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The Conditions of Generation for the Au–Ag Epithermal Mineralization in the Amguema–Kanchalan Volcanic Field, Eastern Chukotka

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Abstract—This paper discusses the conditions of generation for the Au–Ag epithermal mineralization in the Amguema–Kanchalan Volcanic Field (AKVF), which is situated at the western termination of the East Chukchi flank zone of the Okhotsk–Chukchi Volcanogenic Belt (OChVB). The AKVF contains the potentially large Valunistoe Au–Ag deposit and several promising deposits and ore occurrences (Zhilnoe, Shakh, Gornoe, Ognennoe, and Osennee). Thermal and cryometric studies of fluid inclusions in quartz and calcite in epithermal veins showed that the solutions were dominated by Na and K chlorides. The epithermal mineralization was deposited by heterogeneous hydrothermal fluids with low salt concentrations (0.2–3.6 wt % equ. NaCl, under moderate temperatures 174–354°C). The fluid pressure reached values of 30–160 bars, which is proper to depths of generation of 0.1–0.6 km under hydrostatic conditions. These results classify the epithermal mineralization studied here as a low sulfide one. Meteoric waters and magma chambers of andesitic magmas are the most likely sources of ore-forming fluids. The information furnished in this paper is of practical value for regional metallogenic predictions, as well as the search for and assessment of epithermal Au–Ag deposits.

Keywords: Eastern Chukotka, Amguema–Kanchalan volcanic field, thermal, pressure, and geochemical features, epithermal mineralization, gold, silver

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INTRODUCTION

The Amguema–Kanchalan Volcanic Field (AKVF) lies in the Anadyr Area of the Chukchi Autonomous District (CAD) in the Arctic zone of Russia, 237 km northeast of the District center, the town of Anadyr, and 218 km along the automobile road from the nearest seaport, Egvekinot (Fig. 1). Geologists of the Anadyr geological expedition prospecting in the AKVF discovered the Valunistoe promising Au–Ag epithermal deposit and several ore occurrences of similar composition in 1960. Their totality makes the Amguema–Kanchalan metallogenic zone (Volkov et al., 2006; Struzhkov, 2010). Materials relating to the AKVF can be found in many publications (Belyi, 1981, 1994; Polin, 1990; Volkov et al., 2006; Struzhkov, 2010, among others) and unpublished reports (V.P. Shabalin, 2005; E.S. Andreeva, 2009; P.P. Polkvoi, 2011, among others).

The main goal of our study was to analyze and generalize the available and our own data in order to reveal thermal, pressure, and geochemical features in the Mesozoic Au–Ag epithermal mineralization of the AKVF, and to make use of the above as a basis for identifying new criteria and improving known criteria for assessment of industrial significance and prediction of epithermal deposits. We also wish to note that the study of the composition and parameters of ore-forming fluids in order to identify their nature has been for many decades one of the central problems in the theory of endogenous mineralization (Bortnikov et al., 2006, among others).

MESOZOIC VOLCANISM AND EPITHERMAL MINERALIZATION IN THE AKVF

The Amguema–Kanchalan volcanogenic field lies at the western termination of the East Chukchi flank zone of the OChVF (see Fig. 1) which overlies the Koni–Tanyurer fold system of the Koryak–Kamchatka fold area in the region. The belt volcanic rocks

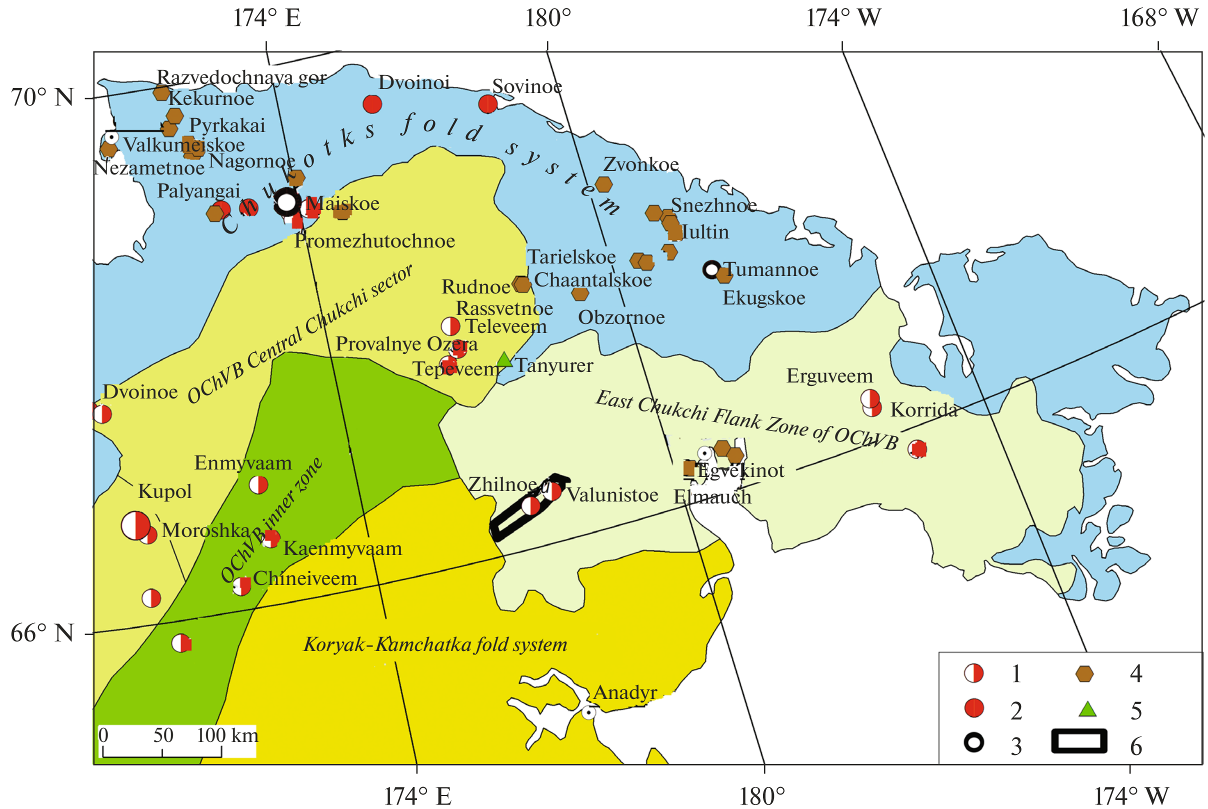

Fig. 1. The location of the Valunistoe deposit among the regional structures, after Belyi (1994). (1–5) deposits: (1) Au–Ag epithermal deposit, (2) Au-quartz deposits, (3) Au-sulfide impregnated deposits, (4) tin deposits; (5) Cu-Mo-porphyritic deposits; (6) Amguema–Kanchalan metallogenic zone.

make a depression striking northeast there that can be traced from the Tanyurer River in the west as far as the Amguema River in the east. The depression is 30–100 km wide. The folded base of the depression is composed of ruptured Paleozoic to Early Cretaceous deposits. Some local patches in the Gachgagyrgyvaam River valley are exposures of Early Carboniferous sandstones, aleurolites with limestone interbeds and lenses, and basic and intermediate effusive rocks, which were treated by V.F. Belyi (1981) as the cover of the Eskimo Massif, as well as penetrating intrusions of gabbro, granodiorites, and granites in the Tanyurer unit (Fig. 2).

The intrusive rocks make three plutonic units in the AKVF, namely, the Murgali, Ekitykii, and Leurvaam, and subvolcanic and extrusive features together with stratified volcanic rocks form six volcanic units (the Amgen, Ekitykii, Leurvaam, Nunligran, Tanyurer, and Ilmyneiveem units) (Sakhno et al., 2010). The comagmatic volcanic and plutonic units of the OChVB are combined into two volcano-plutonic associations, the Ekitykii and the Leurvaam.

The AKVF volcanogenic section is underlain by sheet ignimbrites and by tuffs of rhyolites, rhyodacites, dacites, trachyrhyolites, trachydacites, and by subvolcanic dacites of the Amgen series. The more abundant rocks include mottle volcanic rocks of the Ekitykii series: ignimbrites, lavas, and tuffs ranging from rhyolites to basalts in composition, containing lenses and interbeds of sedimentary rocks, subvolcanic bodies and dikes of andesites, basalts, and dacites. Belyi (1981) considered the Amgen and Ekitykii series to belong to the same rhyolite–andesite–basalt formation. The section of volcanic rocks terminates in basalts, subalkaline basalts, basaltic andesites with occasional tuff interbeds. The isotope U-Pb ages obtained for the AKVF volcanic and subvolcanic rocks range between 67.0 and 88.2 Ma, and were formed during 20 million years (Sakhno et al., 2010).

The volcanogenic rock sequences (of intermediate composition) within the AKVF compose gently dipping volcanic structures, sags, and ridge-shaped dome uplifts striking northeast. The angles of dip do not exceed 30°, with the figure for the Paleogene effusive rocks being 20°. The volcanic dome structures (VDS) are composed of volcanic rocks of the Amgen rock sequence, and of the Ekitykii and Leurvaam suites, and to a lesser degree, of the Nunligran suite. The Mokhovaya, Pravogornenskaya, Zhilninskaya, Shakhskaya, Valunistaya, Shalaya, and Oranzhevaya VDSs, which are 3 to 6 km across, can be traced as a chain striking northeast, along the Kanchalan fault

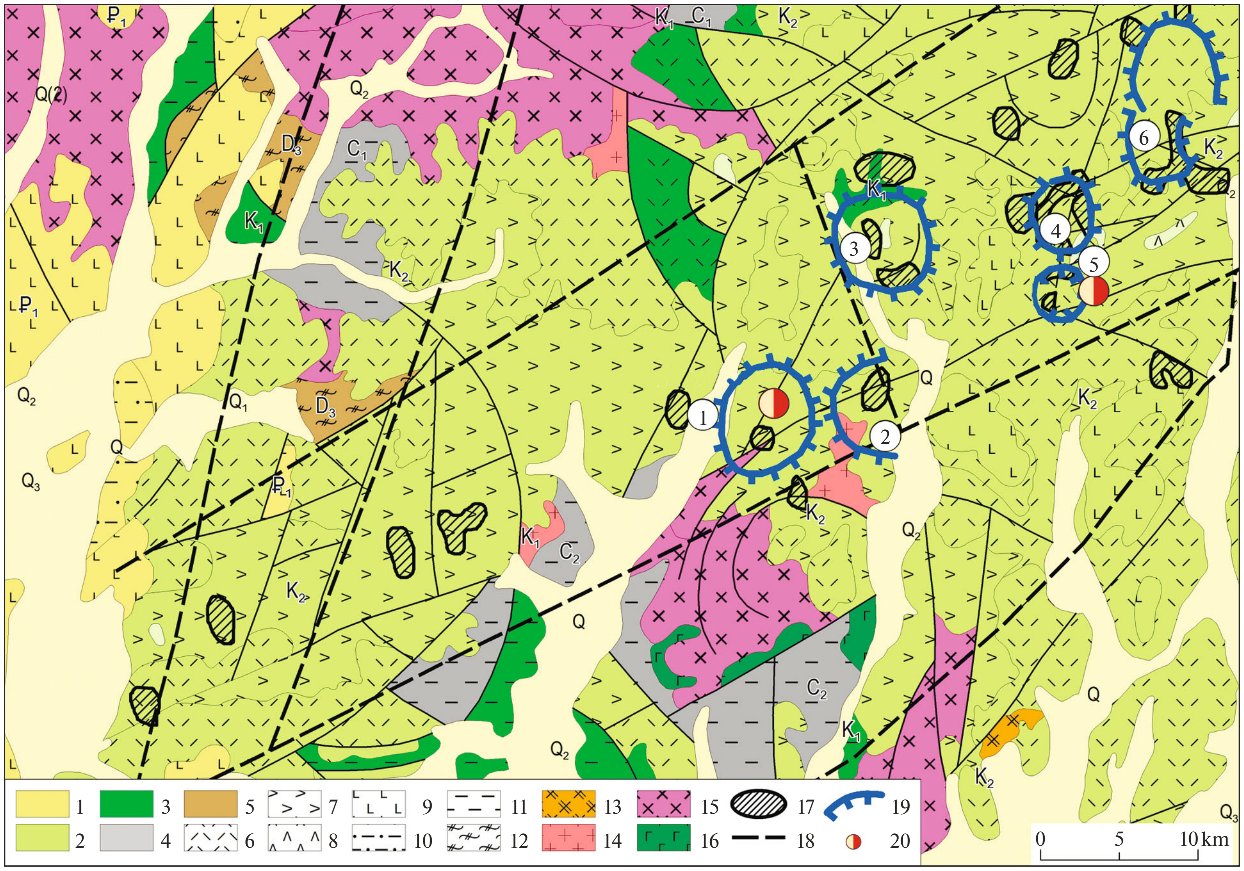

Fig. 2. A geological map of the Amguema–Kanchalan volcanic field based on a geological map to scale 1 : 200 000 Q-60, XV, XVI). (1–5) rock ages: (1) Early Paleogene, (2) Early Cretaceous, (3) Late Cretaceous, (4) Carboniferous, (5) Devonian; (6–9) volcanic rocks: (6) rhyolite, (7) dacite, (8) andesite, (9) basalt; (10) sandstone; (11) clayey schist; (12) metamorphic rocks; (13–16) intrusive rocks: (13) syenite and granosyenite, (14) granite and granodiorite, (15) diorite and monzonite, (16) gabbro; (17) subvolcanic bodies of rhyolite–dacite compositions; (18) major faults; (19) volcanic dome structures ((1) Zhilnaya, (2) Shakhskaya, (3) Oranzhevaya, (4) Valunistaya, (5) Shalaya, (6) Pravogornenskaya); (20) Au–Ag epithermal deposits.

zone (see Fig. 2). These structures harbor several Au–Ag epithermal deposits (Valunistoe, Gornoe, and Zhilnoe) and some promising ore occurrences (Ognennoe, Shakh, Osennee, etc.).

The Kanchalan fault zone, which strikes northeast (65°), can be traced in the folded base of the AKVF volcanic rocks for 300–320 km (see Fig. 2). It is overlain by Paleogene basalts in the southwest and can be traced as far as the Amguema River in the northeast. The zone is 12–30 km wide in the middle. This is the main ore-controlling structure of the AKVF; it contains all deposits identified so far and promising ore occurrences of the Au–Ag formation.

The longest and most persistent faults in this zone strike northeast; this is also the overall direction of the volcanic structures. The faults can reach lengths of 14 km. The vertical displacements on these faults are greater than 400 m. They are frequently accompanied by thick linear brecciated zones where fragments of host rocks are cemented by red to brown pre-ore quartz. Breccia can be as thick as 100 m in some individual exposures. They generally show clear-cut contacts with the host rocks. Metasomatite zones and suites of Au–Ag epithermal veins tend to occur on the northeast striking faults.

The later nearly north–south faults divide the central part of the AKVF into several blocks that are characterized by different degrees of displacement relative to one another, resulting in different degrees of erosion in the blocks. They are accompanied by basaltic dikes and quartz veins that extend for as long as 300 m. These show displacements with amplitudes reaching 10 m on the northeast faults.

The Valunistoe deposit is found within the eponymous VDS, in the middle of the Kanchalan fault zone (see Fig. 2). Here, one finds Upper Cretaceous volcanic rocks like ignimbrites, lavas and tuffs of the Ekityki suite ranging in composition between rhyolite and basalt, lenses and interbeds of sedimentary rocks, subvolcanic bodies and dikes of andesites, basalts, and dacites of the Leurvaam unit. The deposit was found to contain 12 ore-bearing vein zones ranging between a few meters and a few tens of meters in thickness. The Glavnaya and Novaya vein zones are the best known; they are mostly located in subvolcanic bodies of rhyolites and rhyodacites. In regard to their strikes, they consist of several echelon features of varying lengths. Veins within 1 m in thickness are mostly found in these zones. The veins have lengths between 100 and 400 m. The concentration of Au and Ag in the ore varies in the ranges 0–474.3 g/t and 0–3794.23 g/t. The veins frequently involve colloform banded textures that are frequently combined with breccia textures. The ore has an Au/Ag ratio of (1 : 5–1 : 10) and a sulfide concentration of (0.5–5%). The chief mineralogic features of the ore include a great variety of Ag-bearing minerals (Novoselov et al., 2009) and the occurrence of calcite and fluorite (Struzhkov, 2010). The Valunistoe ore bodies date back to the Late Cretaceous (79 ± 2 Ma), judging from determinations of absolute adular datings (Leier et al., 1997; Nyuberri et al., 2000), and were contemporaneous with the effusions of plateau basalts that screened the hydrothermal solutions.

The Gornoe deposit and the Ognennoe ore occurrence are controlled by the Pragornenskaya VDS, which is confined to the same series of proximate discontinuities striking northeast that the Valunistoe deposit is (see Fig. 2). The Ognennoe ore occurrence is the southward extension of the Gornoe deposit (see Fig. 2). The VDS is composed of Amgen acid volcanic rocks, Ekityki andesites, and Leurvaam acid volcanic rocks that have been ruptured by subvolcanic bodies and trachyrhyolite dikes belonging to the Leurvaam volcanic unit. The middle of the VDS contains abundant ring and arcuate faults that not infrequently control series and bundles of quartz veins and contain hydrothermally altered rocks. Twelve veins have been identified by prospecting surveys. The veins strike northeast, nearly north–south, and west–northwest. The dip angles are high (60°–90°). The concentrations of Au reach 9.5 g/t and that of Ag 148.0 g/t, the average thickness of the veins ranges between 0.8 m and 4.6 m, their along-strike lengths are 250 m to 800 m, with the dip length occasionally reaching 300 m. The veins are dominated by fine-crystalline quartz, with adular, calcite, and fluorite being in lesser amounts. The texture is massive, occasionally colloform-banded, pectinate, framework–tabular, and brecciform. The ore minerals are acanthite, pyrite, marcasite, chalcopyrite, native gold, and electrum.

The Zhilnoe deposit lies in the eponymous VDS (see Fig. 2); it is largely composed of acid volcanic rhyolite bodies and dikes of the Leurvaam volcano-plutonic unit. The volcanic and subvolcanic rocks have been hydrothermally altered to varying degrees to become secondary quartzites and argillisites, more rarely chlorite and khlorite-carbonate propylites. Prospecting identified three ore-bearing vein zones: the northern (Udachnaya), the northwestern (Vysokaya), and the northeastern (Krestovaya) zones. High concentrations of Au (reaching 178.6 g/t) and of Ag (reaching 11691 g/t) were only found in lump samples. The best known zone, Udachnaya, was traced nearly north–south (5°) for 3 km. On the southern flank, it lies in a subvolcanic rhyolite stock and consists of two veins that are as thick as 2 m in places. The veins are composed of fine-crystalline quartz of colloform texture with impregnations of ore minerals. The concentrations of Au reach 11.5 g/t in the veins.

RESULTS FROM A STUDY OF FLUID INCLUSIONS

Microthermometric studies of individual fluid inclusions sampled in the gold-bearing quartz of hydrothermal veins were carried out for the Valunistoe, Zhilnoe, and Gornoe deposits, as well as for the Ognennoe ore occurrence. Numerous fluid inclusions that were large enough (over 10 μm) were found only in the productive generation of quartz showing various forms of segregations: pectinate, pinnate, and radiate. These forms arose nearly simultaneously with the adular. Fluid inclusions in calcite were only studied for the quartz–carbonate veins in the Valunistoe deposit.

Visual inspection of fluid inclusions in quartz resulted in the identification of two types of inclusion based on their filling at room temperature: (1) dominantly gas inclusions that contain gas with a small rim of an aqueous solution and (2) two-phase gas–liquid inclusions of low mineralized solutions with a gas bubble that was 5 to 20 vol % of the total volume of an inclusion (Fig. 3). The dominantly gas inclusions of type 1, which have been only identified in the adular–quartz veins of the Zhilnoe deposit and in the Ognennoe ore occurrence, are situated in the same zones or fissures as the gas–liquid inclusions of type 2, which provides evidence of a heterogeneous condition of the mineral-generating fluid during certain periods. Gas–liquid inclusions of type 2 are also encountered in calcite in quartz–carbonate veins of the Valunistoe deposit.

The highest temperatures of homogenization were obtained for boiling heterogeneous fluids, so that no correction for pressure (Roedder, 1984, among others) is required for homogenization temperatures and the temperatures are the crystallization temperatures for the host mineral to within the accuracy of the method. Those fluid inclusions were chosen for thermal and cryometric studies, which were in growth zones or were uniformly distributed throughout the volume of individual quartz grains and classified as being primary inclusions. For the sake of completeness we also studied primary–secondary inclusions and secondary inclusions.

The microthermometric studies of fluid inclusions were conducted using a measuring complex based on a THMSG-600 microthermocamera manufactured by Linkam, England, an Olimpus microscope, Japan, and a controlling computer. The complex can measure

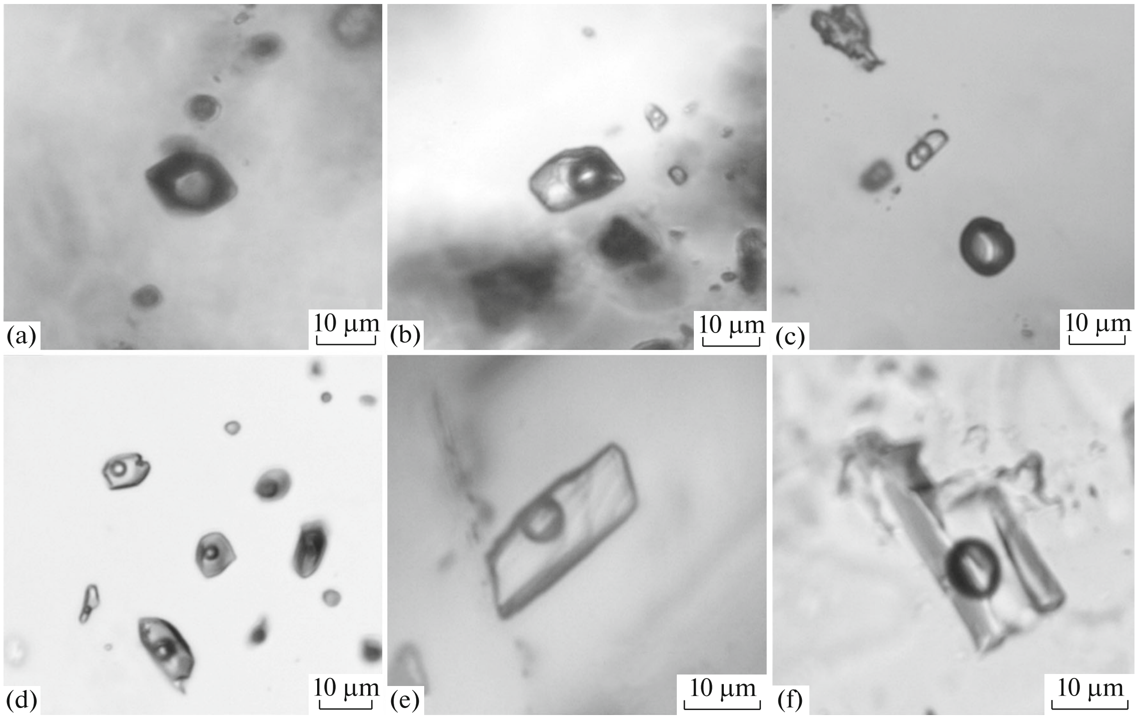

Fig. 3. Fluid inclusions in quartz (a–d) and in calcite (e, f), Valunistoe deposit and ore occurrences. (a) Gas inclusion; (b) two-phase fluid inclusion of type 2; (c) association of gas and two-phase inclusions; (d) primary two-phase fluid incluions; (e, f) two-phase fluid inclusions in calcite. Scale 10 μm.

temperatures of phase transition in real time in the range between –196 and 600°C, observe them at great magnification, and produce digital microphotographs. Individual fluid inclusions were studied in bilaterally polished plates 0.3–0.5 mm thick. After visual inspection and photography, the preparations were disengaged from the glass, washed with ethylene spirit, and the quartz lumps with inclusions chosen for further study were mechanically separated from them. The concentration of salts for inclusions was found from the ice melting temperature using data from (Bodnar and Vityk, 1994). The salt composition of a solution was determined from eutectic temperatures (Borisenko, 1977). Pressure was estimated for associations of syngenetic inclusions of types 1 and 2 with heterogeneous fluid as the pressure of saturated water vapor. The concentration of salts and pressures of water vapor and carbon dioxide was estimated using the FLINCOR software (Brown, 1989).

The bulk analysis of the composition of fluid inclusions was carried out in 0.7-g charges, –0.5 + 0.25 mm of monomineral quartz fractions at the TsNIGRI (Analyst Yu.V. Vasyuta) following the procedure described in (Kryazhev et al., 2006). Inclusions in quartz were opened thermally at 500°C, and in sphalerite at 350°C. Gas chromatography (TsVET-100 chromatograph) was used to find the amount of water required to calculate the concentrations of elements in a hydrothermal solution. We also analyzed carbon dioxide, methane, and hydrocarbons. Aqueous extracts were prepared in the solution using ionic chromatography (TsVET-3006, sensitivity of 0.01 mg/L) to determine Cl, SO_4, and F, while the ICP MS method (Elan-6100 mass spectrometer) was used to determine K, Na, Ca, Mg and other elements.

The results of thermal and cryometric studies of over 500 individual fluid inclusions (Table 1, see Fig. 3) in quartz and calcite showed that the solutions of two-phase fluid inclusions were dominated by Na and K (see Table 1). This is shown by chloride eutectics for solutions of fluid inclusions in the temperature range between –22 and –35°C.

The productive quartz of the Valunistoe deposit and the late calcite in the ore veins were found to contain only gas–liquid inclusions of type 2. Fluid inclusions in quartz are completely homogenized to become a liquid phase at temperatures of 203–284°C; the salinity of the fluids is 0.2–0.7 wt % eqv. NaCl. The fluid had a density of 0.73–0.87 g/cm^3. The fluid inclusions in calcite are homogenized to become a liquid phase at temperatures of 174–237°C, while the salinity of the fluids was 0.2–0.7 wt % equ. NaCl as well. The fluid had a density of 0.81–0.90 g/cm^3.

The bulk chemical composition of fluids from inclusions in quartz of the Valunistoe deposit can be

Table 1. The results of thermal and cryometric studies for individual fluid inclusions in quartz and calcite of the AKVF deposits and occurrences

Sample no.	Types of inclusion*	n	T_{hom}, °C	T_{eut}, °C	$T_{ice\ melt.}$, °C	C_{salt}, wt % equ. NaCl	d, g/cm^3	P, bars
Valunistoe								
V 23	2	7	284	−27	−0.2	0.4	0.73	–
	2	3	276	−33	−0.2	0.4	0.75	–
	2	6	276	−31	−0.2	0.4	0.75	–
	2	4	263	−27	−0.1	0.2	0.77	–
	2	7	262	−31	−0.2	0.4	0.77	–
V 21	2	18	232	−25	−0.4	0.7	0.83	–
	2	2	226	−32	−0.3	0.5	0.83	–
	2	2	224	−25	−0.3	0.5	0.84	–
	2	28	203	−26	−0.2	0.4	0.87	–
V-89	2	6	219	−30	−0.3	0.5	0.85	–
Calcite	2	3	174	−25	−0.3	0.5	0.90	–
V 82	2	11	193	−28	−0.2	0.4	0.88	–
Calcite	2	5	237	−30	−0.1	0.2	0.81	–
	2	13	196	−29	−0.4	0.7	0.88	–
	2	6	199	−29	−0.4	0.7	0.88	–
Ognennyi								
O 29b	2	4	229	−31	−0.2	0.4	0.83	–
	2	14	204	−32	−0.2	0.4	0.86	–
	2	11	201	−31	−0.3	0.5	0.87	–
O 29a	2	11	261	−27	−0.1	0.2	0.77	–
	2	3	231	−28	−0.3	0.5	0.83	–
	2	2	211	−27	−0.3	0.5	0.86	–
	2	5	197	−28	−0.3	0.5	0.87	–
O 35	1, 2	3	321	−22	−0.2	0.4	0.65	110
	2	3	259	−31	−0.3	0.5	0.78	–
	2	11	244	−34	−0.6	1.1	0.81	–
	2	4	233	−32	−0.5	0.9	0.83	–
	2	11	208	−30	−0.4	0.7	0.86	–
	2	8	195	−23	−0.4	0.7	0.88	–
Zhilnoe								
Zh 60	2	4	318	−31	−0.1	0.2	0.65	–
	2	7	294	−31	−0.1	0.2	0.70	–
	2	5	269	−31	−0.1	0.2	0.76	–
	2	4	265	−30	−0.4	0.7	0.77	–
Zh 66	2	7	243	−28	−0.3	0.5	0.81	–
	2	3	240	−28	−0.3	0.5	0.81	–
	2	3	239	−28	−0.2	0.4	0.81	–
	2	3	228	−28	−0.6	1.1	0.84	–
Zh 68	1, 2	6	352	−32	−0.8	1.4	0.58	160
	2	3	280	−30	−0.3	0.5	0.74	–
	2	6	279	−32	−0.5	0.9	0.75	–
	2	3	273	−31	−0.4	0.7	0.76	–
	2	6	253	−32	−0.4	0.7	0.79	–

Table 1. (Contd.)

Sample no.	Types of inclusion*	n	T_{hom}, °C	T_{eut}, °C	$T_{ice\ melt.}$, °C	C_{salt}, wt % equ. NaCl	d, g/cm^3	P, bars
	2	3	248	–30	–0.4	0.7	0.81	–
	2	5	241	–31	–0.3	0.5	0.81	–
	2	3	179	–28	–0.2	0.7	0.90	–
ZD	1, 2	3	350	–35	–0.1	0.2	0.56	160
071/10.5	1, 2	8	317	–33	–0.3	0.5	0.66	105
	2	4	308	–33	–1.0	1.7	0.70	90
	1, 2	5	304	Not det.	Not det.	–	–	90
	2	8	298	–31	–2.2	3.6	0.75	–
	2	6	282	–31	–0.4	0.7	0.74	–
	2	3	275	–32	–0.2	0.3	0.75	–
ZD	1, 2	9	303	–34	–0.6	1.0	0.70	85
074/88.7	2	12	292	–30	–0.6	1.0	0.72	–
	2	16	270	–31	–0.6	1.0	0.77	–
	2	3	253	–32	–0.6	1.0	0.80	–
ZD	1, 2	7	307	–28	–1.1	1.8	0.70	90
073/108.2	2	4	276	–32	–0.7	1.2	0.76	–
	2	9	279	–29	–0.8	1.3	0.75	–
	2	3	298	–28	–0.8	1.3	0.71	–
645-1	1, 2	4	307	–32	–2.0	3.3	0.72	90
	2	13	271	–31	–1.2	2.0	0.78	–
	2	6	270	–33	–1.2	2.0	0.78	–
	2	6	259	–33	–1.5	2.5	0.80	–
	2	3	254	–29	–1.5	2.5	0.81	–
636/229,4	2	3	274	–23	–0.9	1.5	0.76	–
	2	7	273	–22	–1.8	3.0	0.79	–
ZD	2	3	291	–34	–0.8	1.3	0.73	–
015/134.6	2	14	284	–35	–0.8	1.3	0.74	–
	2	4	286	–36	–0.8	1.3	0.74	–
636/315,5	1, 2	16	246	–26	–0.3	0.5	0.80	30
	2	11	252	–25	–0.5	0.8	0.80	–
	2	6	262	–34	–0.6	1.0	0.78	–
Zd	1, 2	2	302	–38	–1.8	3.0	0.73	80
014/61.4	2	5	283	–33	–0.8	1.3	0.74	–
	2	9	276	–33	–0.8	1.3	0.76	–
	2	6	273	–31	–0.6	1.0	0.76	–
	2	14	251	–32	–1.2	2.0	0.81	–
				Gornyi				
G 49	2	4	354	–28	–0.3	0.5	0.56	–
	2	3	248	–29	–0.4	0.7	0.80	–

* Types of fluid inclusion: 1, gas inclusions, 2, two-phase gas–liquid inclusions.

found in Table 2. The cations in the fluid are dominated by (g/kg H_2O) K (2.26) and Na (0.94), while Mg (0.04) is present in lesser amounts. We found appreciable amounts of components such as (g/kg H_2O) HCO_3^- (3.11), CO_2 (5.4), and CH_4 (0.07). In addition, the fluid was found to contain the following microcomponents (mg/kg H_2O): As (128), Li (18.0), B (42), Rb (1.1), Cs (0.24), Sr (4.1), Sb (22), Cu (3.2), Zn

Table 2. The composition of solutions in fluid inclusions in the quartz of the Ognennoe ore occurrence and of the Valunistoe, Gornyi, Zhilnoe, and Kupol deposits (the last is after (Volkov et al., 2012)).

Element	Valunistoe	Ognennyi	Gornyi	Zhilnoe		Kupol
	V 21	O 29c	G 49	Zh 60	Zh 65	KP 01
Macrocomponents g/kg of water						
CO_2	5.36	1.67	1.97	1.96	4.11	4.77
CH_4	0.07	0.02	0.03	0.02	0.02	0.05
Cl^-	–	–	–	–	–	0.16
SO_4^{2-}	–	–	–	2.19	2.21	1.33
HCO_3^-	3.11	2.00	1.87	0.11	2.15	6.64
Na	0.94	0.68	0.48	0.67	0.85	1.62
K	2.26	–	0.12	0.27	0.49	0.75
Ca	–	0.05	0.11	–	0.28	0.36
Mg	0.04	0.01	0.02	0.14	0.21	0.40
Microcomponents, 10^{-3} g/kg of water						
As	128	66.2	35.7	30.6	37.2	56.5
Li	18.0	11.6	8.61	3.37	4.31	9.56
B	41.8	67.1	75.1	72.4	163	492
Rb	1.10	–	0.12	0.70	1.33	1.61
Cs	0.24	0.02	0.005	0.08	0.13	0.31
Sr	4.10	–	–	1.23	4.47	5.63
Mo	–	0.15	0.10	0.51	2.09	0.20
Ag	–	0.017	0.013	0.043	0.021	–
Sb	22.0	8.88	6.72	10.6	24.5	78.1
Cu	3.22	0.62	1.00	0.25	1.48	–
Zn	26.7	4.89	2.38	7.85	16.2	7.01
Cd	0.02	0.04	–	0.13	0.26	0.05
Pb	2.14	1.27	0.29	–	151	–
Bi	0.09	0.03	0.03	0.02	0.03	–
Th	0.01	0.01	–	–	–	–
U	–	–	0.01	0.003	–	–
Ga	0.05	0.02	0.02	–	0.04	–
Ge	0.18	0.10	0.04	0.02	0.21	–
Mn	13.1	3.13	0.78	10.4	29.5	12.26
Fe	104	57.1	19.5	10.9	53.1	–
Co	1.35	0.32	0.13	0.49	0.37	0.18
V	0.09	–	–	–	0.12	0.12
Cr	–	0.06	–	0.12	0.16	–
Y	0.01	0.003	–	–	0.02	–
Zr	0.36	0.16	0.06	0.09	0.29	0.003
Sn	0.07	0.18	0.05	0.02	–	–
Ba	1.40	–	0.20	1.96	2.46	74.8
W	0.003	–	–	–	–	–
Tl	0.03	–	–	–	0.003	0.01
REE	0.05	0.06	4.19	0.04	0.24	0.03
Hf	0.01	–	–	–	0.005	–
Ta	–	0.003	–	–	0.003	–
K/Rb	238.9	–	1042.1	384.1	370.3	466.6

Dash means below detection threshold.

(26.7), Cd (0.02), Pb (2.14), Bi (0.09), Th (0.01), Ga (0.05), Ge (0.18), Mn (13.1), Fe (104), Co (1.35), V (0.09), Y (0.01), Zr (0.36, Sn (0.07), Ba (1.4), W (0.003), Tl (0.03), REE (0.05, and Hf (0.01).

The earlier productive quartz of the Ognennyi ore occurrence was found to contain associations of syngenetic fluid inclusions of types 1 and 2 that were captured during the fluid heterogenization. The complete homogenization of type 2 fluid inclusions occurs into a liquid phase at a temperature of 321°C; the fluid has a salinity of 0.4 wt % equ. NaCl. The aqueous fluid has a density of 0.65 g/cm^3. The saturated water vapor was under a pressure of 110 bars at these parameters.

The bulk chemical composition of fluids from inclusions in quartz of the Ognennyi ore occurrence is given in Table 2. The cations are dominated by (g/kg H_2O) Na (0.68), while Ca (0.05) and Mg (0.01) are present in lesser amounts. We found appreciable amounts of components such as (g/kg H_2O) HCO_3^- (2.0), (CO_2 (1.7), and CH_4 (0.02). In addition, the following microcomponents have been identified in the fluid (mg/kg H_2O): As (66), Li (11.6), B (67), Cs (0.02), Mo (0.15), Ag (0.017), Sb (8.9), Cu (0.6), Zn (4.9), Cd (0.04), Pb (1.27), Bi (0.03), Th (0.01), Ga (0.02), Ge (0.1), Mn (3.13), Fe (57), Co (0.32), Cr (0.06), Y (0.003), Zr (0.16), Sn (0.18), and REE (0.06).

The other grains in the productive quartz of the Ognennyi ore occurrence were found to contain only gas–liquid inclusions of type 2. The complete homohenization of the fluid inclusions occurs into a liquid phase at temperatures of 195–261°C; the fluids had a salinity of 0.2–1.1 wt % equ. NaCl. The fluid had a density of 0.77–0.88 g/cm^3.

The earlier productive quartz of the Zhilnoe deposit was found to contain associations of syngenetic fluid inclusions of types 1 and 2 that were captured during fluid heterogenization. The complete homogenization of type 2 fluid inclusions occurs into a liquid phase at temperatures of 246 to 352°C; the fluid has a salinity of 0.2–3.3 wt % equ. NaCl. The aqueous fluid had a density of 0.58–0.80 g/cm^3. The saturated water vapor had a pressure varying between 30 and 160 bars at these parameters.

The complete homogenization of fluid inclusions in the other grains of the productive quartz sampled from the Zhilnoe deposit occurs at temperatures of 228–318°C and the concentration of salts was 0.2–3.6 wt % equ. NaCl. The fluid had a density varying between 0.65 and 0.84 g/cm^3.

The bulk chemical composition of fluids from inclusions in quartz of the deposit is listed in Table 2. The cations in the fluid are dominated by (g/kg H_2O) Na (0.85–0.67) and K (0.49–0.27), while Ca (0.28) and Mg (0.21–0.14) are present in lesser amounts. We found appreciable amounts of components such as (g/kg H_2O) HCO_3^- (2.15–0.11), SO_4^{2-} (2.21–2.19), CO_2 (4.11–1.96), and CH_4 (0.02). In addition, the fluid was found to contain the following microcomponents (mg/kg H_2O): As (37.2–30.6), Li (4.3–3.4), B (163–72), Rb (1.3–0.7), Cs (0.13–0.08), Sr (4.5–1.2), Mo (2.1–0.5), Ag (0.04–0.02), Sb (24.5–10.6), Cu (1.5–0.25), Zn (16.2–7.9), Cd (0.26–0.13), Pb (151), Bi (0.03–0.02), U (0.003), Ga (0.04), Ge (0.21–0.02), Mn (29.5–10.4), Fe (53–10.9), Co (0.49–0.37), V (0.12), Cr (0.16–0.12), Y (0.02), Zr (0.29–0.09), Sn (0.02), Ba (2.5–1.96), Tl (0.003), REE (0.24–0.04), and Hf (0.003).

The productive quartz from the ore veins of the Gornyi deposit was found to contain only type 2 gas–liquid inclusions. The complete homogenization of fluid inclusions in quartz occurs into a liquid phase at temperatures of 248–354°C; the fluids have a salinity of 0.5–0.7 wt % equ. NaCl. The fluid density is 0.56–0.80 g/cm^3.

The bulk chemical composition of fluids from inclusions in quartz of the Gornyi (?) deposit is given in Table 2. The cations in the fluid are dominated (g/kg H_2O) by Na (0.48) and K (0.12), while Ca (0.11) and Mg (0.02) are present in lesser amounts. We found appreciable amounts of the following components (g/kg H_2O): HCO_3^- (1.87), CO_2 (1.97), and CH_4 (0.03). In addition, the fluid was found to contain the following microcomponents (mg/kg H_2O): As (35.7), Li (8.6), B (75), Rb (0.12), Cs (0.005), Mo (0.1), Ag (0.01), Sb (6.7), Cu (1.0), Zn (2.4), Pb (0.3), Bi (0.03), U (0.01), Ga (0.02), Ge (0.04), Mn (0.8), Fe (19.5), Co (0.13), Zr (0.06), Sn (0.05), Ba (0.2), and REE (4.19).

Overall, the data indicate similar temperatures in compositionally similar hydrothermal K–Na-chloride solutions that are typical of the formation of the most abundant generation of productive vein quartz in all objects under study here. At the same time, we must note some differences. In the first place, the Valunistoe deposit has no predominantly gaseous inclusions and shows lower temperatures of homogenization, 203–284°C in quartz and 174–237°C in calcite, as well as the lowest concentrations of salts, 0.2–0.7 wt % NaCl (see Table 1). At the same time, the quartz of the Ognennoe ore occurrence and the Zhilnoe deposit were found to have a heterogeneous fluid and appreciably higher temperatures of homogenization: up to 321°C for the former and up to 352°C for the latter. The concentrations of salts in these fluids are higher as well: up to 1.1 wt % equ. NaCl for the Ognennyi and up to 3.6 wt % equ. NaCl for the Zhilnoe (see Table 1, Fig. 4a). These differences can be related to the mineral and geochemical features of the Valunistoe ores where later fluorite and calcite are abundant.

It should be emphasized that the data obtained thus far show homogenization temperatures and composi-

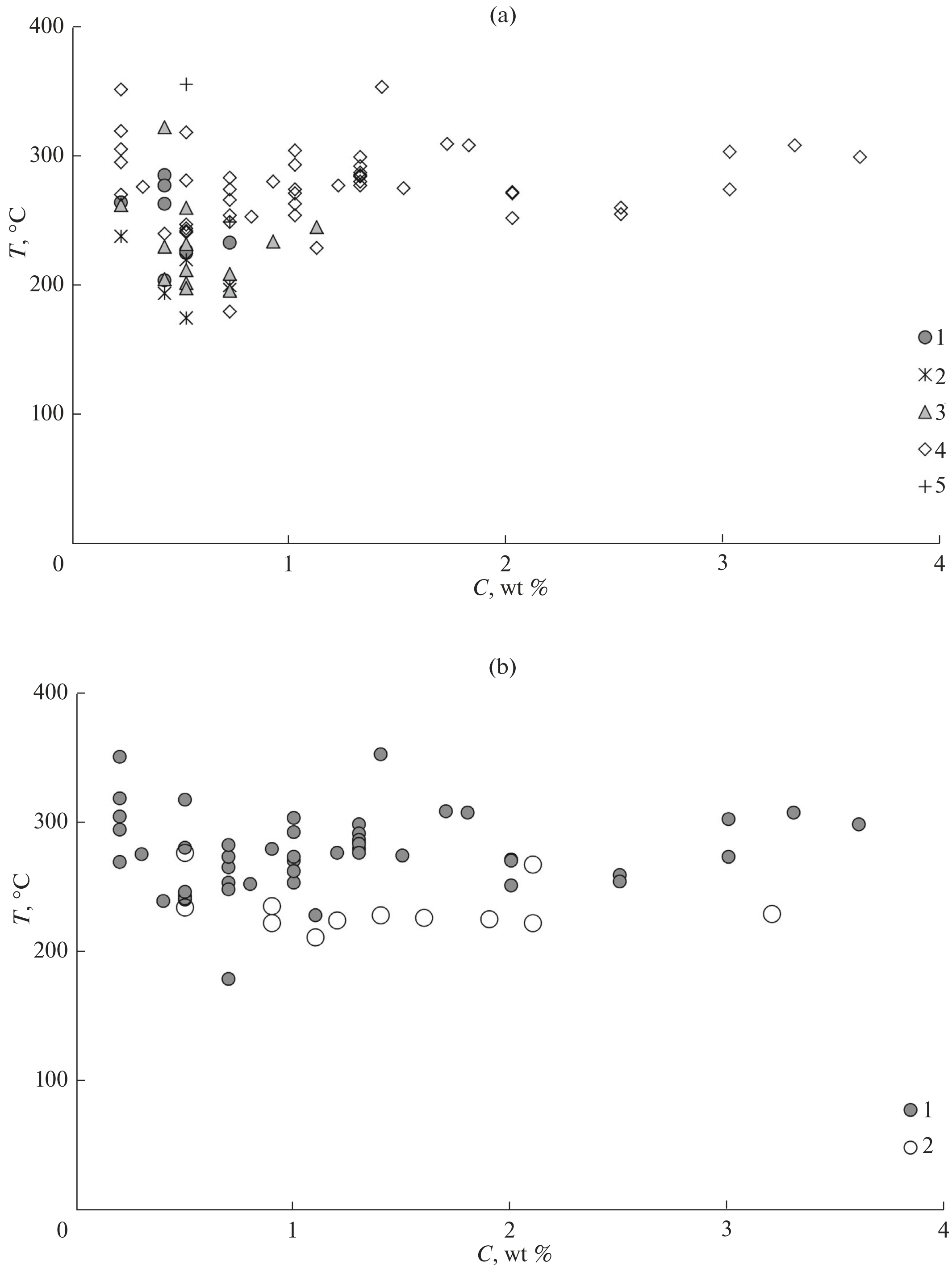

Fig. 4. A temperature versus salt concentration diagram (a) for hydrothermal fluids from fluid inclusions in quartz sampled in the AKVF deposits and occurrences, as well as a comparison of Zhilnoe and Kupol deposits (b). (a) (1, 2) Valunistoe deposit (1, quartz, 2, carbonate), (3) Ognennoe occurrence, (4) Zhilnoe deposit, (5) Gornoe occurrence; (b) (1) Zhilnoe deposit, (*2*) Kupol deposit.

tions of fluid inclusions in the quartz and calcite of the deposits in the Amguema–Kanchalan volcanic field that are similar to the parameters of quartz and amethyst in the Kupol deposit, which is the best studied gold deposit in the region (Volkov et al., 2012).

Thermal and cryometric studies of individual fluid inclusions in the Kupol quartz and amethyst showed (Volkov et al., 2012) that the solutions of the two-phase fluid inclusions were also dominated by Na and K chlorides. This can be seen from the chloride eutec-

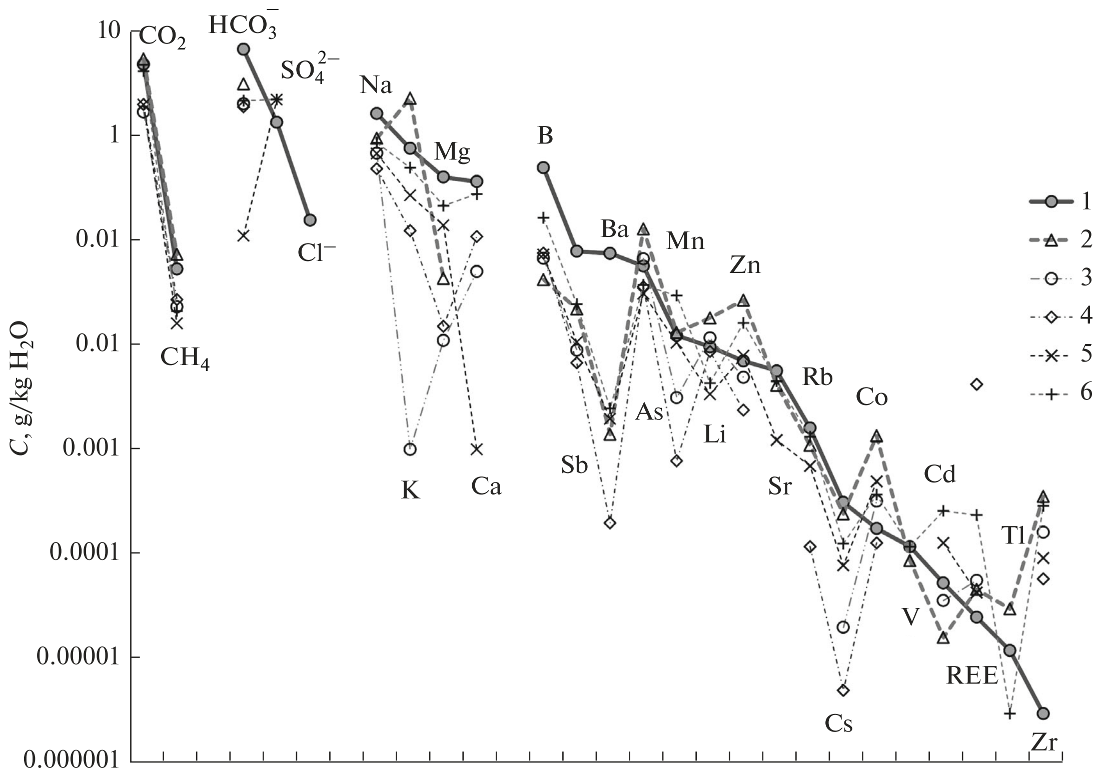

Fig. 5. The composition of mineralizing fluids: Valunistoe deposit (2), Ognennoe (3), Gornoe (4), and Zhilnoe (5, 6) occurrences compared with the Kupol deposit (1).

tics of inclusion solutions at temperatures of –21 to –34°C. The complete homogenization of fluid inclusions occurs at temperatures of 211 to 276°C; the concentration of salts varies between 0.5 and 3.2 wt % equ. NaCl. The fluid density is 0.75–0.86 g/cm^3. The pressure as determined for associations of the inclusions that were captured during fluid heterogenization was 25 bars, thus providing evidence of shallow conditions (Volkov et al., 2012).

It can be concluded that the fluids that gave rise to the deposits of the Amguema–Kanchalan volcanic field and the fluids that gave rise to the Kupol deposit have very similar physico-chemical parameters (see Figs. 4a, 4b). The similarity between the respective mineralizing fluids of the Zhilnoe and Kupol deposits is especially noticeable (see Fig. 4b).

The bulk chemical composition of fluids from inclusions in the productive quartz of the Kupol deposit is given in Table 2. The cations in the fluids are dominated (g/kg H_2O) by Na (1.6) and K (0.75), while Mg (0.4) and Ca (0.36) are found in lesser amounts. We found appreciable amounts of components such as (g/kg H_2O) HCO_3^- (6.64), SO_4^{2-} (1.33), CO_2 (4.77), and CH_4 (0.05). In addition, the fluid was found to contain the following microcomponents (mg/kg H_2O): As (56.5), Li (9.56), B (492), Rb (1.6), Cs (0.3), Sr (5.6), Mo (0.2), Sb (78), Zn (7), Cd (0.05), Mn (12.3), Co (0.18), V (0.12), Zr (0.003), Ba (74.8), Tl (0.01), and REE (0.03).

Judging from Table 2 and Fig. 5, the Valunistoe deposit is similar to the nearby ore occurrences with regard to fluid composition. In addition, the fluids in the AKVF deposits and ore occurrences have compositions (see Table 2) that show some similarities with the Kupol fluids (Volkov et al., 2012). The similarity between the Zhilnoe fluids and the Kupol fluids is emphasized by the presence of sulfate ions in the fluids. At the same time, the Kupol deposit is somewhat different from the AKVF features in having a higher mineral content in the respective hydrothermal solutions (see Fig. 5) and a relatively low gas pressure during the generation of the quartz veins (Volkov et al., 2012).

DISCUSSION OF THE RESULTS AND CONCLUSIONS

The low concentrations of salts and the low temperatures that existed during the generation of the epithermal ores sampled in the AKVF deposits and occurrences are analogous to the fluids of epithermal low sulfide deposits (Simmons et al., 2005; Bodnar et al., 2014, among others). Taking the exceptionally low mineral content of fluid inclusions in quartz and calcite into account, we must infer that the solutions that have given rise to the quartz veins were condensed vapor that separated from the hydrothermal fluid by boiling occasioned by a sharp change in pressure. The pressure that was determined for predominantly gaseous inclusions in quartz was 30–160 bars (see Table 1).

Our study of the physico-chemical parameters for the generation of calcite allowed us to emphasize its important role in the formation of productive mineralization in the AKVF. The wide occurrence of calcite in ore veins is a peculiarity of this mineralization compared with the other epithermal deposits that are found at the Chukchi segment of the OChVB. As an example, carbonate minerals are nearly absent in the Kupol and Dvoinoe deposits (Volkov et al, 2012, 2018).

We note that the deposition of calcite was rather frequently preceded by the formation of predominantly colorless fluorites which intersected, cemented, and leached out fragmented quartz–adular veins; this may indicate the active participation of F-bearing fluids in the destruction and subsequent replacement of quartz veins with calcite.

The intervein space harbored, along with propylitization, other processes of metasomatic alteration in rocks that occur at lower temperatures. These are K-feldspatization, sericitization, and argillization. This fits the lower temperature of calcite formation (below 240°C) as determined by the microthermometric study of fluid inclusions.

This indicates, in turn, possible rejuvenation, i.e., partial destruction of primary mineralization and redeposition of ore components accompanied by their possible spatial separation and by the formation of rich bonanza ores dominated by Au in a favorable environment. The occurrence of fluorite during later stages seems to have been due to the influence of fluorine-rich fluids coming from the tin-bearing intrusions that are known to exist in the region during postintrusive hydrothermal activities.

It is quite likely that the AKVF Au–Ag ores were formed by spatial superposition of hydrothermal processes that were substantially removed from each other in time and which seem to have been related to different-age stages of volcanic activity in the AKVF (Akinin, 2011). This inference is not of theoretical significance alone, but is also important for practical assessment of vein productivity.

The thermal, pressure, and geochemical features of the ores identified in this study provide evidence of a high oxidizing potential of the mineralizing environment, which might have been due to a mixing of ore-bearing fluids and highly aerated meteoric waters and a low level of erosional truncation, and indicate a relationship to a Cu-porphyritic mineralizing system. The latter is large; this allows one to predict the discovery of new rich ore bodies within the AKVF (including those not reaching the ground surface).

The analysis of results from the study of fluid inclusions in vein quartz and calcite suggests a wider depth interval of productive epithermal veins reaching depths of over 400 m. This mineralization range has been found on the practically analogous Kupol deposit, which is the best studied deposit in the OChVB Chukchi segment where the ore veins penetrate to depths over 450 m, as found by drilling (Volkov et al., 2012). According to modern views (Simmons et al., 2005), the vertical range of mineralization on epithermal Au–Ag deposits can reach 600–1000 m.

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