magma.
2. The isotopic-geochemical characteristics of the gabbro-tonalite formation rocks of the Gedabek intrusion (depletion of large ion lithophile elements (LILE) in the gabbroid phase, and their enrichment in the granitoid phase, with $\varepsilon Nd(t) > 1$ and $^{87}Sr/^{86}Sr$ ratios ranging from 0.70402 to 0.70595) confirm the melting of the primary magma from the mantle wedge and its contamination with approximately equal amounts of continental crust material prior to the Cambrian.
3. It has been determined that granitoids crystallized under various pressure conditions (4.2±1.1 - 6.6±1.0 kbar) at significantly

different temperatures (700±50 - 770±50°C) from oxidized magma ($lgf(O_2)=10^{-17.0}$ to $10^{-13.2}$).

4. Based on the results of U-Th-Pb (SHRIMP II) and isotopic-geochemical (Sm-Nd and Rb-Sr) studies, along with petrochemical data, a mechanism and petrogenetic model for the formation of the gabbro-tonalite formation rocks of the Gedabek ore district have been proposed. It has been concluded that the rocks of the gabbroid phase of the gabbro-tonalite formation (165±1 - 159±1 million years ago) resulted from the differentiation of a depleted magmatic source, while the I-type granitoid phase rocks (144±1 - 138±2 million years ago) were formed due to the melting of subducted sediments and other magmatic processes, resulting in the enrichment of the magmatic chamber with incompatible elements during the mature development phase of the Lok-Qarabağ island arc.

5. The formation of gold-sulfide ores in the Gadir area has been determined to occur at depths of 200-500 m and temperatures of 100-300°C. The gold mineralization in the Gadir ore mass is closely associated with mineral associations such as semi-massive pyrite, chalcopyrite-pyrite, chalcopyrite-pyrite-sphalerite, chalcopyrite-sphalerite-galena-magnetite, and quartz-hosted pyrite. The indicators of sulfur isotopes in the ores confirm their magmatic-hydrothermal origin and that they originated from the same magmatic source.

6. It has been identified that the Gadir low-sulfidation epithermal deposit, concentrated in the eastern flank of the Yoğundağ epithermal system located south of the Gedabek-Bittibulag ore belt, is genetically related to the granitoid phase of the Gedabek intrusion.

Thus, the petrogenetic model for the formation of the gabbro-tonalite (Gedabek, Chaykend, Qabaqtapa) rocks of the Gedabek ore district and the geological-genetic model of the Gadir gold-copper-polymetallic deposit can serve as a fundamental benchmark for scientific research and future geological exploration and prospecting activities in the Lok-Qarabağ structural-formation zone of the Lesser Caucasus. The application of this model in those efforts is recommended.

List of main publications on the topic of the dissertation

1. Valiyev, A.A., **Bayramov, A.A.,** Mursalov, S.S. Geology, resource, and future ore perspective of the Gedabek gold deposit, Azerbaijan // Conference on Recent Research Activities and New Results about the Regional Geology, the Geodynamics and the Metallogeny of the Lesser Caucasus, – Tbilisi, Georgia, – April 16-18, – 2013, – p. 23.
2. **Bayramov, A.A.** Petrographic characteristics of the multiphase Gedabek intrusive // 5th International Conference of Young Scientists and Students on "Fundamental and Applied Geology: Achievements, Perspectives, Problems and Solutions", dedicated to the 90th anniversary of the national leader of the Azerbaijani people Heydar Aliyev, – Baku: Nafta-Press Publishing, – November 14-15, – 2013, – p. 39-40. (in Azerbaijani)
3. **Bayramov, A.A.** The role of intrusive complexes in the formation of hydrothermal metasomatic altered zones in the Gedabek deposit // Republican Scientific Conference on "Actual Problems of Geology" dedicated to the 91st anniversary of the national leader of the Azerbaijani people Heydar Aliyev, – Baku: "Baku University" Publishing House, – 2014, – p. 122-123. (in Azerbaijani)
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7. Baba-zadeh, V.M., Veliyev, A.A., Abdullayeva, Sh.F., Imamverdiyev, N.A., Mammedov, S.M., Ibrahimov, J.R., **Bayramov, A.A.** New perspective Gadir mineralization field in Gedabey ore region // The reports of National Academy of Sciences of Azerbaijan, – Baku: – 2015. vol. 71, № 2, – p. 74-79.
8. Babazadeh, V.M., Valiyev, A.A., Abdullayeva, Sh.F., Imamverdiyev, N.A., Mammadov, S.M., Ibrahimov, J.R., **Bayramov, A.A.** A new prospective Gadir mineralization field in the Gedabey ore region // News of Baku University, series of natural sciences, – Baku: – 2015. No. 2, – p. 92-97. (in Azerbaijani)
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16. Valiyev, A.A., Westhead, S.J., **Bayramov, A.A.,** Ibrahimov, J.R., Mammadov, S.M., Gadimov, Sh.M., Jafarov, Z.A. Lithological-structural setting and mineralization styles of Reza high sulfidation epithermal gold deposit of Ugur exploration area, Gedabek ore district, Lesser Caucasus, Azerbaijan; A Newly Discovered Orebody in the Western Asian // Ore Deposits of Asia: China and Beyond., Society of Economic Geologists Conference, – Beijing, China: Society of Economic Geologists, – 2017, – p. 1.
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The defense will be held on 28 October 2025 at 12:00 at the meeting of the Dissertation council FD 2.21 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at the Baku State University of the Ministry of Science and Education of the Republic of Azerbaijan.

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Dissertation is accessible at the Scientific Library of the Baku State University.

Electronic version of the abstract is available on the official website of the Baku State University.

Abstract was sent to the required addresses on 26 September 2025.

Signed for print: 24.09.2025
Paper format: 60x84$^{1/16}$
Volume: 36070
Number of hard copies: 20