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On the contribution of basic and ultrabasic rocks in the accumulation of the products of volcanic and hydrothermal activity in the Balygychan–Sugoi Trough (NE Russia)

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Abstract. The data available on the crustal structure of the Balygychan–Sugoi Trough and the mineralogy and geochemistry of the Mesozoic and Cenozoic gabbro, acid volcanics, and post-magmatic minerals of the Dukat Au–Ag ore field, Sn–Ag occurrences, and zones of dispersed multimetal mineralization are used to show the great role of basic magma material in the shaping of their chemical composition. The data reported here for the Sr isotopic compositions of the contrasting volcanic rocks and the post-magmatic minerals of the ore-bearing areas and for the mineral compositions of mafic and ultramafic inclusions in the acid volcanics suggest a connection between the successive periods of endogenic activity in the region and mantle convection and the belonging of the resulting products to a mantle-plume rock association.

Introduction

The Balygychan–Sugoi Trough is the largest transverse structural element of the North Okhotsk region, bordering the Okhotsk–Chukotka volcanic belt in the north (Figure 1). The accumulation of the Meso-Cenozoic volcanic and plutonic rocks of this region are associated conventionally with the reactivation of endogenic activity in the zone of the Kolyma–Kamchatka roughly N-trending lineament and with the formation of the Okhotsk–Chukotka volcanic belt. The study of the volumetric ratios between the products of subaerial volcanic activity and granitoids resulted in the view that the formation of the Sn–Ag and Au–Ag ore deposits of the area, including the unique Dukat Au–Ag ore deposit, had been connected with a rhyolite–granite association [*Konstantinov et al.,* 1998; *Kravtsova and Zakharov,* 1996]. It is believed that the main metallic elements had been derived from the enclosing rhyolite by way of meteoric water infiltration and recycling. The initial accumulation of volatile and metallic elements in the rhyolite is believed to have been associated with the process of residual concentration.

The data available on the geologic structure of the region, the mineralogy and geochemistry of the acid volcanics [*Filimonova,* 1995, 2002; *Filimonova et al.,* 1990; *Konstantinov et al.,* 1998; *Sidorov,* 1989], as well as the new data we have obtained recently for the products of volcanic, post-magmatic, and hydrothermal activity, suggest the great role of basic materials in their formation. Moreover, the territory of the Balygychan–Sugoi Trough can be ranked as a mantle plume province where the periods of endogenic activity were controlled by the reactivation of convection in the mantle.

Structural Position of the Balygychan–Sugoi Trough and Some Special Features of its Deep Structure

The Balygychan–Sugoi Trough is located between the Kolyma and Omolon ancient massifs and extends for 120 km in a submeridional direction having a width of roughly 60 km (Figure 1). At the present time this region is an arch rising high above the sea level, complicated by ring structures of various sizes. The maximum absolute heights (1200 m) and

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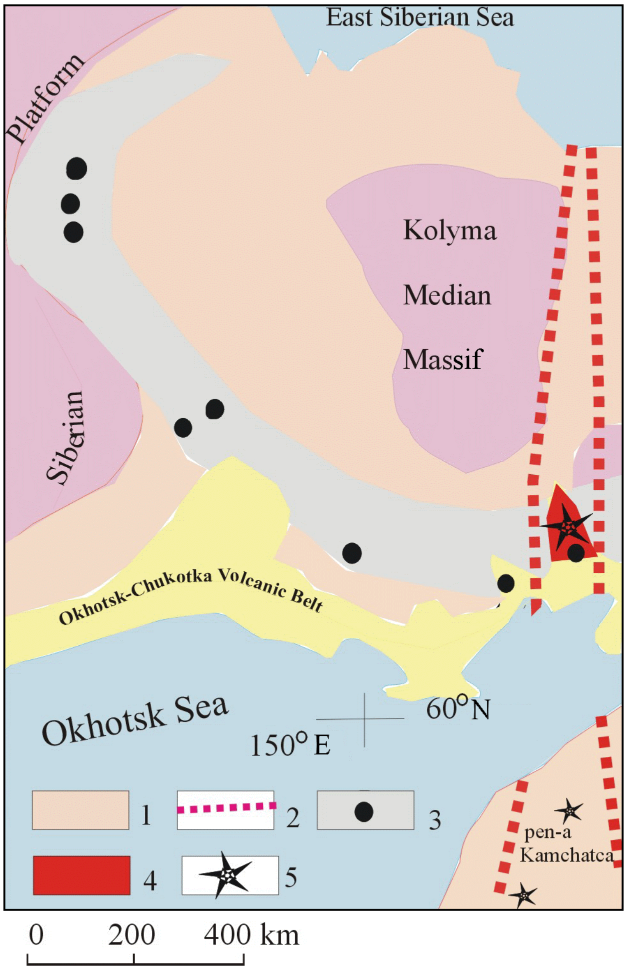

Figure 1. Schematic geostructural map of Northeastern Russia.
(1) Mesozoic and Cenozoic fold systems (Kamchatka); (2) fold systems in the Kolyma–Kamchatka Lineament; (3) Verkhoyansk–Chukotka silver-base metal belt with Ag–Pb–Zn and Sn–Ag mineralization; (4) Balygychan–Sugoi Trough; (5) Dukat Au–Ag ore deposit and occurrences in Kamchatka.

relative elevations (about 400 m) are restricted to the Dukat volcanoplutonic system, namely, to the water divide of the rivers flowing to the Arctic Ocean and the Sea of Okhotsk. The level of the present-day erosion in the area of the trough is fairly high varying around 1500 m.

Kazanskii [1979], *Sidorov* [1989], and *Konstantinov* [1995] believe that the trough is localized in the area of the junction of two global structural and metallogenic provinces (Figure 1). One of them is a fragment of the Kolyma–Kamchatka submeridional transform lineament, which crosses the Okhotsk–Chukotka volcanic belt, and the Kamchatka Peninsula which controlled the position of the Au–Ag mineralization. The depths of its faults were estimated from geophysical data [*Shilo et al.,* 1979] to be as great as 100 km. Another structural element is a fragment of the Verkhoyansk–Chukotka silver-bearing belt surrounding the Kolyma–Omolon median massif. This arc-shaped zone surrounding the core of a huge dome, more than 2000 km across, controls the positions of silver–lead–zinc and cassiterite–sulfide ore deposits in the West Verkhoyansk region. In terms of this great domal structure, the Balygychan–Sugoi Trough is interpreted as one of the large radial crustal faults.

As follows from the data available for the geological structure of the Balygychan–Sugoi Trough and the adjacent areas, and also from the results of gravity measurements [*Konstantinov et al.,* 1998; *Shilo et al.,* 1979; *Sidorov,* 1989], the total thickness of the crust in the region is as great as 52 km. The depth to the top of the basalt layer is about 26 km. Its thickness (26 km) is greater significantly than the similar values for the areas of the adjacent anticlinal highs, where this value varies within 10–15 km. As follows from geophysical data, the axial region of the trough is marked by a zone of undulating meridional gravity anomalies, some of them controlling the distribution of ore fields.

Methods of Study

The data available for mineral assemblages in crustal rock inclusions and for post-magmatic (PM) mineral associations were obtained from studying bedrock samples collected from natural outcrops, bulldozer cleanings, and boreholes. We examined and analyzed about 500 lump samples, from which we extracted xenocrysts, inclusions, and PM aggregates, restricted to networks of microcracks. In addition, rock samples weighing 10–15 kg were collected. The bulk of the study xenocrysts and inclusions of basic and ultrabasic rocks were extracted from man-made concentrates, prepared from the crushed rock material. The chemical compositions of individual minerals were studied using an MS-46 Cameca spectral analyzer by analyst I. P. Laputina. Our data on the chemical compositions of some minerals extracted from the concentrated specimens and found in thin sections showed good agreement [*Filimonova,* 2000]. The morphology and relationships between individual crystals in the mineral aggregates were studied visually, in thin sections, and using a scanning electron microscope by N. V. Trubkin. Electron microdiffraction patterns were obtained for microdispersed mineral phases using a JEM-100C scanning electron microscope equipped with an X-Ray energy-dispersion spectrometer capable of recording chemical elements from Na to U. The statistic frequency of various prismatic and pyramidal faces in zircon xenocrysts was estimated by A. D. Chervinskaya; some of the most characteristic grains were measured by N. N. Smolyaninova using a goniometer. The Rb–Sr isotope studies of the specimens were carried out in the Laboratory of Isotope Geochemistry and Geochronology, Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM), Russian Academy of Sciences, using conventional methods and techniques.

Table 1. Whole rock chemistry (%) of xenocrysts and minerals from peridotite inclusions in acid volcanics of the Balygychan–Sugoi Trough

Suite	Ascolda, Early Cretaceous				Nayakhan, Late Cretaceous		
Sample	45/86		21/89		24/86	21/86	
Inclusion	xenocryst		Hornblende peridotite		xenocryst	Harzburgite	
Mineral	Aegirine, centre	Aegirin, margin	Olivine	Hornblende	Hornblende	Cr-spinel	Clinopyroxene
SiO_2	50.85	50.42	36.71	43.14	40.25	0.50	51.60
TiO_2	1.17	0.51	0.03	3.59	2.12	1.00	0.17
Al_2O_3	1.68	0.34		13.55	9.20	8.10	1.15
Fe_2O_3	26.56	35.95				6.29	
FeO			20.05	9.34	25.39	27.00	3.40
$Cr_{2}.O_{3}$			0.10			53.50	1.60
MnO	0.04	0.04	0.35		0.37	0.40	
MgO	9.96		41.55	13.69	7.06	9.00	16.60
CaO		0.11	0.15	11.51	10.85	0.22	24.10
Na_2O	8.48	12.43		2.20	1.71		1.01
K_2O	0.47			0.88	0.99		
Total	99.21	99.80	99.09	97.90	97,67	99.72	99.58
Fe/Fe+Mg	0.57	1.00	0.21	0.27	0.67	0.67	0.10

Cyclic Evolution of Magmatic and Hydrothermal Activities: Evidence of Their Association with Basic Rocks

The evidence available for the geological structure of the study area, and of the Dukat volcanoplutonic system, in particular, as well as the K–Ar and Rb–Sr ages of the volcanic rocks and products of hydrothermal activity [*Konstantinov et al.,* 1998], suggest the cyclic evolution of the postmagmatic and hydrothermal processes in the region.

The products of the early cycle of the magmatic and postmagmatic activity were formed during the Early Cretaceous (during 30–35 million years) in connection with the tectonic and magmatic reactivation of the Kolyma–Kamchatka submeridional lineament in the conditions of subsidence. These rocks occur as a thick sequence of volcanic and sedimentary rocks resting on the Mesozoic Verkhoyansk rocks. This rock sequence is dominated by the K-rhyolites of the Askolda Formation (some members being as thick as 1000 m) and by the volcanic and sedimentary rocks of the Omsukchan Formation (as thick as 2000 m) with minor sheets of amygdaloidal basalt. These volcanic and sedimentary rocks had accumulated in some lagoonal–continental environments. This thick stratified rock sequence is dominated by tuffite of various types, massive basaltic andesite sheets, as thick as 60 m, conglomerates, sandstones, siltstones, carboniferous argillizates, and coals. The K-rhyolites were dated 123.5±3 Ma using a Rb–Sr isochron with a low $^{87}Sr/^{86}Sr$ ratio, close to the mantle initial value of 0.7031±3 (Figure 2).

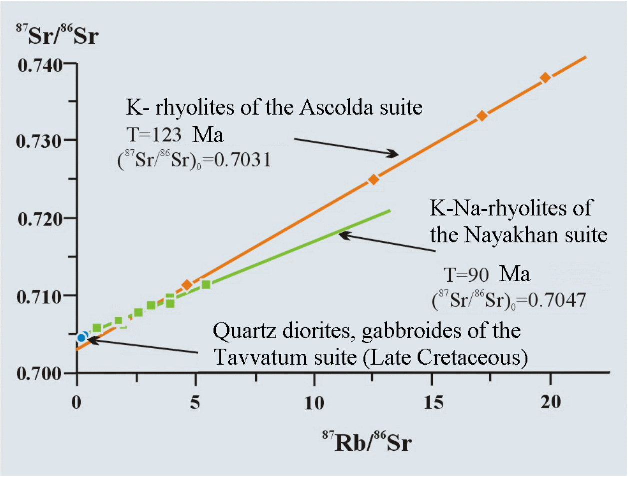

Figure 2. Rb–Sr diagram for the orogenic volcanic rocks of the Balygychan–Sugoi Trough.

The K-rhyolites contain ultramafic inclusions. Some of them are two-mineral aggregates with sizes <0.25 mm. They consist of colorless translucent crystals of olivine and brown Ca-amphibole. The low Fe number of the olivine and the elevated contents of alkalis and Ti in the pargasite hornblende (Table 1) allows one to classify these inclusions as high-pressure hornblendite–cortlandite ultramafics [*Zimin et al.,* 1989]. The other inclusions are represented by the microaggregates of aegirine xenocrysts of two generations. The earliest fine (<100 μm) grains contain Mg (Fe number = 0.57, Table 1). The late grains are almost devoid of this element.

Widespread among the accessory elements are the elongated xenocrysts of translucent, colorless, or pinkish-yellow zircon. The wide development of a prismatic face 100 gives the crystals a "zircon" habit (Figure 3). The tips of the crystals are dominated by the facets of an obtuse dipyramid 111.

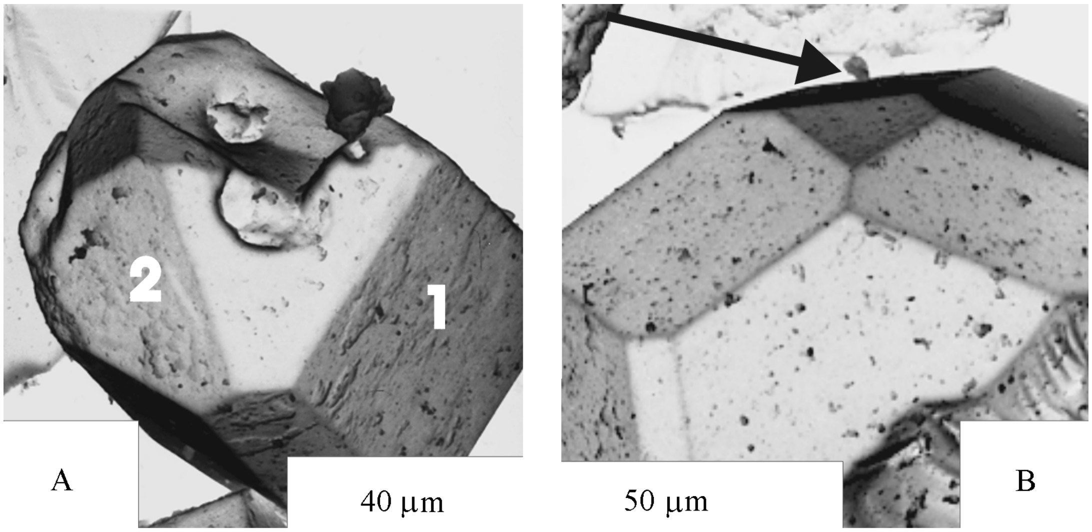

Figure 3. Zircon xenocrysts from Early Cretaceous K-rhyolite. The morphology of an elongated crystal (A) shows the perfect development of the faces of a zircon prism 100 (1) and an obtuse pyramid (2) and the perfect development of a prismatic hyacinth-type face. The surfaces of the pyramid faces show dissolution cavities. The pinnacle of the other crystal (B) is complicated by a basipinacoid (arrow), typical of zircons in ultrabasic gabbro-norite intrusions.

Some scarce crystals show basopinacoid faces typical of zircons from gabbro–norite–ultrabasic intrusions [*Chernyshev and Plaksenko,* 1982]. The surfaces of some crystals show fissures filled with mixed-layer minerals, and also dissolution funnels. The zircons show high Zr and Hf ratios. Taking into account the data published on the morphology and chemical compositions of zircons [*Bagdasarov,* 1989; *Pupin,* 1980], we believe that the K-rhyolite xenocrysts might have crystallized from high-temperature (800–850°C) dry basic melts with highly active alkalis and other mineralizers.

During a pause between the early and late cycles of volcanic activity, multimetal disseminated mineralization (MDM) was formed in the sublatitudinal weak zones of the Buyunda–Gizhiga system of crustal faults. Its products are represented by grains, <0.25 mm in size, located mainly in the leaching cavities of quartzose fluidal K-rhyolite.

In the Dukat volcanoplutonic system, they were found in the middle of the system where they are traced by various geochemical and heavy concentrate anomalies (Figure 4). The most abundant are dark microaggregates produced in a reducing environment. They are represented by Nb-bearing anatase, Th-bearing REE phosphate, Fe-chlorite, Fe-phengite, bitumens, graphite, and native Ag, Sn, Pb, and Bi sulfides (Figure 5a and b). The most characteristic minerals that had formed during high O_2 activity are sericite, hydrophosphates, acanthite, native Ag, and Mn hydroxide. These minerals occur as microaggregates of yellow, brown, and light gray colors. The minute (<0.5 μm) rhombohedral particles of eskolaite are closely associated with the minerals of Mn hydroxides and are the characteristic components of the materials produced under oxidizing conditions. They yielded distinct microdiffraction patterns characteristic of Cr oxide.

The subsequent evolution of volcanic activity in the trough area was associated with the formation of the Okhotsk–Chukotka volcanic belt. A contrasting volcanogenic rock sequence composed of calc-alkalic andesite, basaltic andesite, dacite, and K–Na rhyolite accumulated during 20–25 Ma in the Late Cretaceous. Its diorite and gabbro-diorite are characterized by low $^{87}Sr/^{86}Sr$ ratios varying from 0.7044 to 0.7045 (Figure 2). The K–Na rhyolites of the Nayakhan Formation also showed the low values of this ratio (0.7047±3) with their Rb–Sr age being 90.5±2.5 Ma [*Kolesnikov et al.,* 1998].

Similar to the Early Cretaceous rhyolites, the Late Cretaceous rhyolites contain ultramafic inclusions. Some of them were found in harzburgite fragments as black perfect crystals of Cr-spinel less than 100 μm in size and light green shapeless transparent grains of Cr-bearing clinopyroxene (Figure 6). The cracks adjacent to the contacts between the minerals are filled with a fine-dispersed massif compositionally close to bronzite. Some of its fragments were found to contain mineral phases enriched in K and Mn. The chemical compositions of the two associating minerals (Table 1) differ from the compositions of similar minerals in the ultramafic rocks from the geosynclinal fold areas of the Anadyr–Karyak fold systems [*Pinus et al.,* 1973]. Spinel and clinopyroxene from the inclusions showed higher Cr oxide contents: 53.5 and 1.60 wt.% against 24.55 and 0.75 wt.%, respectively. The distinctive features of the clinopyroxene chemistry are the higher Fe content (0.10 against 0.05) and the presence of acmite (up to 4%) and TiO_2.

The xenocrysts of edenite hornblende from the Late Cretaceous K–Na rhyolites showed a high Fe content with the significant contents of alkalis (Table 1). These properties are very characteristic of amphiboles from anorogenic sub-

Figure 4. Schematic geostructural map of the Dukat volcano-plutonic system. (1–3) Orogenic volcanic rocks (a) and their subvolcanic analogs (b): (1) Early Cretaceous K-rhyolite of the Askolda Suite, (2) Late Cretaceous K-Na rhyolite of the Nayakhan Suite, and (3) andesite of the Tavvatum Suite; (4) sedimentary and metamorphic rocks of the Verkhoyansk Triassic-Jurassic Complex; (5) coal-bearing deposits of the Omsukchan Suite; (6) outline of the Dukat volcano-plutonic rock system; (7) faults; (8) crustal fault systems of the Buyunda–Gizhiga Zone and of the Kolyma–Kamchatka submeridional lineament; (9) areas of multimetal mineralization; (10–11) outer (10) and inner (11) zones of quartz-clinozoisite-chlorite and quartz-chlorite-phengite associations; (12) area of basalt dikes; (13) linear propylite zones including epidote-quartz-chlorite mineral association and Sn–Ag mineralization.

alkalic rocks [*Dobrokhotova,* 1986]. Their $^{87}Sr/^{86}Sr$ ratio is 0.7057 with the Rb and Sr contents being 186 and 1425 ppm, respectively.

The zircon xenocrysts from the K–Na rhyolites resemble those from the Early Cretaceous K-rhyolites in some of their morphologic features (the presence of zircon prism faces and an obtuse pyramid). Characteristic of their habit is the ubiquitous presence of a poorly developed hyacinth-type facet 110 and acute bipyramid facets 331 and 113. This results in the expansion of the population of the morphotypes that formed at lower temperatures (700–750°C) and in the lower activity of alkalies. Characteristic of these zircons are the higher HfO_2 contents compared to the zircons from the K-rhyolites (1.3–1.9 against 1.0–1.1 wt.%) and the lower Zr/Hf ratios (60–90), typical of zircons from gabbro.

After the final formation of the subaerial volcanic rock sequence the region experienced hydrothermal activity. A unique Au–Ag deposit (Dukat), as well as large sulfide–cassiterite (Sn–Ag) and cassiterite–silicate deposits, and also numerous zones of noncommercial mineralization, had been formed in the areas of old extensive geothermal fields.

Our studies of preore minerals from the zones of local alteration in the ore fields, in particular in the Dukat ore field, revealed that the basic rock material had played a significant

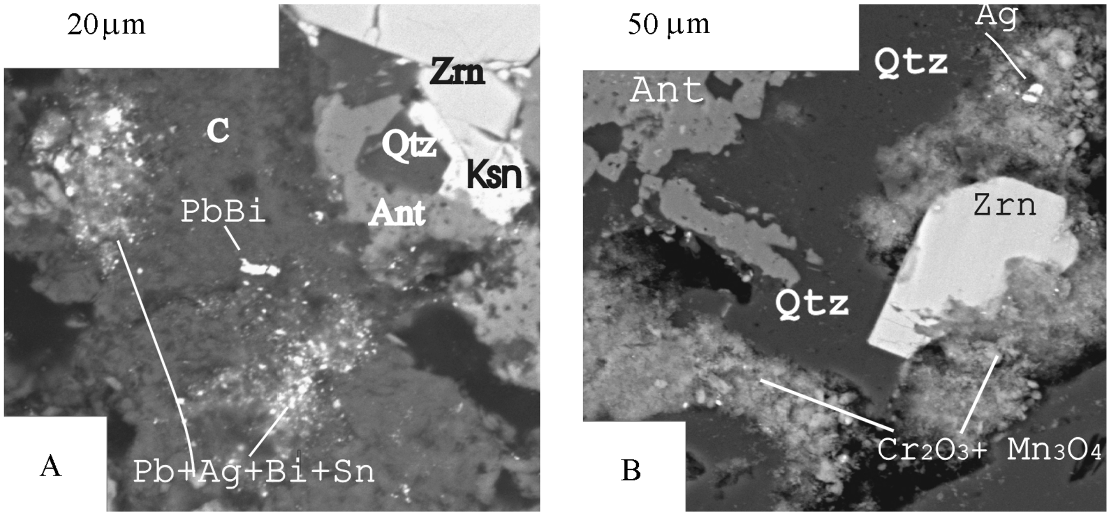

Figure 5. SEM photographs of the surfaces of polished sections showing idiomorphic grains of anatase (Ant), zircon (Zrn), quartz (Qtz), and xenotime (Xen). The microaggregate formed during the early mineralization phase (A) is enriched in carbonaceous matter and graphite (C) and in native Ag, Pb, Sn, and Bi. The microaggregate formed in oxidation environment (B) is enriched in Mn hydroxides, eskolaite Cr_2O_3, and native Ag.

role in the formation of the compositions of the hydrothermal solutions [*Filimonova,* 2002]. This is imprinted in the wide development of femic minerals (clinozoisite, epidote, ilmenite, sphene, Fe-chlorite, Fe-phengite, and calcite), and Cr-bearing minerals (fuchsite, Cr-bearing hematite, and eskolaite) in the zones of the local preore alterations in tin-and silver-bearing ore fields (Figure 7). The preore minerals of these types are known to be developed in the products of postmagmatic activity, localized in substantially basic rocks [*Bird et al.,* 1984]. The products of hydrothermal solutions that had circulated in the rhyolites are dominated by sericite and low-Fe chlorite.

Our data for the Sr isotope composition indicated that a great role in the formation of the early hydrothermal solutions in the ore forming systems had been played by a source with low $^{87}Sr/^{86}Sr$ ratios. All values of these ratios for these minerals are below 0.7060 (Table 2). For this reason the Early Cretaceous acid rocks that had high $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios by the time of preore mineral generation (84 Ma) could not have served as a source of strontium with a low isotope composition or of other femic components for the early portions of hydrothermal solutions. The earliest pre-ore minerals, including those of the epidote group (clinozoisite for the Dukat ore field and epidote for the zones of tin mineralization) showed the lowest contents of the radiogenic component. Their points plotted in the coordinates of 1/Sr and $(^{87}Sr/^{86}Sr)_{84}$ (Figure 8) do not show any notable trends, which indicates that the Sr isotope variations in the early portions of the hydrothermal solutions had been caused by complex mixing at great depths. The data points of calcite and feldspar from the western flank of the Dukat ore field showed a distinct linear relationship (Figure 8). It can be described by a model of Sr isotope mixing from two sources differing in the $^{87}Sr/^{86}Sr$ ratio. This ratio was >0.7060 for one of them, and <0.7046 for the other. The old rocks of the lower crust with low Rb/Sr ratios might have been a source

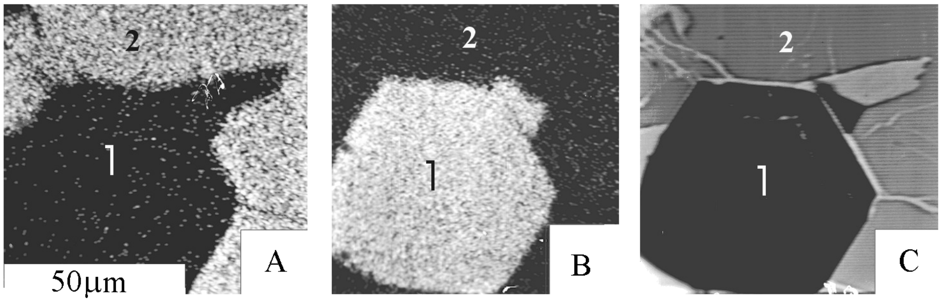

Figure 6. A fragment of harzburgite inclusion in K–Na rhyolite. A perfectly formed grain of Cr-spinel (1) is included in clinopyroxene mass (2). Photographs in characteristic Ca (1) and Cr (2) radiation and in reflected electrons (c).

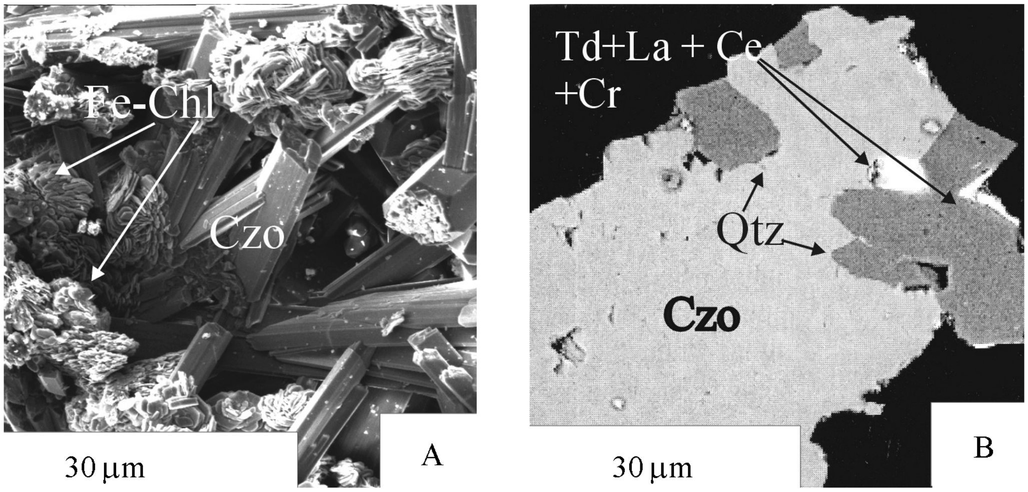

Figure 7. SEM photographs of the natural surfaces (A) and polished sections (B) of the aggregates of preore hydrothermal minerals from the outer zone of the Dukat orefield. One can see the close growths of the large grains of clinozoisite (Czo), quartz (Qtz), and Fe-chlorite (Fe-Chl) with the inclusions of C–Pb–Tl todorokite, rare-earth minerals, and eskolaite (Td + La + Ce + Cr).

with low ^{87}Sr/^{86}Sr values, or some igneous rocks that had separated from the mantle during the Cretaceous. However, the great development of the above-mentioned femic and Cr-bearing minerals in the ore field testifies in favor of the association of the early portions of the hydrothermal solutions with some deep mantle source. The rhyolites of the Askolda Suite and various rocks of the basement might have served as sources with high ^{87}Sr/^{86}Sr ratios.

A great role for the creation of a reducing environment during the early formation history of the Dukat ore-forming system was played by the compounds of carbon in its hydrothermal solutions. Carbon-bearing materials were characteristic of the preore dike-shaped zones of Ca-bearing metasomatites, carbonized rocks of explosive breccias, and some orebodies, especially those that had contacts with the host rhyolites. *Konstantinov et al.* [1998] emphasized the trends toward the growing concentration of carbon dioxide in the mineral-forming solutions enriched in Au and Ag. The simultaneous migration of Ca compounds and ore metals has been proved by our findings of C–Pb–Tl-bearing todorokite [*Filimonova,* 2002].

Our data on the Pb isotope composition of galena from the Dukat ore deposit and from some tin and gold–silver deposits of the region suggest the contribution of some mantle source into the formation of some ore-producing hydrothermal solutions of the region. The ^{206}Pb/^{204}Pb ratios vary within 18.2–18.4 and are close to these ratios for basalts from a number of mantle-plume provinces reported by *Grachev* [2000].

The Late Cretaceous and Paleogene basalt dikes date the last (Late Cretaceous) period of igneous activity in the region. They are characteristic of the Dukat ore field and also of some large tin ore deposits, where they cut across all known igneous and hydrothermal rocks and are believed to

Table 2. Rb-Sr isotopes of the postmagmatic minerals from acid volcanics of the Dukat ore field

Sample	Mineral	Ore	Enclosed rocks	Rb, ppm	Sr, ppm	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
27/86	Epidote	Sn–Ag	K–Na-rhyolite	3.20	255	0.036±2	0.70456±2
58/86				1.40	1440	0.0028±4	0.70467±2
24/86				3.40	693	0.014±5	0.70522±2
59/86				1.00	1809	0.002±1	0.70474±1
9/86	Clinozoisite	Au–Ag		0.07	289	0.001±5	0.70494±4
4/87				1.40	171	0.02±1	0.70491±4
4/87	Adularia			8.70	196	0.128±1	0.70475±2
9/86	Calcite			0.03	161	0.001±3	0.70469±2
4/87				1.00	58	0.046±8	0.70597±3
29/86				0.40	148	0.008±5	0.70474±6
7/87	Clinozoisite		K-rhyolite	7.00	358	0.055±1	0.70521±2
7/86	Calcite			0.13	263	0.0015±6	0.70611±2

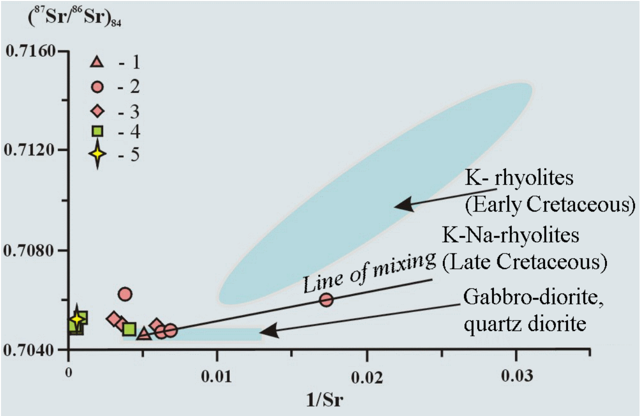

Figure 8. Variation of $^{87}Sr/^{86}Sr$ values in a premineralization Ca-amphibole crystal and in the host rhyolite versus retrograde Sr concentration in them. The Sr isotope composition was calculated for the time of the ore deposit formation (84 Ma). Legend: (1) K feldspar, (2) calcite, (3) clinozoisite, (4) epidote, (5) Ca-amphibole.

be the root systems of the eroded basalts that had flowed over the ground surface. In terms of their chemical composition the dike basalts resemble continental tholeiite basalts, except for their higher contents of Na and K oxides and higher Fe numbers [*Kalinin,* 1985].

Discussion of Results

The data reported here on the geological structure of the Balygychan–Sugoi Trough and on the mineralogy and geochemistry of the products of magmatic, post-magmatic, and hydrothermal activities suggest a great contribution of basic and ultrabasic magmas into the formation of their chemical compositions. The direct products of these magmas are subvolcanic gabbro and quartz diorite bodies with low $^{87}Sr/^{86}Sr$ ratios (0.7044–0.7045), basalt dike swarms, and hornblende peridotite. These rocks are typical representatives of mantle plume materials. No acid volcanics have been found. However, the low values of the initial $^{87}Sr/^{86}Sr$ ratios (0.7031–0.7047) found for the Early and Late Cretaceous rhyolites of the region, as well as the inclusions of mafic and ultramafic rocks in them, allow us to rank them as the products of mantle plumes. We believe that the acid magma generated in a mafic magma source rose rapidly toward the surface, its contamination along this rise being extremely limited. The experimental data available for the conditions of Ca amphibole crystallization and Al, Fe, Mg, and Na redistribution among the coexisting minerals of deep inclusions [*Johnson and Rutherford,* 1989; *Sobolev,* 1974] suggest that edenite hornblende and spinel–clinopyroxene rock associations had been formed at pressures of 5–8 kbar and temperatures of 500–700°C. The values of these parameters do not contradict the data available for the crystallization temperature of zircon xenocrysts which might have been formed at 700–850°C. These values agree with the boundary conditions at the lower and upper boundaries of the crust in the region and suggest that the magma chambers where the acid magma had been generated and from where mafic and ultramafic inclusions had been derived had been a mantle diapir. The region of intersection between the submeridional rift, as deep as 100 km, and the peripheral zone of a very large dome was very favorable for the free rise of mantle diapirs into the lithosphere. The specific features of the outer appearance and chemical compositions of minerals in inclusions (intensive development of zircon prisms in zircon crystals, as well as the presence of pargasite and edenite hornblende, acmite, and acmite-bearing clinopyroxene) suggest that the basic magma had been highly alkalic. The maximum values of alkalinity had been characteristic of Early Cretaceous magma chambers, where acmite had crystallized. The alkalinity decline in the magmas of Early Cretaceous chambers seems to have been associated with crustal assimilation which might have been especially active during the orogenic tectonomagmatic history of the region when the processes concerned operated under compression conditions. This inference is supported by the high values of the initial Sr isotope ratios in the Late Cretaceous K–Na-rhyolites, where these values as high as 0.7047, compared to 0.7031 in the Early Cretaceous K-rhyolites.

The results obtained in this study for some mineralogic and geochemical features of the Late Cretaceous disseminated mineralization and the preore minerals of the Late Cretaceous Sn- and Ag-productive geothermal systems suggest that the products of this hydrothermal fluid activity had been associated with mantle plumes. The main source had been the material of differentiated mantle diapirs and the fluids separating from them. We believe that a great contribution to the formation of the Early Cretaceous metallic mineralization was made by the reduced fluids associated with the emplacement of basic and ultrabasic magmatic bodies into the lithosphere, typical of rift zones [*Pierce et al.,* 1987]. The products of the post-magmatic activity were enriched in carbonaceous matter, graphite, HFSE ions (Ti, Nb, Zr, P, REE, Cr), and native elements.

The basic rocks of mantle origin also contributed to the formation of the chemical compositions of the preore minerals of some Late Cretaceous productive geothermal systems, including the Dukat ore field. This is indicated by the abundance of femic and Cr-bearing minerals and by the low Sr isotope ratios in them. However, some contribution was also made by mixing processes. Some portions of hydrothermal solutions, from which epidote-group minerals with the $^{87}Sr/^{86}Sr$ ratios of 0.7047–0.7053 crystallized might have been produced as a result of the mixing of components from the basic rocks and the deep lithosphere, having low Rb/Sr ratios. The later preore minerals of the western Dukat ore field originated from the mixing of two sources. One of them had low $^{87}Sr/^{86}Sr$ values (<0.7046), typical of mantle-plume formations, the other had higher values of this ratio (>0.7060) typical of the enclosing rhyolite.

The formation of a thick crust with a thick basalt layer in the area of the Balygychan–Sugoi Trough might have been associated also with the processes operating in a mantle plume region. The growth of the crust from below took place at the expense of the emplacement of basic and ultrabasic intrusions. The latter can be interpreted as the products of the rest magma that remained after the melting of acid magma from the ultrabasic melt, or, as suggested by *Grachev* [2000], as the intrusive analogs of plateau basalts, which usually represent magmatic activity associated with mantle plumes.

To conclude, the data available at the present time for the periodicity of volcanic and postvolcanic activities in the area of the Balygychan–Sugoi Trough and for the unique Dukat Au–Ag ore field located in its limits, as well as new data on the mineralogy and geochemistry of the resulting products, suggest that the impulses of endogenic activity might have been associated with the intrusion of mantle diapirs into the lithosphere. These high-temperature magma chambers and the fluids rising from them stimulated the development of volcanic, postvolcanic, and hydrothermal processes. These impulses of endogenic activity corresponded in their duration to two periods of the Meso–Cenozoic reactivation of mantle convection, first mentioned by *Vogt* [1972], which operated roughly 70–80 and 110–120 million years ago.

Conclusion

The previously known peculiarities of the crustal structure of the rifting-related Balygychan–Sugoi Trough and our new data on the mineralogy and geochemistry of the products of the Meso-Cenozoic volcanic, postmagmatic, and hydrothermal activities suggest that this region can be classified as a mantle-plume province. The emplacement of thick Early and Late Cretaceous volcanic rocks and the associated products of dispersed and productive hydrothermal fluid activities were controlled significantly by deep basic magmas.

The periodic emplacement of the products of volcanic, post-volcanic, and hydrothermal activities is believed to have been associated with the reactivation of convection in the lower mantle and with the subsequent intrusion of mantle diapirs into the lithosphere, which controlled endogenic activity in various volcano-plutonic structures.

A thick volcanogenic and sedimentary rock sequence with its dispersed multimetal mineralization accumulated during a period of 30–35 million years in the Early Cretaceous time with the participation of subalkalic basalts and hydrocarbon fluids. The disseminated minerals are enriched in carbonaceous material, titanium, multivalent cation phosphate, and native metals, the main ore components of the region.

During the late Cretaceous a contrasting sequence of volcanic rocks and Au–Ag and Sn–Ag ores, including the unique Dukat Au–Ag ore deposit, accumulated during 10–15 million years under orogenic conditions. The compositional evolution of acid magmas and hydrothermal solutions involved the mixing of sources characterized by different ^{87}Rb/^{86}Sr ratios. Hydrocarbon fluids played a significant role in the formation of the Dukat ore deposit.

The latest period of endogenic activity in the Balygychan–Sugoi Trough (65–70 million years ago) was marked by the emplacement of basalt dikes which are interpreted as feeding channels for the now eroded lava plateaus.

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