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GEOLOGY

Geology and Formation Conditions of the Unique Gold–Silver Deposit in Chukotka

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The position of the Kupol gold–silver deposit in the general structure of the outer zone and base of the Okhotsk–Chukotka Volcanic Belt (OCVB) is discussed in [1]. Vartanyan et al. [2] highlighted the following issues: (1) the geological setting of the Kaiemraveem ore node, which includes the large Kupol deposit and six coeval gold–silver occurrences; (2) the paleovolcanic interpretation of its structure as a large Late Cretaceous stratovolcano complicated by caldera; and (3) detailed characteristics of the mineral composition of ores. In addition, we obtained the first thermobarogeochemical data on conditions of ore formation. The new interesting data make it possible to refine the general geostructural position of the Kaiemraveem ore node, to propose an alternative interpretation of the paleovolcanic setting of its evolution, and to discuss some lithostructural and genetic aspects of ore mineralization.

In terms of the geological section, composition, succession, and taxonomy of stratons, the Kaiemraveem volcanic field (KVF) is assigned to the Anadyr sector of the outer OCVB zone. In [2], the volcanic field is shown as a nearly isometric structure (25–27 km across) with an area of 680 km^2 (Fig. 1). The section of the KVF is divided into five lithostratigraphic complexes (volcanoplutonic associations). The lower complex (andesites, basaltic andesites, and basalts) is exposed in the southern part of the volcanic field. The exposed area is ~35 km^2 (5.1% of the total KVF area). We believe that rocks of this complex match the late Albian Vilkov Formation recognized in southern areas of the outer zone of the Anadyr sector. The second (K_2^1) and third (K_2^2) complexes match the lower and upper sequences, respectively, of the Eropol Formation, which contains the Cenomanian Amka flora in the southwestern area. The second (dacite–trachyrhyolite–ignimbrite) complex is primarily exposed in the eastern and southwestern sectors of the outer zone of the KVF. The exposed area is 325 km^2 (47.8% of the total area).

The third (andesite–basalt–dacite) complex occupies the central area and extends to the northern and northwestern sectors of the outer zone of the KVF, and partly to the southern sector. The exposed area is 265 km^2 (39% of the total area).

The fourth (K_2^3) and fifth (₽) complexes occupy 15 km^2 (2.2%) and 40 km^2 (5.9%), respectively. They can represent formations of the late stage of OCVB evolution. However, they are most probably products of the terminal phase of the Eropol volcanism.

The late Albian (Vilkov) andesitic volcanism was nearly ubiquitous in the outer zone of the Anadyr sector. Outcrops of the Vilkov Formation are insignificant in the study region, and its distribution pattern is unknown. Nevertheless, we believe that late Albian eruptions of andesites, basaltic andesites, and peraluminous basalts played a crucial role in sequential volcanism and structure evolution. The results of the study of Cenozoic and recent volcanism in various geodynamic settings show that extensive manifestations of intermediate and basic volcanism of the calc-alkaline type are accompanied by the formation of intricate caldera complexes related to crustal sources of acid magma. They commonly do not inherit any specific volcanic structures of the preceding andesitic volcanism. The scenario of structure evolution was presumably similar in the KVF. The proposed paleovolcanic reconstruction of the KVF evolution is based on empirical generalizations of the issue of caldera formation.

Termination of Albian andesitic volcanism (Vilkov Formation) at the junction of the Imravaem– Kaiemraveem, Krestovyi–Salamikha, and Anyui deep faults, which are recorded by geophysical methods at the base of the outer zone of the OCVB, gave rise to the crustal

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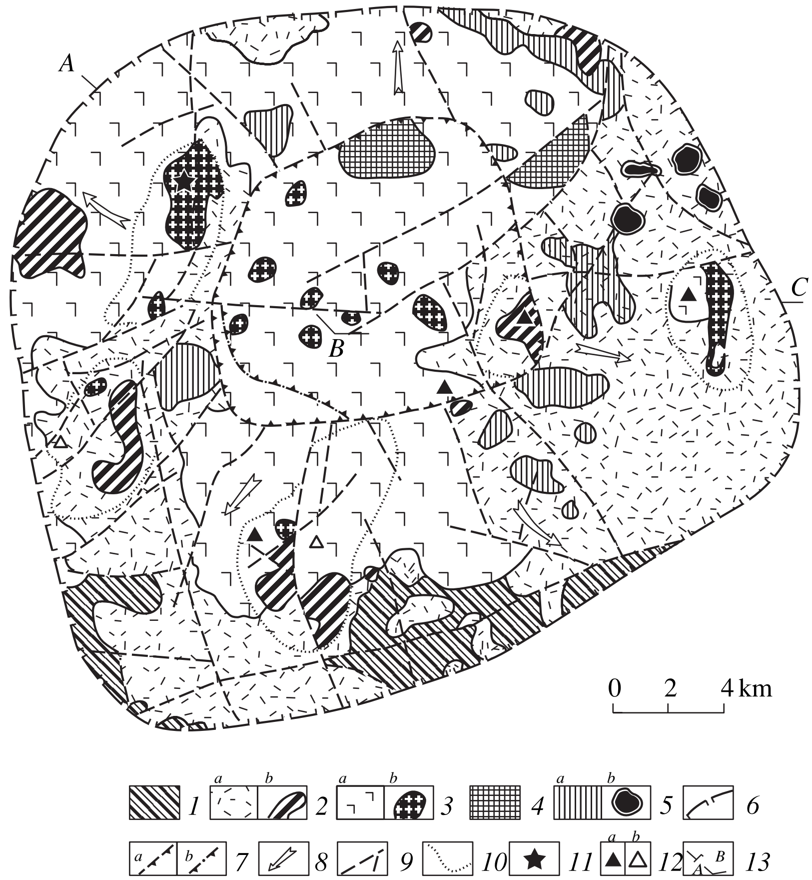

Fig. 1. Schematic geostructural map of the Kaiemraveem volcanic field (modified after [2]). (*1–5*) Lithostructural complexes of the volcanic field: (*1*) Vilkov Formation, upper Albian (andesites, basaltic andesites, and andesites), (*2, 3*) Eropol Formation, Cenomanian: (*2a*) lower sequence (ignimbrites, tuffs, and lavas of rhyolites, dacites, and trachyrhyolites), (*2b*) subvolcanic intrusives (dacites, rhyolites, and granite porphyries), (*3a*) upper sequence (two-pyroxene basaltic andesites, andesites, basalts, and dacites), (*3b*) subvolcanic intrusives (andesites, basalts, and diorite porphyries), (*4*) ignimbrites and rhyolite tuffs and lavas, (*5a*) basalt lavas, (*5b*) subvolcanic intrusives of dolerites; (*6–9*) structural designations: (*6*) boundary of the Kaiemraveem volcanic field, (*7*) Varmekai Caldera: (*a*) boundary of caldera, (*b*) level of the caldera wall; (*8*) direction of the predominant inclination of volcanic sequences of the Eropol Formation, (*9*) faults; (*10–12*) ore mineralization zones: (*10*) boundary of the ore field (demonstrated and inferred), (*11*) Kupol deposit, (*12*) ore occurrences: (*a*) gold–sulfosalt, (*b*) gold–galena–sphalerite; (*13*) line of section (*A–B–C*) and paleovolcanic reconstructions.

(peripheral) source of acid magma (Fig. 2, *I*). Study of Cenozoic caldera complexes [3, 4] revealed that expansion of the magma chamber was accompanied by the formation of domes (swelling). The culmination stage of the magma chamber formation (and dome formation) was marked by large-scale eruptions of pyroclastic material and the formation of the Varmekai (our anagram version of the name "Kaiemraveem") Caldera with an area of 110–115 km^2 (Fig. 2, *II*). The caldera resembles an irregular trapezium (11.5 × 9.5 km) with rounded corners. The erupted material (ignimbrites, tuffs and lavas of the rhyolitic, trachyrhyolitic, and dacitic compositions) in the lower sequence of the Eropol Formation was primarily deposited beyond the caldera, i.e., in near-caldera depressions (konca depressions [5]) partly covered with younger sediments. The terminal stage of caldera eruptions in konca depressions (mainly in the southwestern sector) and inside the caldera in some places was marked by the formation of subvolcanic bodies represented by extrusive structures (probably, domes) of dacites, rhyolites, and granite porphyries (up to 3–4 km across) confined to arcuate and radial faults.

Detailed investigation of recent volcanism in Kamchatka revealed that the Quaternary caldera formation was stimulated by reactivation of the larger sources of basaltic magma. The geology of the KVF suggests that caldera formation in this region is related to the ascent of basaltic andesites from a deeper source. Effusives of this magma make up the upper sequence of the Eropol Formation. The apical zone of the expanding basaltic andesite source was presumably located beneath the Varmekai Caldera (Fig. 2, *III*). The evolution of the new magma source was accompanied by resurgent dome formation and the consequent uplift of the caldera and its adjacent area. The major centers of lava effusion

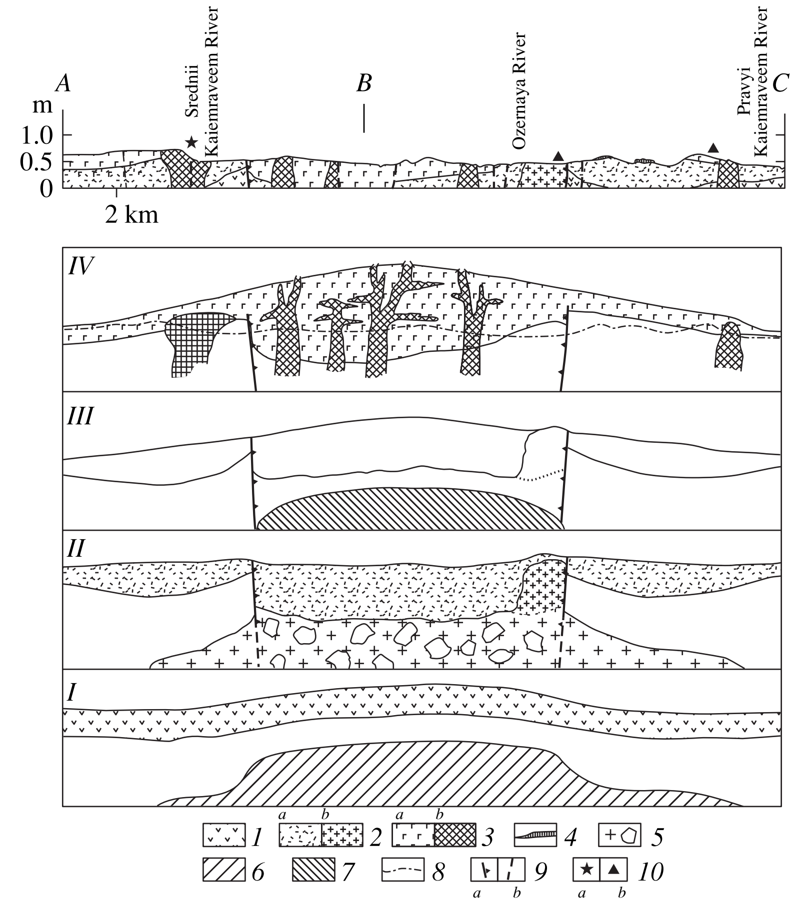

Fig. 2. Geological section of the Kaiemraveem volcanic field (KVF) along profile *A–B–C* and paleovolcanic reconstruction of the KVF evolution. (*1–4*) Lithostructural complexes of the volcanic field: (*1*) Vilkov Formation, (*2, 3*) Eropol Formation: (*2a*) lower sequence, (*2b*) acid subvolcanic intrusives, (*3a*) upper sequence, (*3b*) subvolcanic intrusives and inferred volcanic necks, (*4*) basalt lavas; (*5*) granitoids and rock blocks of the roof; (*6, 7*) sources of acid and basaltic andesite magmas, respectively; (*8*) smoothed line of the present-day relief (in *IV*); (*9a, 9b*) caldera walls and faults, respectively; (*10a, 10b*) Kupol deposit and ore occurrences, respectively. Paleovolcanic reconstruction of evolution stages (vertical scale is arbitrary): (*I*) precaldera dome formation, (*II*) termination of caldera formation, (*III*) resurgent dome formation, (*IV*) formation of stock-shaped volcano and compensation subsidence of its base.

were probably located in the Varmekai Caldera. For example, among eleven small (1 km^2 or less in area) andesite and diorite porphyry bodies (necks and cryptovolcanic edifices), eight bodies are located inside the calderas (Figs. 1, 2, *IV*). However, two large diorite porphyry bodies (6 and 4 km^2), which accommodate the Kupol deposit and Tokai ore occurrence, are located beyond the caldera.

Lavas of two-pyroxene andesites, basaltic andesites, and basalts flowed along slopes of the dome and produced structures resembling the shield volcano. According to [2], the ancient volcano had the following parameters: steepness of slopes 5°–7°, transverse dimension 30 km (with allowance made for erosion), and relative height 1.5 km. These parameters match those of large Quaternary shield volcanoes in Kamchatka (e.g., the Nikolka Volcano [6]).

The above statement apparently contradicts the fact that the well-known shield volcanoes are composed of basalts rather than andesites. However, the validity of our interpretation of morphostructures in the KVF is indirectly supported by the following observations. Cretaceous volcanic deposits of the OCVB incorporate the two-pyroxene andesite formation. This formation is represented by the Ulyn Formation (outer zone of the Okhotsk sector), the upper sequence of the Eropol Formation (Anadyr sector), and the Koekvun Formation (Central Chukotka sector). Hence, andesite melts can produce morphologies typical of basaltic effusion under certain physicochemical circumstances.

The fourth (ignimbrites and rhyolite tuffs and lavas) and fifth (basalts and dolerites) complexes make up a minor portion of the KVF. Their development is extremely irregular (mainly, in the northeastern and eastern sectors). One relatively large exposure of acid volcanics of the fourth complex is located in the northern part of the Varmekai Caldera. Another exposure is located beyond the caldera in the buried Krestovyi–Salamikha fault zone. A major part of small lava fields (inliers of basalts of the fifth complex) is scattered

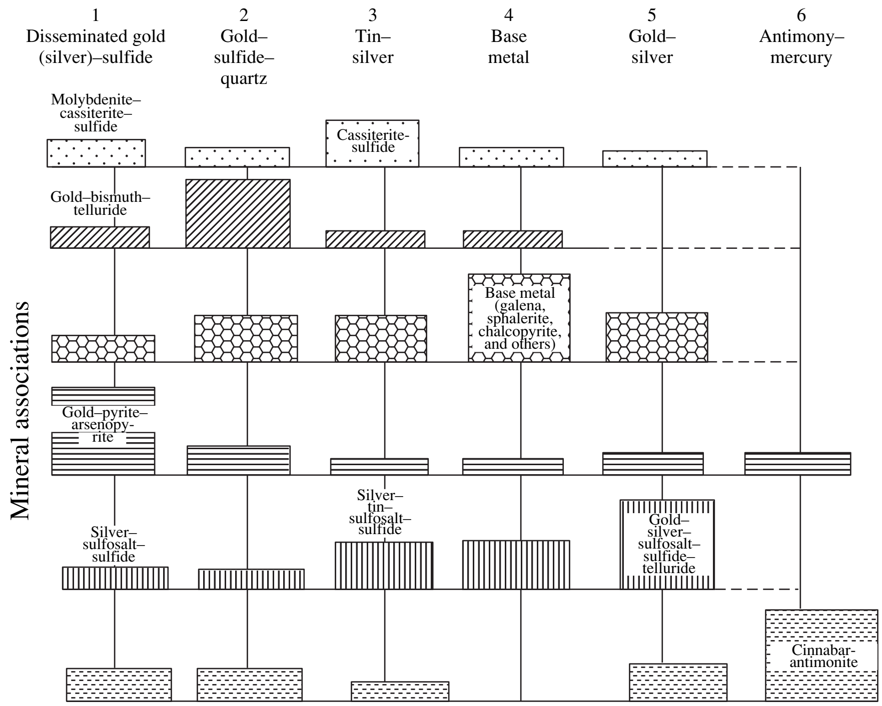

Fig. 3. (1–6) Ore types in central Chukotka (ore-formation series).

around the Varmekai Caldera. They overlie both andesites of the upper sequence of the Eropol Formation and ignimbrites and tuffs of the lower sequence. Hence, the basaltic eruption postdated a short-term hiatus and partial erosion of the shield-shaped volcano in the upper sequence of the Eropol Formation. Based on the distribution of volcanics of the fourth and fifth complexes, they are presumably derived from local residual sources of the Eropol stage of volcanism. However, geochemical data are needed for elucidation of this issue.

The Kupol deposit is characterized by confinement of the ore zone to the thick and extended (>4 km) rhyolite dike. This structural feature fostered the bonanza-type epithermal mineralization and its significant scale in both the vertical and lateral directions. The medium-scale Dvoinoe gold–silver deposit (Au reserve up to 29 g/t) is located in an analogous setting in the adjacent Ilernei ore district (western Chukotka).

Based on study of productive complexes, ore deposits of the KVF are referred to the sulfosalt mineral type [2]. We investigated multistage ore associations of gold–silver deposits and occurrences in the adjacent regions. The deposits are located at various erosion levels [7, 8] ranging from the root zone (Maisk, Sil'noe, and Promezhutochnoe deposits) to the argillization level with relicts of the supraore zone (Sopka Rudnaya deposit). Therefore, we can reconstruct the most complete characteristics of mineral complexes. Figure 3 shows ore-formation relationships between gold and gold–silver mineralizations in the region [9]. The lower stages of epithermal mineralization are represented by fine-disseminated gold–pyrite–arsenopyrite ores (Maisk type) and porphyry gold–silver ores (within porphyry copper–molybdenum or porphyry tin–silver series).

Thermobarogeochemical investigations of epithermal gold–silver ores from the Kupol deposit were carried out using devices and methods described in [10]. Only aggregates of amethyst and quartz crystals developed in some crustification cavities of epithermal veins were sufficiently transparent for the study of fluid inclusions. For the sake of comparison, we also investigated the barren amethyst veins in the Arykvaam ore field located 100 km south of the Kupol deposit (the samples were taken by V. Belyi).

Amethyst from ore veins of the Kupol deposit contains primary two-phase fluid inclusions (1–70 μm) of negative crystalline or irregular shape. Zones of crystal growth contain numerous fluid inclusions, suggesting the rapid crystallization of quartz. The results of the thermo- and cryometric investigations of the primary, pseudosecondary, and secondary inclusions in quartz are presented in the table and Fig. 4. The two-phase fluid inclusions in quartz and amethyst from the Kupol deposit homogenize into the liquid phase at 267–222°C. They contain a water solution with a salt concentration of 3.2–1.2 wt % NaCl equiv (table). The solution is mainly composed of sodium and magnesium chlorides (eutectics temperature varies from –34 to –21°C). The fluid density is 0.78–0.86 g/cm^3. The samples also contain gas-rich inclusions that are coeval with late fluid inclusions with the homogenization temperature

Results of thermo- and cryometric investigations of individual fluid inclusions in quartz from ore veins of the Arykvaam (AM) and Kupol (Kr) deposits

Sample no.	Mineral	n	Temperature, °C			C_{salts}, wt % NaCl equiv	d, g/cm^3	Pressure, bar	$\frac{P_{tot}}{P_{H_2O}}$
			homogenization	eutectics	ice melting				
AM-1	Amethyst	2	267G	–28	–0.3	0.5	n.d.	50	1.0
	The same	14	248	–30	–0.2	0.4	0.80		
	"	17	245–234	–33	–0.4	0.7	0.82	–	–
	"	7	243	–36	–0.5	0.9	0.81		
	"	3	242	–31	–0.5	0.9	0.81		
	"	23	237	–33	–0.5	0.9	0.82	–	–
AM-2	Amethyst	4	257	–29	–0.5	0.9	0.79		
	The same	3	254	–30	–0.6	1.1	0.80		
	"	5	244	–28	–0.7	1.2	0.81		
Kr04-295a-328.8	Amethyst P	11	267	–21	–1.2	2.1	0.78	–	–
	Amethyst P-V	8	222	–21	–1.2	2.1	0.86	–	–
Kupol 2	Quartz	3	229	–34	–1.9	3.2	0.86	25	1.0
	The same	6	225	–33	–1.1	1.9	0.85	–	–
	"	5	224	–28	–0.7	1.2	0.84	–	–

Note: (n) Number of inclusions studied; (d) density of solution.

equal to 229°C. The water vapor pressure is 25 bar, which is typical of the healing of cracks and formation of late inclusions in the near-surface environment. Amethyst from veins in the Arykvaam deposit contains gas and gas–liquid inclusions. The gas inclusions contain water vapor with a salt concentration of 0.5 wt % NaCl equiv. They homogenize into gas at 267°C. The water vapor pressure is 50 bar. Fluid inclusions contain a chloride water solution with a salt concentration of 1.2–0.4 wt % NaCl equiv. The homogenization temperature varies from 257 to 234°C.

The results of the study demonstrated that, in contrast to barren veins from the Arykvaam deposit, fluid inclusions in quartz and amethyst from ore veins of the Kupol deposit contain solutions with two to three times higher concentrations of salts (table, Fig. 4).

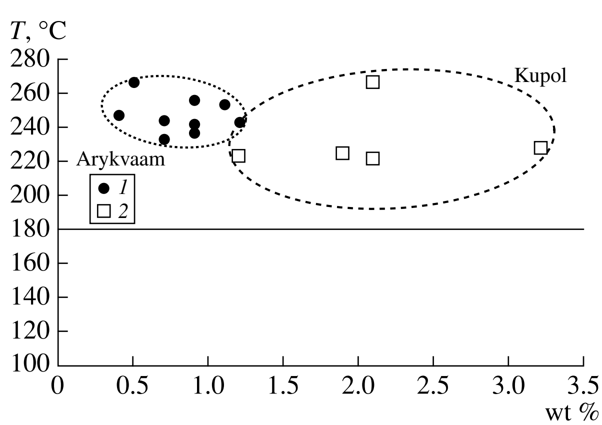

Fig. 4. Temperature vs. salt concentration diagram for ore-forming fluids. Deposits: (*1*) Arykvaam, (*2*) Kupol.

Thus, the results of the paleovolcanic reconstruction show that the Kaiemraveem Volcano differs fundamentally from other well-known ore-bearing caldera complexes with a resurgent dome formation, such as San Juan (Colorado, United States). Hence, the concept of the KVF as a stratovolcano [2] is invalid.

Our interpretation of the morphostructure related to eruptions of andesites from the upper sequence of the Eropol Formation suggests the presence of a shield volcano (Fig. 2). New data on the epigenetic mineralization support our reconstructions of the geological setting, structure of ore fields, and mineral composition of ores based on the study of adjacent regions [7, 8]. Thermobarogeochemical data testify to the healing of cracks in an epithermal near-surface environment and the high rate of quartz crystallization in ore veins.

The results reported in this paper can be used in prospecting for large epithermal gold–silver deposits in the Chukotka segment of the OCVB.

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