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PETROLOGICAL FACTORS OF FORMATION OF CENTRAL LOK-GARABAKH ZONE INTRUSION COMPLEXES OF UPPER JURASSIC – EARLY CRETACEOUS AGE

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Summary. The presented paper is dedicated to the study of the formation of the Gadabay-Soyudlu intrusion of Upper Jurassic – Lower Cretaceous age based on complex geological-mineralogical researches. As a result, it was proved that the intrusion and its comagmatic volcanic analogues have been formed within the mature volcanic island arc setting. By the results of titaniferous magnetite-ilmenite and pyroxene thermobarometers gabbroid rocks of the first phase have been crystallized in the high thermobaric conditions. Ni (millerite) and Co (cobaltite) ore mineralizations related to this phase of the intrusion are found in the rocks. The vein rocks of the gabbroid phase are fine grained crystalline rocks such as micro-gabbro, spessartite, diabase. Rock members of the gabbroid phase have been formed under the control of crystallization-differentiation in magmatic chambers located in the upper crust under relatively high thermobaric conditions.

The derivatives of the quartz-diorite or second phase crystallized under the lower thermobaric conditions ($T \approx 780^oC$). The vein rocks of this phase are aplite and granite-pegmatite occurring in the areoles of the second phase. The second phase has also formed within the upper crust, but crystallization temperature was dropped and partial pressure of oxygen was increased.

Both first phase and second phase derivatives have been crystallized from the primary tholeiitic magma relatively enriched in Al_2O_3 within the mature volcanic island arc setting under the control of differential crystallization process.

The gold-pyrite, gold-polymetallic and gold-barite-copper-polymetallic ore mineralization were justified to be related to the quartz diorite phase magmatism.

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Introduction

Nowadays, the results of petrological and geodynamic researches are one of the principal criterions in the study of formation and localization of natural mineral resources. In this context, the initial composition of magmatic melts and the geologic-geodynamic situtations controlling their evolution process have the crucial role. The formation of initial melts with different compositions directly depends on physical-chemical and geological-geodynamic situations. These melts can pass different evolution paths depending on existing geodynamic situations. In this context, in the mature ensialic island arc environment the representative typomorphic calc-alkaline basaltic intrusive rocks and their derivatives, as well as their effusive comagmatites are formed through the staged processes, whereas in the ensimatic island arc environment the derivatives of tholeiitic basalt magma are formed. In other geodynamic situations absolutely different magmatic rocks are formed.

Geology of the Region

The Lok-Garabakh zone in the structural-geological context is situated in the central part of the Mediterranean folding belt, more precisely in the Caucasus-Zagros segment of the belt and formed as a result of the northern subduction of the Mesotethys ocean (Rustamov, 2019; Panov, 2013; Adamia etc., 1977). In the early Jurassic ages Mesotethys had larger width in the east and the narrower in the west dividing Gondwana and Laurasia. This mature island arc starts from the Aras river in the eastern south and extends to the western north along the main Caucasus direction to the Lok-Garabakh crystallic massive. From here the zone turns to west, that is, continues along latitude direction to the Pond moun-

tains. That's why most geologists call this zone as Lok-Garabakh-Pond mature island arc.

In the Azerbaijan territory the Lok-Karabakh zone is situated in the north-eastern slopes of the Lesser Caucasus. In the geological structure of the zone, magmatic, volcanic, metamorphic, volcano-sedimentary and normal sedimentary rock complexes of Paleozoic and Mesozoic age are present. The oldest basement rocks in the studied region are exposed in the deep erosional cross-section of Asrik, Akhinja, Hasansu, Khrami rivers in the western extension of the zone. Here, the complexes of this crystallic basement consist of intensively metamorphosed schists and graphitized, sericitized, amphibolized gneisses. Basal conglomerates of quite thickness (250 m) of Hettangian age are superposed on them.

Referring to researchers (Rustamov, 2019; Adamia et al., 1977), it can be highlighted that the upheaving environment in the basement part of this zone within the Lesser Caucasus predominated during the Upper Carbon – Early Jurassic period. Hence, transgressive basal conglomerates of quite thickness were formed here. In the valleys of both Hasansu and Asrik rivers intensively metamorphosed schists (Sinemurian, Pliensbachian, Toarcian, Early Aalenian) argillites, fine grained sandstones of small thickness occur. The contacts of Early and Middle Jurassic ages can be observed in Shamkir, Shamsaddin, Allahverdi anticlinoria.

The pause in geological "lull" was interrupted with the Early Bajocian volcanism. Volcanic rocks are presented in the geological structure of Shamkir, Murovdagh, Shamsaddin, Allahverdi anticlinoria mostly as lava-pyroclastic and sub-volcanic facies (Abdullaev, 1963). The thickness of the Lower Bajocian stage varies between 1500-2000 meters. In composition they correspond to porphyritic basalt, basaltic andesite and rarely andesite. In the Upper Bajocian stage the volcanic facies of quartz-plagioclase rhyolite, rhyodacite composition and their comagmatic intrusive analogues widely distributed in the studied area and demonstrated bimodal relationship with the Lower Bajocian volcanic rocks were formed. These comagmatites are presented in the geological structure of Murovdagh, Goy-gol, Shamkir, Shamsaddin, Allahverdi anticlinoria. And volcanic rocks conformably overlay the basalts and basaltic andesites of the Lower Bajocian stage. Intrusions of the Upper Bajocian age are exposed as Atabay-Slavyanka, Gilanbir, Mehrab, Tovuz, Akhpat outcrops. Their age to be Upper Bajocian (166±1 Ma, 176±1 Ma) is proved by conducted geochronological studies (Sadygov, 2019) and by the geological position of intrusions (Abdullaev, 1979). The mentioned intrusions and their volcanic rock analogues non-conformably lay upon Bajocian volcanic rocks in Shamkir, Murovdagh and Goy-gol anticlinoria of the Lok-Karabagh zone.

Volcanic and volcanic-sedimentary rocks of the Bathonian stage within the Shamkir horst anticlinorium are distributed scarcely comparing with the Garadakh, Murovdagh, Shamsaddin, Allahverdi anticlinoria. They are mostly composed of agglomerate tuff, tuff-breccia, volcanic breccia and conglomerates. The composition of volcanic breccia and lava covers is mainly basaltic, andesite-basaltic, andesitic, dacitic and in limited amount rhyolitic. The subvolcanic facies of the described volcanic rocks occur as dikes, stocks of small diameter and sills.

Sedimentary rocks of the Callovian-Oxfordian stages lay upon narrowly spread volcanic rocks of the Bathonian stage in the north-western and south-eastern flanks of the Shamkir anticlinorium. This geological lull was interrupted by the Upper Jurassic (Kimmeridgian) volcano-plutonic magmatic processes. These processes were more intensive in the Kimmeridgian – Early Cretaceous period in the north-eastern flanks of the Shamkir anticlinorium.

The volcanic processes have widely developed in the north-western and north-eastern flanks of the anticlinorium, more precisely in its contact with the Kazakh synclinorium. Along with this the Kimmeridgian volcanism is widely spread along the eastern slope of the Lesser Caucasus, especially in the downstream parts of the Injachay and Tartar rivers in the northern flanks of the Aghchakand synclinorium. The rocks of pyroclastic facies predominate within the Kimmeridgian – Lower Cretaceous volcanic rocks. Effusive rocks of small thickness consist of andesite, dacite, andesitic dacite. In the north-western part of the Shamkir horst anticlinorium volcanic rocks of the Early Cretaceous (Valanginian) are subalkaline trachyandesitic, trachyandesitic in composition. Besides, these rocks occur in the south-eastern part of the Murovdagh anticlinorium.

In comparison with the middle Jurassic intrusions the Upper Jurassic – Lower Cretaceous intrusive rock complexes are widespread in the Lok-Karabagh zone. They widely occur in the geological structure of the Allahverdi, Shamkir, Murovdagh, Aghdam, Goy-gol, Gaphan anticlinoria and Dashkasan, Agchakand, Aghdara etc. synclinoria of the Lok-Karabakh zone. Their age to be Upper Jurassic (159 Ma, 138 Ma) is proved by determining of the absolute age (Sadygov, 2019) and by the geological studies (Abdullaev, 1979).

The Gadabay-Soyudlu intrusion itself has a great petrogenetic importance in the formation of ore forming and ore-bearing metasomatites as well as in the formation of phases and facia compared to the aforementioned intrusions. This fact really requires further study of the geological, petrogenetic and metallogenic peculiarities of this intrusive complex.

The Gadabay-Soyudlu intrusion of the Upper Jurassic – Lower Cretaceous age in present topography starts from the same named settlement in the north-west to the confluence of Gadabaysu and Shamkir rivers in the northeast. Its north-western border extends until Arikhdam and Qaradagh villages. Plagioclase rhyolites of the Upper Jurassic in the north-western contact of the intrusion have been changed to secondary quartzite of various intensity, while in the south-eastern, eastern contacts in the Soyuqbulaq village scarnization occurs. Volcanic rocks of the Lower Bajocian stage are intensively exposed to chloritization, limonitization. By the calculation of H.I.Karimov (Karimov, 1963) the total area of intrusion is 42 km^2.

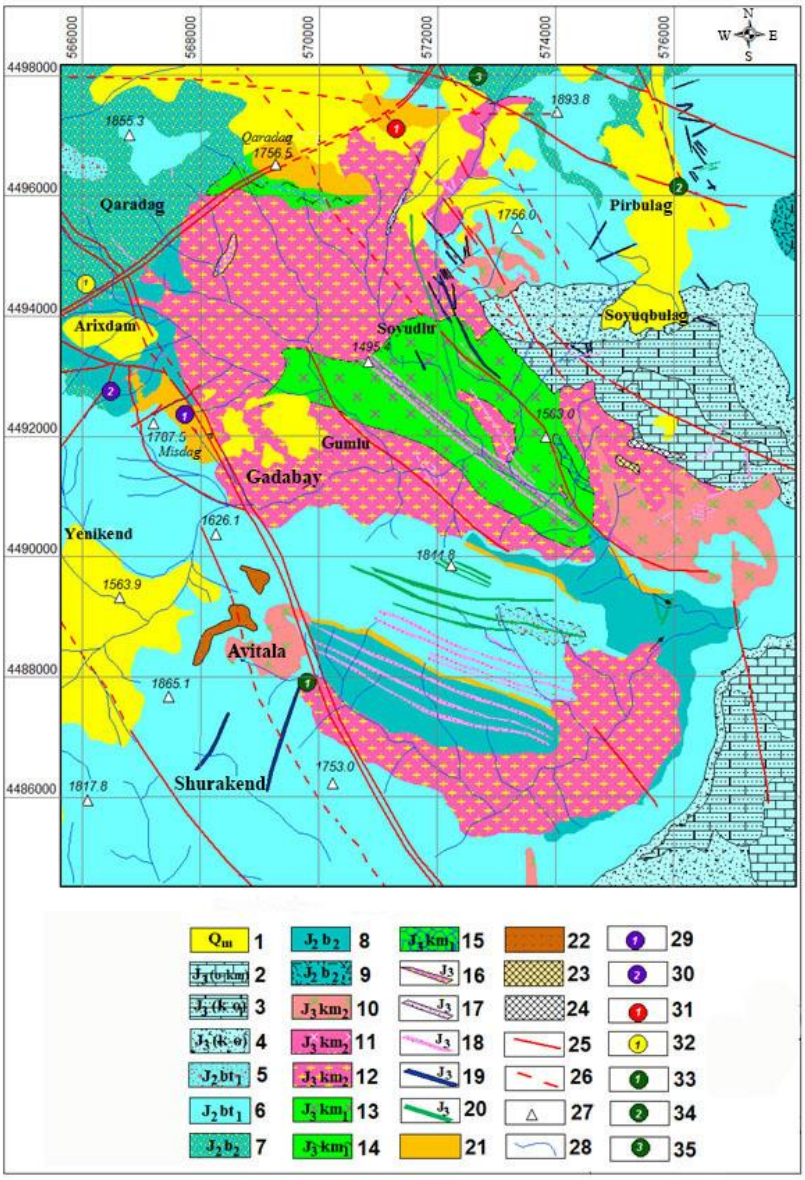


Fig 1. Lithological-structural map of the south-eastern part of the Gadabay ore region

Legend: 1 – Quaternary sediments; 2 – Limestone layer (Lusitanian): alternation of limestones with limestones and tuff-sandstones; 3 – Upper tuff-conglomerate layer: tuff-sandstones, alternation of tuffs and limestones, sandy limestones and sandstones; 4 – Lower tuff-conglomerate layer: tuff-conglomerates, tuff-breccias, tuff sandstones; 5 – Metamorphically altered tuffs; 6. Bathonian sub-volcanic layer: tuff-breccias containing tuff, tuff-conglomerates; 7 – Upper Bajocian stratum: rhyolite-riodacitic lava fascia; 8 – Lower Bajocian volcanic layer: andesitic lava fascia; 9 – Lower Bajocian stratum: pyroclastic fascia of tuff-breccia and andesite porphyries; 10 – Garagaya-Garamurad hypabyssal sub-intrusion: diorite, keratospilit; 11 – The second phase of Gadabay intrusion: diorites; 12 – The second phase of Gadabay intrusion: granodiorites, quartz diorites, diorite-syenites, diorites; 13 – The first phase of Gadabay intrusion: gabbro-diorites, gabbro; 14 – The first phase of Gadabay intrusion: gabbro-norites, gabbro; 15 – The first phase of Gadabay intrusion: gabbro-pyroxenites; 16 – Syenite-diorite dykes; 17 – Aplite dyke, 18 – Quartz-diorite dyke; 19 – Andesite dykes; 20 – Diabase dykes; 21 – Metasomatites; 22 – Greisenization (metasomatic quartzites with tourmaline); 23 – Skarns (garnet-vollastanite-calcite fascia); 24 – Skarns (carbonate-epidote fascia); 25 – Faults; 26 – Presumed faults; 27 – Altitude references, 28 – Rivers; 29 – Gadabay deposit; 30 – Gadir mineralization area; 31 – Great Galacha copper-porphyry ore manifestation; 32 – Cholpan sulfur-pyrite ore manifestation; 33 – Ayitala copper-pyrite ore manifestation; 34 – Pirbulag copper-pyrite ore manifestation; 35. Parakand-su copper-pyrite ore manifestation.

The described intrusion has been studied by numerous researchers with different approaches (Abdullaev, 1963; Karimov, 1963; Mustafaev, 1977; Ramazanov, 1993; Sadygov, 2019 etc.). All these researchers have mainly investigated the geology, petrography and mineralization of outcrops of the Bajocian and Upper Jurassic – Lower Cretaceous intrusions in the Gadabay mineralization zone. However, they haven't analyzed the geological formation conditions, physical-chemical conditions of crystallization, mineralization and localization of intrusion from point of view of plate tectonics.

Methodology

In the paper the results of analyses of 19 rock samples have been used to study the geological-geodynamic and physical-chemical conditions of the formation of the phases of the Gadabay-Soyudlu intrusion. To determine the physical-chemical conditions of the crystallization of the magmatic rocks, the results of microprobe analyses (Jeol, JSM-66 10LV) of 6 samples of pyroxene and 8 samples of iron-titanium oxide minerals have been used. Furthermore, X-ray diffractometric (Oxford instruments, X-Max) analyses of 19 samples have been run to analyze the homogeneity of the pyroxenes and iron-titanium oxide minerals. The petrographic description of the relevant rocks has been done using "Carl Zeiss Axio Imager A2m" polarized microscope. All aforementioned analyses and procedures have been done in the Institute of Geology and Geophysics of Azerbaijan National Academy of Sciences. Monomineralic separation of magmatic rocks has been conducted in the Geological and Geophysical Institute of Russian Federation. Polished sections of the ore minerals also have been studied with "Carl Zeiss Axio Imager A2m" polarized microscope.

Petrographic and mineralogical characteristics

From the presented map (Fig. 1) it can be seen that the Gadabay-Soyudlu intrusion is composed of two phases. The first phase consists of gabbroid rocks and the second one of quartz-diorite. However, along with this rock the diabase (dolerite, microgabbro) and dikes of acidic composition with northwestern orientation are widespread in the area. The first type dikes are the derivatives of gabbroid rocks and the second ones are of granodiorites.

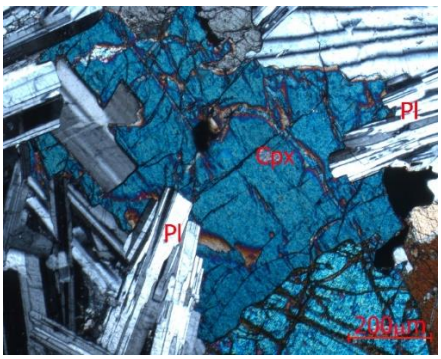
Derivatives of the first phase occur in the outcrops located in the central part of Gadabay-Soyudlu intrusion. Besides, these petrographic type rocks are found near the Almali-tala settlement. The first derivatives of the first phase are considered to be coarse grained, total crystalline gabbro and gabbro-norite of dark black color. Under the microscope gabbro-norite has gabbro-ophitic texture (Fig. 2a). The first idiomorphic granular, non-oval crystalline phase is composed of gialosiderite (Fa_{35-40}) (Fig. 2b).

Its concentration changes between 3-6% in the rock. It is distinguished by characteristic looped texture. According to the crystallization sequence the next mineral is a short prismatic hypersthene. It mostly forms intergrowths with basic plagioclase. And its concentration doesn't exceed 7-8% in the rock. The main rock forming mineral is considered to be plagioclases of the labradorite-bytownite composition. They are presented in two generation making characteristic polysynthetic twinning. The first generation is more likely to undergo alteration processes. The second generation is fresh and predominates in the rock. Clinopyroxene predominates over hypersthene in the rock. Compositionally it is composed of Mg augite (Ng=1.720; Np=1.694; 2V=54-56; CNg=44-46) (fig. 2d). Along with the described minerals Cr magnetite and magnetite are present in gabbro-norite and normal gabbro.

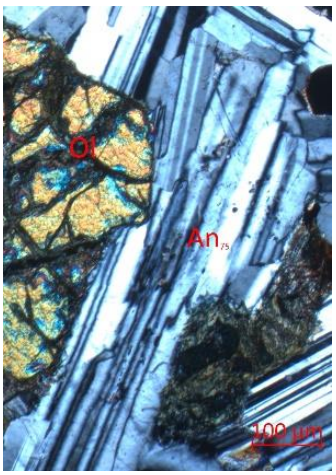
As we noted, within the intrusion gabbro and gabbro-norite of dark black color are gradually replaced by melanocratic gabbro of pale black color and they in turn by leucocratic gabbro of greyish black color. This gradual transition is distinguishable under the microscope. Olivine is practically absent, the content of ortho- and clinopyroxene decreases along the transition, while the content of plagioclase increases and anorthite – decreases. Besides, biotite, hornblende, even secondary uralite, epidote are present in the described rocks. Clearly formed middle titan magnetite is observed in these rocks.

Finally, in the next transition leucocratic gabbroids are replaced by quartz bearing gabbro-diorites. These rocks have a light gray colour, the naked eye can see small grains of quartz with a glassy luster, rare elongated narrow grains of hornblende, straw-yellow grains of biotite with a predominance of plagioclase grains. It should be noted that both pyroxenes undergo uralitization and even chloritization to varying degrees. Very tiny grains such as magnetite and blood red hematite are scattered within these minerals. Fine quartz grains are present in a shapeless, xenomorphic form among the plagioclase grains. Biotite sheets are also distributed narrowly.

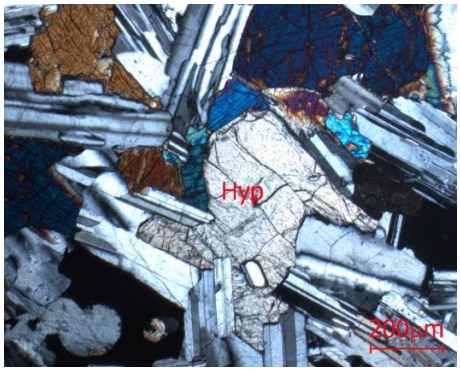
The rocks of gabbroid phase cut through by dykes of kersantite, microgabbro or dolerite in insignificant thickness. From the point of view of petrochemistry (Table 1) it is obvious that the rocks of the first phase have formed under the control of fractional differentiation in the intrusive chamber. The initial derivatives of the intrusion such as gabbro-norite, hypersthene-bearing gabbro-norite, melanocratic gabbro have gradual transition into each other and are olivine normalized (Table 1, an. 1, 2, 3).



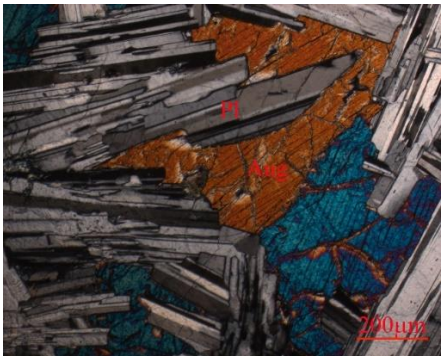
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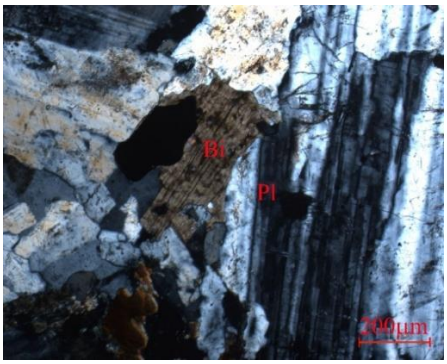
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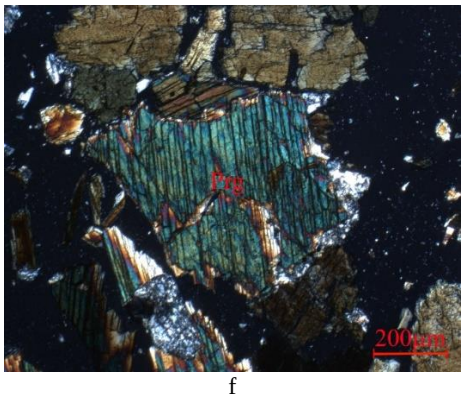
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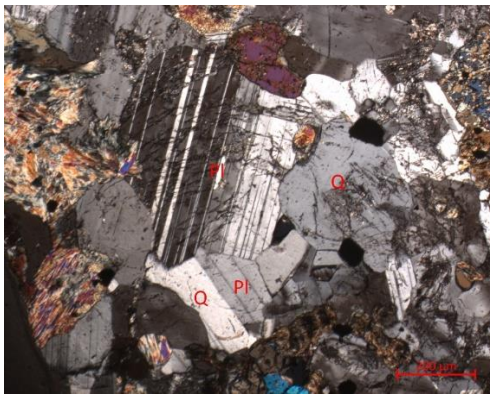
d



e



f



g

Fig. 2. Photomicrographs of the thin sections of rocks of the Gadabay-Soyudlu intrusion

a – gabbro-norite, b – olivine gabbro, c – hypersthene gabbro-norite, d – gabbro, e – diorite, f – pargasite diorite, g – quartz-diorite

Besides, the exceeding of Na_2O over the K_2O is characterized by predominance of normative albite. The behavior of normative anorthite molecule in the rocks can be clearly seen in the table (Table 1). The crystallization temperature of olivine-norite – the first derivative of the described intrusion has been calculated based on (Lindsley, 1983) orthopyroxene-clinopyroxene equilibrium (Table 2, an. 1, 2, 3).

As seen from Table 2, enstatite molecules in both olivine-bearing gabbro-norite and hypersthene-bearing gabbro-norite are close to each other (En=84–85%) in composition and are in equilibrium with Mg-augite (table 2, an. 1, 2).

In quartz diorite concentration of the ferrosilite component of the orthopyroxene increases and the pyroxene has a ferro-hypersthene composition (Table 2). Hence, the fractional differentiation in the intrusive chamber caused an increase of ferrosilite molecule concentration and a decrease of enstatite molecule within the ortho- and clinopyroxenes.

Based on the above data, it can be justified that most likely the primary magma of the Gadabay-Soyudlu intrusion could be high-magnesium tholeiitic basalt partially enriched in Al_2O_3. The first or gabrroid phase of the intrusion has been formed by fractionation in the magmatic chambers under the control of crystallization-differentiation. The geological setting represented the upper horizons of a mature volcanic island arc.

As noted earlier, the second phase of the Gadabay-Soyudlu intrusion is a quartz-diorite complex. This is justified by the fact that both in the Gadabay intrusion and in other intrusive outcrops the predominant petrographic rock types are quartz-diorites, besides gabbroid xenoliths of various sizes occur within these rocks. Along with this, their vein rocks cut gabbroid rocks and sometimes quartz-diorites. In all this, thermal contacts are observed in gabbroid rocks.

Table 1

Chemical and CIPW composition of the representative samples of the Gadabay-Soyudlu intrusion

Components \ Analyses	1	2	3	4	5	6	7	8	9
SiO_2	49.46	48.64	49.35	52.73	58.75	60.41	63.51	67.85	57.10
TiO_2	0.48	0.64	0.64	0.67	0.36	0.11	0.16	0.41	0.64
Al_2O_3	18.75	18.64	16.33	19.55	16.64	17.43	15.26	14.54	16.48
Fe_2O_3	3.31	3.26	3.26	3.21	3.28	2.75	3.23	1.96	2.56
FeO	5.86	5.46	7.56	3.27	4.76	3.52	5.36	2.38	3.75
MnO	0.16	0.16	0.24	0.01	0.16	0.11	0.12	0.02	0.14
MgO	6.36	6.42	6.73	4.76	3.82	3.39	2.12	2.24	4.21
CaO	9.21	9.66	9.92	8.70	0.42	6.60	5.16	2.31	5.34
Na_2O	3.42	3.22	3.40	4.42	3.78	3.42	2.38	5.11	3.36
K_2O	0.06	0.38	0.78	0.47	0.42	0.75	1.10	1.54	4.28
P_2O_5	0.14	0.14	0.20	0.01	0.11	0.10	0.16	0.16	0.28
n,n	2.32	2.85	1.48	1.87	0.43	1.20	1.39	1.33	1.38
∑	99.53	99.33	99.77	99.67	99.93	99.79	99.95	99.85	99.52
Ap	0.3	0.3	0.5	-	0.2	0.2	0.4	0.4	0.7
Il	0.9	1.2	1.2	1.1	0.7	0.2	0.3	0.8	1.2
Mt	4.8	4.7	4.7	4.7	4.7	4.5	4.6	2.8	3.7
Or	0.3	2.2	4.5	1.7	2.5	4.5	6.8	9.1	25.3
ab	28.9	27.3	29.8	37.4	32.0	29.0	20.1	43.2	28.4
an	35.6	35.3	26.8	32.1	27.2	30.0	24.7	10.5	11.2
wo	3.8	4.9	8.9	4.6	1.6	0.9	-	-	3.1
en	2.4	3.2	5.2	3.5	1.0	0.6	-	-	2.1
fs	1.16	1.3	3.3	0.6	0.6	0.3	-	-	0.8
fo	1.6	3.3	6.9	-	-	-	-	-	-
fa	0.86	1.5	4.8	-	-	-	-	-	-
en	11.4	10.4	1.7	8.4	8.5	7.9	5.2	8.1	8.4
fs	5.25	3.3	1.1	1.6	6.1	3.9	3.3	2.1	3.2
cs	-	-	-	-	-	-	1.0	0.4	-
Q	-	-	-	0.9	14.2	35.2	31.7	21.8	4.0

1 – olivine gabbro; 2 – hypersthene gabbro-norite; 3 – melanocratic gabbro; 4 – gabbro-diorite; 5 – diorite; 6 – quartz diorite; 7 – banatite; 8 – granodiorite; 9 – monzonite

Table 2

Chemical composition and crystallochemical formulas of the gabbroids and diorites of the Gadabay-Soyudlu intrusion

Rock	Olivine-bearing gabbro-norite (Almali-tala)		Hypersthene-bearing gabbro (Arikhdam)		Quartz diorite (Soyudlu)	
mineral / Components	opx	cpx	opx	cpx	opx	cpx
SiO_2	53.75	50.86	54.25	50.21	50.38	50.60
TiO_2	0.10	0.48	0.12	0.46	0.11	0.16
Al_2O_3	2.15	2.32	1.85	1.82	2.60	1.38
Cr_2O_3	0.46	0.26	0.47	0.18	-	-
Fe_2O_3	3.26	2.97	2.12	5.05	1.88	1.66
FeO	9.11	7.03	10.04	6.28	23.91	14.71
MnO	0.23	0.21	0.22	0.24	0.16	0.19
MgO	30.46	14.46	30.10	14.76	20.18	12.31
CaO	0.38	20.68	0.25	20.45	0.18	18.50
Na_2O	0.04	0.36	0.03	0.40	0.04	0.05
∑	99.94	99.63	99.45	99.85	99.44	99.56
Si	1.905	1.904	1.931	1.883	1.913	1.941
Al	0.090	0.103	0.003	0.080	0.116	0.062
Ti	0.003	0.013	0.077	0.013	0.003	0.005
Cr	0.013	0.008	0.013	0.005	-	-
Fe^{+3}	0.087	0.084	0.057	0.142	0.053	0.048
Fe^{+2}	0.270	0.260	0.299	0.197	0.759	0.472
Mn	0.007	0.007	0.007	0.007	0.005	0.006
Mg	1.608	0.806	1.596	0.824	1.141	0.703
Ca	0.014	0.829	0.010	0.821	0.007	0.760
Na	0.003	0.026	0.002	0.029	0.003	0.004
∑	4.00	4.00	3.995	4.001	4.000	4.001
Ca	0.7	44.5	0.5	44.6	0.4	39.3
Mg	85.0	43.5	83.8	44.7	59.8	36.3
Fe	14.3	13.0	15.7	10.7	39.8	24.4
t°C	800		780		850	

As we have already mentioned, quartz-diorites are the most widely distributed petrographic rock type of the Gadabay-Soyudlu intrusion. These are macroscopically spotted grey, coarse grained, holocrystalline rocks. Rare dark black amphibole grains with metallic luster, as well as pyroxene and goldish yellow biotite grains are distinguishable in macroscopic background color. Under microscope diorites are hypidiomorphic, holocrystalline rocks. The major mineral of the rock is plagioclase. It predominates in the rock, in most cases forms idiomorphic polysynthetic twinning grains. In composition it corresponds to andesine (An_{38-48}). In quartz-diorites the anorthite molecule is reduced to 32-36%. In the center of zonal grains, chloritization, pellitization, and sometimes epidotization of varying intensity are observed. In normal diorites quartz grains present in limited amount among plagioclase grains.

As can be seen, from the normal diorites toward their quartz-bearing analogues the amount of colored minerals decreases. These minerals are ortho- and clinopyroxenes, amphiboles, biotite, while the secondary minerals are epidote, uralite, chlorite, calcite, prehnite. The first-generation iron-titan oxide minerals form mutual intergrowths with ortho- and clinopyroxenes. Their secondary analogues are found in the uralite and amphibole grains in the dot like, sometimes brownish tiny leaf-like forms. The gradual increase of quartz grains in normal diorites changes them to quartz-diorite varieties. Besides, quartz grains become larger and their undulose extinction is clearly observed. Along with clinopyroxene, a greenish-blue hair-like uralite is formed in most cases. These pyroxenes are distinguished by their pale green color and characteristic pleochroism. They correspond to iron augite ($Wo_{39-40}En_{35-38}Fs_{60-66}$) by their optical features and chemical composition. Orthopyroxene occurs as solitary grains and is a hypersthene in composition (CNg=0, Ng=1.730, Np=1.714). Both in west, north-western and south-eastern contacts and near contact zones of the Gadabay-Soyudlu intrusion quartz-diorites gradually change to granodiorites, tonalities, banatites. However, with the decrease of colored minerals, the amount of plagioclase also decreases. Consequently, beginning from the quartz-diorites toward the granodiorites the amount of quartz increases.

After the quartz-diorites and hornblende-biotite diorites the second most spread rock variety of the Gadabay-Soyudlu intrusion is considered to be granodiorites. These rocks have a pinkish hue on a gray background and are mostly medium- and coarse-grained. They mainly occur in the south-eastern and north-western parts of the intrusion.

Plain-like prismatic, rarely irregular plagioclase grains predominate within the rock. In composition they correspond to acidic andesine (An_{31-40}) and are exposed to alteration processes not too much. Pellitization and sericitization are occasionally observed in the central part of zonal crystals. As noted earlier, the second most common mineral in the rocks is quartz. It occurs among the plagioclase grains as xenomorphic ones. Along with this, they form intergrowths with alkaline feldspars. According to the results of optical studies (2V=65-70, CNp=3-5, d_{hkl}=4.18-4.2) and XRD analyses, the transition phase is a weakly homogeneous orthoclase. Here the concentration of perthite varies from 15 to 22%.

As mentioned before, of the colored minerals ferro-hypersthene, ferro-augite, hornblende, and sometimes pargasite and biotite present in limited amounts. Secondary (uralite, hematite, limonite, magnetite, sericite, clinochlore, epidote) and accessory (apatite, garnet, titan magnetite, sphene etc.) minerals occur in insignificant amounts.

It should be noted that the amount of biotite and hornblende sometimes increases in granodiorites causing the formation of biotite and hornblende varieties of these rocks. And sometimes granodiorites change into tonalite and banatite. In this context the amount of quartz decreases in their composition comparing with granodiorites. Besides, in tonolite the alkaline feldspar doesn't occur at all or occurs as isolated grains. In banatites orthoclase occurs along with quartz. These rocks also have hornblende and biotite varieties of granodiorites. Granites and their hornblende and biotite varieties are considered to be the last or final petrographic type of rocks of the Gadabay-Soyudlu intrusion. They are mainly spread in north-western and south-western contacts of the intrusion. It should be noted that in the Soyudlu village within the gabbroids there are outcrops of granoaplite as a form of stockwork and ring. Besides, quartz-monzodiorite was found in the exploration well near the Soyugbulag village in the north-eastern flank of the Gadabay-Soyudlu intrusion. In addition, the same rock was found by AIMC Company while they drilled exploration well in the north-western flank of the intrusion.

Monzonites and their quartz-bearing analogues are macroscopically coarse-grained rocks of pale pinkish-gray color. Under the microscope it has a characteristic monzonite structure. It is a holocrystalline rock. Minerals are presented as plagioclase within labradorite, transitional orthoclase, quartz, hornblende, biotite, moderately titanium magnetite. And the accessory minerals are apatite, zirconium, whereas the secondary minerals are chlorite, epidote and limonite. Plagioclase predominates among the aforementioned minerals and has prismatic, idiomorphic, polysynthetic twinnings. They sometimes are sericitized and sometimes epidotized. Orthoclase is xenomorphic comparing with plagioclase and occurs as irregular dusky grey grains. Of colored minerals, elongated prismatic pargasite with its strong pleochroism is present. A limited number of diopside occurs as pyroxenes. There are more biotite sheets compared with other colored minerals. Magnetite occurs in pargasite and diopside as inclusions in the long vein like grains form. Monzonites make transitions sometimes to diorites and sometimes to syenites.

The vein rocks of the second phase of Gadabay-Soyudlu intrusion are spread especially in the north-western part of the intrusion and consist of aplites, plagiogranites, quartz-albite rhyolites, etc.

Quartz-diorites, in other words rocks of the second phase are also normal alkaline rocks except monzodiorite, and they belong to sodium series rocks, which are mainly controlled by fractional crystallization. Besides, except monzodiorites they are silica saturated and are characterized by predominance of Na_2O over K_2O (Table 1, an. 5, 6, 7, 8). Along with this, neither modal nor normative olivine is represented, but limited amounts of corundum are present in tonalite and granodiorite due to decreased silica content (Table 1, an. 7, 8). In monzonites the amount of normative orthoclase molecule increases up to 28.4%.

Since biotite and orthoclase spread in quartz diorites is limited, they were accumulated in the residual melt. Such and other geochemical and physical-chemical constraints caused the accumulation of potassium and related elements, such as Rb, Ba, and partially Sr, in the residual melt, i.e., monzodiorite, monzonite, and led to the crystallization of orthoclase and biotite.

Another evolutionary path of the quartz-diorites led to formation of granodiorites and granites. All of these varieties, in turn, formed corresponding derivatives, which determined the petrogenetic variations of vein rocks of different facies.

The crystallization temperature of some quartz-diorite phase derivatives was calculated by existing geothermometers based on the magnetite-ilmenite equilibrium (Lindlsey, 1983; Kawai, 1956; Lindsley, Spencer, 1982).

Moderately titanium magnetite and ilmenite are present in quartz-diorite phase rocks in tiny amount.

Moderately titanium magnetite occurs as inclusions in colored minerals such as clinopyroxene, pargasite and sometimes biotite. Sometimes it forms intergrowths with clinopyroxene, and ilmenite forms very fine sheet-like grains between the colored and felsic minerals. It can be observed in magnetite in the form of a needle-like net.

As we have already mentioned, the magnetite-ilmenite equilibrium (Lindsley and Spencer, 1982) was used to calculate the crystallization temperature and oxygen partial pressure for the quartz-diorite phase derivative rocks. The results of their chemical analyses and crystallochemical formulas are given in Table 3. As can be seen from the table, most of the derivative phases crystallized at close temperatures (t=700-770ºC) and partial pressures of oxygen (lgf_{O_2}=-13.2-15.0). So, the upper crystallization temperature limit is being observed for quartz-monzonites (t=770ºC).

Interpreting the data presented, we can conclude that the second quartz diorite phase was also formed in the upper crust as the gabbroid phase, but crustal assimilation acted together with fractionation, resulting in amphibolization, micalization, and uralization.

The impact of the Gadabay-Soyudlu intrusion on the contact and host rocks resulted in the formation of several ore-forming and host metasomatites. However, prior to this impact within the intrusion itself, the pyroxenes were mostly replaced by amphibole, epidote, magnetite, hematite, calcite, and chlorite. Lower Jurassic volcanic rocks underwent intense limonitization and secondary silicification on the northwestern flank of the intrusion, especially in the Bitdibulak area.

Based on the obtained petrological differences of the intrusion phases, it was found that at the end of the first stage of crystallization of the gabbroic melt, the presence of hydrogen sulfide caused mineralization of such elements as Co, Ni, Cr. (Table 4, an. 9-12), while the hydrothermal solutions of the quartz diorite phase had a more oxidizing environment. Consequently, they caused crystallization of hematite and maghemite. They also oxidized pyrite crystals. The formation of ore minerals such as chalcopyrite, sphalerite, galena, and pyrrhotite is also associated with the tonalite and monzonite subphases of quartz diorites.

Table 3

Chemical compsoition and crystallochemical formulas of the representative samples of the Gadabay-Soyudlu intrusion

rock / analysis	Gabbro-diorite		Quartz-diorite		Granodiorite		Quartz-bearing monzonite	
	5		6		8		9	
mineral / Components	Mt	Ilm	Mt	Ilm	Mt	Ilm	Mt	Ilm
SiO_2	0.09	0.11	0.14	0.07	0.08	0.06	0.07	0.09
TiO_2	2.10	48.60	2.38	48.84	5.20	49.25	6.38	49.26
Al_2O_3	2.35	0.12	1.23	0.18	0.58	0.26	0.78	0.34
Fe_2O_3	62.45	6.91	63.15	6.94	58.63	5.55	55.52	5.86
FeO	31.20	43.09	31.47	42.96	33.84	43.62	36.44	43.31
MnO	0.38	0.21	0.26	0.34	0.29	0.28	0.18	0.41
MgO	1.16	0.28	1.21	0.39	1.18	0.31	0.25	0.39
NiO	0.08	0.10	0.09	0.11	0.08	0.06	0.09	0.04
∑	99.81	99.42	99.93	99.83	99.88	99.39	99.71	99.70
Si	0.003	0.003	0.005	0.002	0.003	0.001	0.003	0.002
Ti	0.060	0.929	0.068	0.929	0.148	0.942	0.183	0.937
Al	0.104	0.004	0.055	0.005	0.026	0.005	0.035	0.010
Fe^{+3}	1.770	0.132	1.799	0.132	1.672	0.106	1.594	0.111
Fe^{+2}	0.983	0.916	0.996	0.908	1.072	0.927	11.63	0.916
Mn	0.012	0.004	0.005	0.007	0.009	0.006	0.006	0.009
Mg	0.065	0.010	0.068	0.015	0.067	0.012	0.014	0.015
Ni	0.002	0.002	0.003	0.002	0.002	0.001	0.003	0.001
Mt	93.4	-	92.5	-	84.7	-	81.1	-
Usp	6.6	-	7.5	-	15.3	-	18.9	-
Ilm	-	87.0	-	87.0	-	89	-	88.3
Hem	-	13.0	-	13.0	-	11	-	11.7
tºC	700		700		750		770	
fo_2	10^{-15}		10^{-15}		$10^{-13.4}$		$10^{-13.2}$	

Table 4

The results of mineralogical analyses of the Gadabay-Soyudlu ore deposit and manifestations

rock	pyrite		chalcopyrite		sphalerite		galena	argento chalcopyrite	cobaltite
analysis / Components	1	2	3	4	5	6	7	8	9
Fe	47.12	46.73	30.46	29.75	7.80	7.40	-	28.74	2.80
Cu	0.21	0.18	34.23	34.45	-	-	-	32.86	-
Zn	-	-	-	-	58.43	58.56	0.25	-	-
Pb	-	-	-	-	-	-	85.86	-	-
Mn	-	-	-	-	0.07	0.08	-	-	-
Ni	0.20	0.03	0.011	0.02	-	-	-	-	0.16
Co	0.26	0.64	0.012	0.04	-	-	-	-	32.36
Ag	-	-	0.06	0.10	-	-	-	3.80	-
Cd	-	-	-	-	0.20	0.28		-	-
As	-	-	0.10	0.18	-	-	-	-	45.24
Se	-	-	0.04	0.16	-	-	-	-	-
S	52.14	52.36	34.48	34.78	32.90	33.25	13.46	34.15	18.92
∑	99.93	99.94	99.39	99.48	99.40	99.52	99.66	99.55	99.70

rock	Cobaltite	millerite	
analysis / Components	10	11	12
Co	32.44	3.16	2.72
Fe	2.74	2.42	2.51
Ni	0.18	58.60	58.64
Cu	0.24	0.46	0.36
As	45.12	35.20(S)	35.25(S)
∑	99.92	99.84	99.51

Galena, sphalerite and sometimes chalcopyrite were found in barite-polymetallic veins drilled by an exploration well in the northwestern part of the Gadabay-Soyudlu intrusion.

Gold and silver in various concentrations were found in these different zones of mineralization.

Summarizing, the interpretation of conducted complex petrological, geodynamical studies and as well as a study of gold-polymetallic, gold-sulfide, copper-sulfide mineralization show that cobalt and nickel mineralization are related to the hydrothermal stage of the gabbroid phase, while gold-bearing copper-iron-sulfide mineralization is thought to be controlled by numerous hydrothermal metasomatites of the quartz-diorite phase derivatives. Derivatives of the Bajocian plagiogranite intrusion of varying intensity have undergone metasomatism. Here, kaolinization, sericitization, and secondary silicification changes are mainly observed. And in the north-eastern part of the Gadabay-Soyudlu intrusion the Callovian-Oxfordian volcanic-sedimentary rocks and limestones are scarnized. In the north-western flank of the intrusion the Bathonian dusky sedimentary rocks are intensively kaolinized, sericitized, limonitized, etc. In all contact and alteration zones quartz-diorites occur. However, in the north-western part of the intrusion in quite deep horizons derivatives such as quartz-monzonite, monzonite occur. Here, gold-bearing chalcopyrite, sphalerite and galena mineralisation has been identified in barite veins of varying orientation. Thus, in some words, we can say that, gold-bearing copper-pyrite mineralization is associated with quartz-diorite phase derivatives, whereas gold-bearing polymetallic mineralization is associated with quartz-monzonite.

Discussion

The Gadabay-Soyudlu intrusion of the Upper Jurassic – lower Cretaceous age is located in the conjunction of the Shamkir horst anticlinorium and Dashkasan synclinorium. The Lock-Garabagh-Pond Zone was formed as a result of north-directed subduction of the Mesothetics Ocean in the Early Jurassic. However, during the Permian – Early Jurassic period of the geological evolution of the zone, the intensive upheaval environment dominated. The Early Jurassic basal conglomerates overlie intensely metamorphosed basement rocks. Therefore the Early Jurassic basal conglomerates with a thickness of 250 m transgressively lay upon the intensively metamorphosed basement rocks. Quite thick (200 m) metamorphic schists of the Lias can be traced at short intervals. Volcanic

rocks of the Lower Bajocian stage also most times demonstrate inconsistences. The contact rocks of the studied Gadabay-Soyudlu intrusion consist of the Bathonian, Callovian, Oxfordian rocks. Two phases are distinguished in the intrusion, where the rocks of the first gabbroid phase such as norite, gabbro-norite, melanocratic gabbro by pyroxene thermometer have crystallized in the intrusive chamber at temperatures 800-870°C. As quartz-diorites are the most common rocks and the first derivative of the second phase, they are accepted as the main type of the second phase rocks. According to moderately titanium magnetite-ilmenite thermometer, derivatives of the second phase crystallized at 700-770°C and partial pressure of $10^{-13.2}$ – $10^{-15.0}$. Monzodiorites of this phase have crystallized at 870°C.

Petrochemical studies have established that the norites, gabbro-norites and melanocratic gabbroids are olivine normative, while the leucocratic gabbroids are already hypersthene and quartz normative. This fact and the modal mineralogical constitution demonstrate that, the first phase of the intrusion was formed under the control of fractional crystallization.

The fractional crystallization of the second phase has played the principal role in the evolution of the intrusion. From quartz-diorite melts the evolution followed two paths. In the first case normal alkali diorites gradually evolved to quartz-diorite–banatite–tonalite–granodiorite–granite. In the second case quartz-diorites evolved into quartz-monzonite-monzonite and no less into syenite.

Hydrothermal liquids of gabbroid phase caused millerite and cobaltite mineralization, while liquids of quartz-diorite derivatives are associated with the gold-bearing copper and iron pyrite, as well as with the gold-polymetallic mineralizations.

Results

As a result of complex geological and geochronological studies, it was proved that the Gadabay-Soyudlu intrusion is of the Upper Jurassic – Early Cretaceous age (138-159 Ma). The intrusion was formed within the mature volcanic arc with its volcanic complexes.

The intrusion was formed in two phases, as confirmed by its geological, petrographic, petrochemical and mineralogical characteristics. Each phase has vein rocks beside the intrusive bodies. Rock members of the gabrroid phase were formed under the control of crystallization-differentiation in magmatic chambers located in the upper part of the Earth's crust under relatively high thermobaric conditions. Increase of fugacities in the second or quartz-diorite phase, as well as assimilation of wall rocks and increase of incoherent elements concentration led to molybdenum mineralization in limited local areas bordering the gold-pyrite mineralization areas.

The petrological diversity of the phases is confirmed by the structural-optical types of feldspars.

This research paper presented important results on the thermobaric conditions and crystallisation sequence of the rocks of the Gadabay-Soyudlu intrusion phases. At the same time, the influence of fugacities, including oxygen fugacities, controlling the thermal conditions of crystallisation has been studied.

One of the most important approaches in the paper is that it interprets the processes producing ore mineralisation of both phases.

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ПЕТРОЛОГИЧЕСКИЕ ОСОБЕННОСТИ ФОРМИРОВАНИЯ ПОЗДНЕЮРСКО-РАННЕМЕЛОВЫХ ИНТРУЗИВНЫХ КОМПЛЕКСОВ ЦЕНТРАЛЬНОЙ ЧАСТИ ЛОК-ГАРАБАГСКОЙ ЗОНЫ

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Резюме. В статье на основе петрологических особенностей анализируются геологические и физико-химические условия формирования Гядабей-Соютлинского интрузива. Установлено, что позднеюрско-раннемеловые эффузивные комагматиты данного интрузива широко распространены в северо-восточной и западной частях Шамкирского антиклинория. Ранняя габброидная фаза интрузива кристаллизовалась при относительно более высокой температуре. Гидротермальные растворы в Гадирском рудопроявлении способствовали кристаллизации кобальтина и миллерита. В отличие от ранней фазы, расплав второй кварц-диоритовой фазы эволюцинировал свой состав в двух направлениях. В ранней стадии формировалась кварц-диорит–тоналит–бонатит–гранодиорит–гранитовая, а позже кварц-диорит–кварц-монцодиорит–кварц-монцосиенитовая ветви кварц-диоритовой магмы. С гидротермальными растворами этих ветвей связаны золотоносные, медные, железные колчеданные месторождения и проявления Гядабейского района. Однако установленное золотоносное барит-полиметаллическое орудение, выявленное на северо-западной окраине Гядабейского месторождения пространственно тяготеет к монцонитовой ветви кварц-диоритовой фазы. Температура и парциальное давление кристаллизации пород рассчитывались с помощью двух, пироксенового и магнетит-ильменитового, термометров. Исходя из умеренного титано-магнетит-ильменитового равновесия, присутствующего в этих породах, температуры кристаллизации дифференциатов отдельных фаз Гядабей-Соютлинского интрузива варьируются от 800 до 870°C. Парциальное давление кислорода, контролирующего процесс кристаллизации, колеблется в пределах 10^{-13}-10^{-15}, что соответствует магнетит-гематитовому буферу. Исходная известково-щелочная базальтовая магма интрузива, будучи вовлеченной в процесс кристаллизации в очагах в зависимости от активности магматических разломов в различных частях земной коры, послужила основой для формирования фаз интрузива. Остаточная часть или гидротермальные растворы каждой фазы путем термического воздействия на контактные породы интрузивных и ранее кристаллизованных комплексов горных пород способствовали образованию рудовмещающих (золото, серебро, медь, цинк, свинец, никель и др.) метасоматитов. На основе комплексных геолого-геодинамических и петрологических исследований установлено, что Гядабей-Соютлинский многофазовый интрузив формировался в зрелых палеоостроводужных условиях.

Ключевые слова: *Гядабей-Соютлинский интрузив, температура и парциальное давление кристаллизации, габброидная фаза, кварц-диоритовая фаза*

LÖK-QARABAĞ ZONASININ MƏRKƏZİ HİSSƏSİNİN GEC YURA VƏ ERKƏN TƏBAŞİR YAŞLI İNTRUZİV KOMPLEKSLƏRİNİN FORMALAŞMASININ PETROLOJİ XÜSUSUYYƏTLƏRİ

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Xülasə. Məqalədə petroloji xüsusiyyətlər əsasında Gədəbəy-Söyudlü intruzivinin formalaşmasının geoloji və fiziki-kimyəvi şəraiti araşdırılır. Müəyyən olunmuşdur ki, Gec Yura-Erkən Təbaşir yaşlı bu intruzivin effuziv komaqmatitləri Şəmkir horst antiklinoriumunun şimal-şərq və qərb hissəsində yayılmışdır. İntruzivin fəaliyyətinin erkən fazası nisbətən yüksək temperaturda kristallaşmışdır. Bu fazanın hidrotermal məhlulları Qədir təzəhüründə kobaltin-millerit filizləşməsinin əmələ gəlməsinə və yerləşməsinə zəmin

yaratmışdır. İkinci, kvarslı diorit fazasının diferensiatları isə iki istiqamətdə təkamül etmişdir: öncə diorit–kvars-diorit–tonalit–banatit–qranodiorit–qranit diferensiatları formalaşmışdır. Bunların hidrotermal məhlulları ilə qızıllı dəmir kolçedanı və mis kolçedanı filizləşməsinin əlaqədar olması göstərilir. İkinci halda kvarslı diorit-kvarslı monsodiorit-siyenit diferensiatları qızıllı polimetal filizləşməsi ilə əlaqədardır. Sonuncu Gədəbəy-Söyüdlü intruzivinin şimal-qərb cinahında aşkar olunmuşdur. Tədqiq olunan diferensiatların kristallaşma temperaturları və oksigenin parsial təzyiqləri iki–piroksen və maqnetit-ilmenit termometrlərindən istifadə etməklə hesablanmışdır. Bu süxurların tərkiblərində iştirak edən mötədil titanlı maqnetit-ilmenit tarazlıqları əsasında Gədəbəy-Söyüdlü çoxfazalı intruzivinin ayrı-ayrı fazalarının diferensiatlarının kristallaşma temperaturları 800-870ºC arasında dəyişir. Kristallaşma prosesinə nəzarət edən oksigenin parsial təzyiqi isə maqnetit-hematit buferinə uyğun gəlməklə 10^{-13}-10^{-15} arasında dəyişir. İntruzivin ilkin əhəngli-qələvi bazalt maqması yer qabığının müxtəlif hüdudlarında maqmadaşıyan qırılmaların aktivliyindən asılı olaraq kameralarda kristallaşma prosesinə cəlb olunmaqla intruzivin fazalarının əmələ gəlməsinə zəmin yaratmışdır. Hər fazanın qalıq hissəsi, yaxud hidrotermal məhlulları intruzivin təmas süxurlarına və onlardan əvvəl kristallaşmış süxur komplekslərinə termiki təsir edərək filizyerləşdirən metasomatitləri əmələ gətirmişdir. Kompleks geoloji-geodinamik və petroloji tədqiqatlar əsasında müəyyən olunmuşdur ki, Gədəbəy-Söyüdlü çoxfazalı intruzivi yetgin adalar qövsü şəraitində formalaşmışdır.

Açar sözlər: *Gədəbəy-Söyüdlü intruzivi, diferensiatların kristallaşma temperaturları və oksigenin parsial təzyiqləri, qabroid fazası, kvars-diorit fazası*