

Composition of Fluid Inclusions from Intrusive Rocks of the Norite–Cortlandite Complex, Kamchatka

E. G. Konnikov and O. N. Vasyukova

Institute of Experimental Mineralogy, Russian Academy of Sciences, Chernogolovka, Moscow oblast, 142432 Russia

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Abstract—Fluid inclusions in rocks of the Kuvalrog and Shanuch plutons, located in Kamchatka and belonging to the Ni-bearing norite–cortlandite association, have been studied. Microthermometry (heating and freezing) and Raman spectroscopy indicate differing composition of fluid inclusions from these plutons. High-density CO₂ inclusions are characteristic of Kuvalrog, whereas N₂–CH₄–CO₂ and aqueous inclusions dominate in Shanuch. The presence of methane in the fluid of the Shanuch pluton is an indicator of its resource potential in respect to high-grade sulfide mineralization.

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INTRODUCTION

The effect of the fluid regime of mafic–ultramafic intrusions on their resource potential is widely discussed in the Russian literature devoted to the origin of Cu–Ni deposits. Neruchev and Prasolov (1995), Nivin and Chashchin (1996), and Konnikov et al. (2000) were the first to demonstrate a relationship between the enrichment of these intrusions in fluid components (reduced gases, in particular) and the content of sulfide phase. This problem is not discussed in any foreign publications.

Abundant magmatic amphibole and biotite in the Ni-bearing norite–cortlandite complex of Kamchatka indicate saturation of the parental melt with fluid components (Shcheka and Chubarov, 1987). Previous gas chromatography studies revealed that the fluids entrapped during crystallization of these plutons are enriched in gases, including methane (Konnikov et al., 2005). The total content of entrapped gases is $(15\text{--}49) \times 10^{-3} \text{ cm}^3/\text{g}$, which is still more than in the Noril'sk ore-bearing intrusions $((1\text{--}3) \times 10^{-3} \text{ cm}^3/\text{g}$, after (Neruchev and Prasolov, 1995)). A linear correlation between the methane concentration in the rocks of the Kamchatka Ni-bearing intrusions and the contents of Ni, Fe, and S as the major sulfide ore components has been established. These elements define the metallogenic specialization of the complex. In this paper, we present the results of fluid inclusion (FI) study in minerals from the Kamchatka Ni-bearing intrusions, which have not been investigated before in this respect.

BRIEF CHARACTERISTICS OF THE STUDIED INTRUSIONS

The Ni-bearing norite–cortlandite intrusive complex occurs in the Sredinny Range of Kamchatka at the

northern and southern margins of an inlier that is composed of Proterozoic (?) high-grade metamorphic rocks of the Kolpakovo and Kamchatka groups. This complex comprises stock- and sill-shaped plutons oriented conformable to the strike of terrigenous country rocks, including black shales of the Middle–Upper Paleozoic (?) Kheivan Formation (Poletaev, 2004). According to recent data (Konnikov et al., 2006), the norite–cortlandite plutons were emplaced in the Early Paleogene, 50–57 Ma ago. The thermodynamic conditions of crystallization of these plutons were established by Shcheka and Chubarov (1987). According to their study, the formation temperature of cortlandite and pyroxene–garnet hornfels estimated from two-pyroxene and biotite–garnet thermometers falls within the range from 720 to 750°C. The pressure estimated from the orthopyroxene–plagioclase–garnet geobarometer at this temperature varies from 6 to 8 kbar. The norite–cortlandite complex formed from a water-saturated Mg-rich tholeiitic melt close to traps in geochemistry. A prevalence of orthopyroxene, amphibole, and phlogopite over other mafic minerals in intrusive rocks is a characteristic feature of this complex. Most researchers recognize two stages in the formation of this complex: (1) amphibole- and phlogopite-bearing harzburgite (cortlandite) and olivine norite and (2) amphibole pyroxenite, norite, gabbro, and garnet diorite. The presence of graphite and accessory ilmenite in these rocks indicates reduced crystallization conditions of these plutons. Shcheka and Chubarov (1987) reported that $\log f_{\text{O}_2}$ in magma of the norite–cortlandite intrusions ranged from -20 to -22 . Judging by initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios ranging from 0.70403 to 0.70507 and from 0.512593 to 0.512829, respectively, and low ϵNd varying from -0.88 to $+3.7$, magma of the norite–cortlandite complex is derived from a primitive, PREMA-type mantle source and is not contaminated with crustal components.

Corresponding author: E.G. Konnikov. E-mail: konn@iem.ac.ru

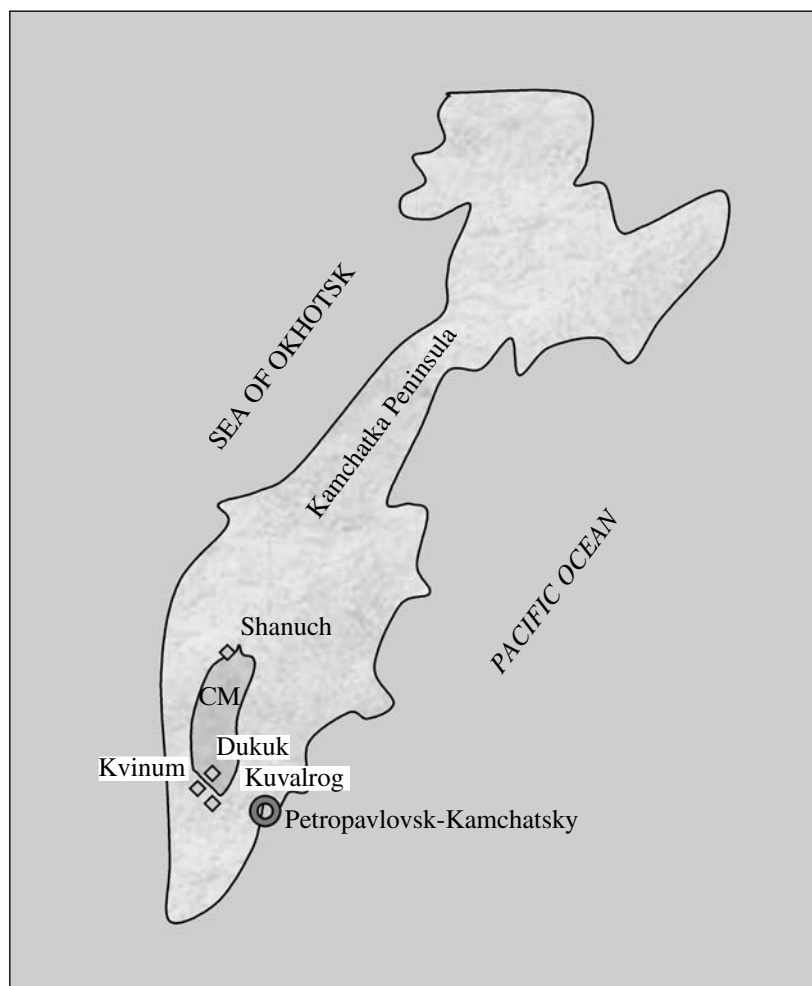


Fig. 1. Location of the major plutons of the norite–cortlandite type in Kamchatka. CM is an inlier of the pre-Mesozoic basement.

PGM-bearing nickel sulfide deposits are related to the studied complex in this and other regions of the Far East (Zimin, 1973). The medium-size Shanuch nickel sulfide deposit is related to this complex in Kamchatka. The average Ni grade in ore is about 6 wt %. This deposit is situated in the northern part of the Sredinny Range (Fig. 1). A number of Ni occurrences hosted in plutons of the norite–cortlandite complex are known at the southern end of this range. The exposed area of the largest, the Kuvalrog pluton, is approximately 30 km².

ANALYTICAL TECHNIQUE

Rocks from the Kuvalrog and Shanuch plutons were sampled for FI study. Double polished plates 0.3 mm thick were prepared from collected samples and examined under a polarized microscope. Fragments of these plates containing FIs were drilled out with a diamond-reinforced brass tube and then cleaned from dust in an ultrasonic bath.

According to the classification of Roedder (1984), most studied FIs are pseudosecondary (or primary–sec-

ondary), with secondary inclusions being less frequent. The pseudosecondary FIs are related to the fractures formed during crystal growth; in fact, these FIs are primary. The fractures where pseudosecondary inclusions are localized do not extend beyond the host crystals and are distinguished in this respect from the cracks that crosscut boundaries of mineral phases and control secondary inclusions.

FIs were studied with a Linkam THMSG-600 microscope heating stage that allows implementation of programmed heating/freezing of a sample with a rate varying from 0.1 to 90°C/min within a temperature range of –195 to +600°C. Temperatures were determined accurate to ±0.1°C. The equipment was calibrated using the triple point (–56.6°C) of the CO₂ standard (Camperio, Alps) and the melting temperature of pure H₂O from synthetic FIs.

The composition and density of fluid from inclusions entrapped during mineral crystallization were determined from temperatures of homogenization and ice melting. In the case of aqueous–salt inclusions, the fluid composition was estimated from the initial ice

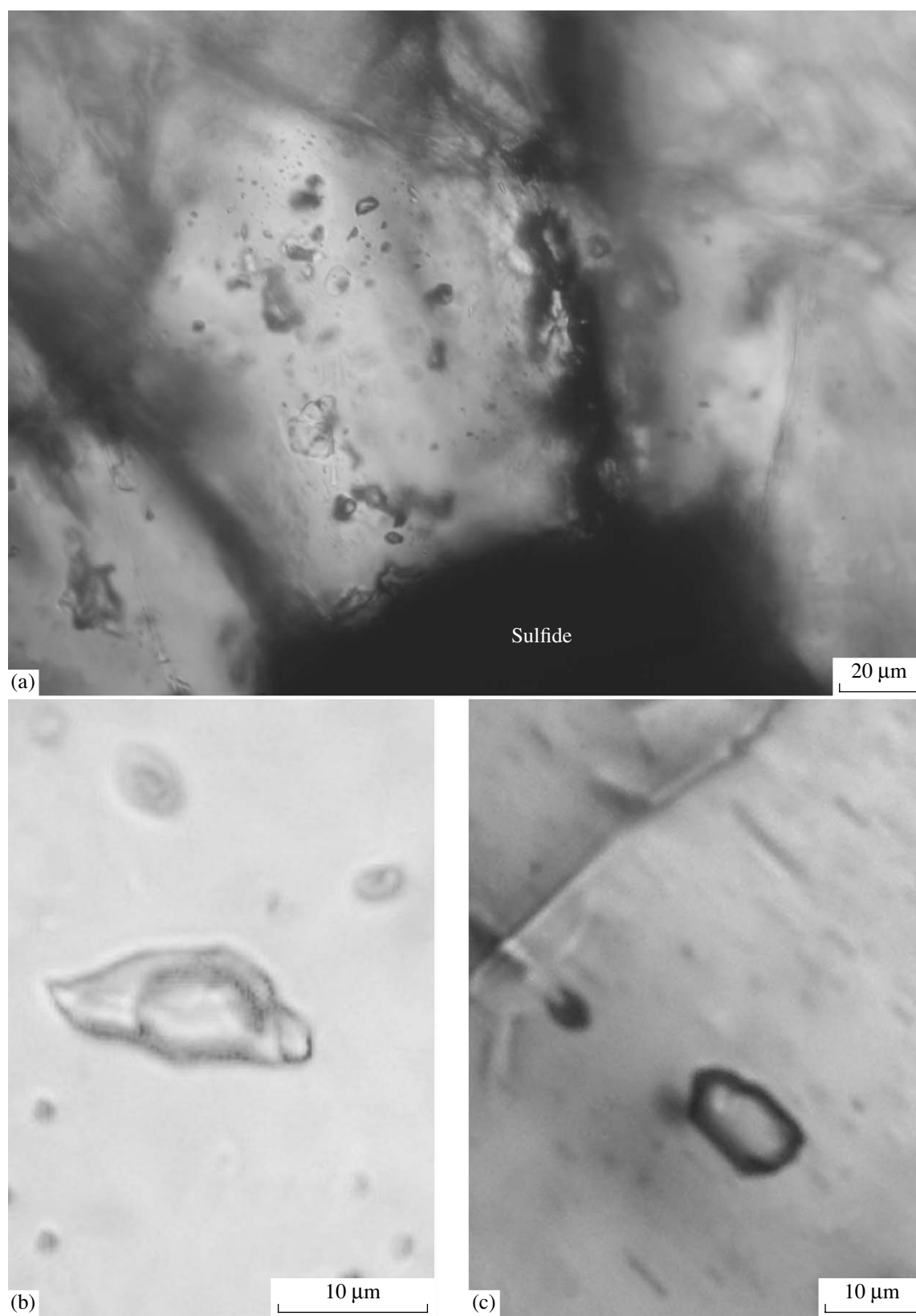


Fig. 2. Fluid inclusions in rocks from the Kuvalrog pluton. (a) Pseudosecondary inclusions in plagioclase; (b) H₂O–CO₂ inclusion in plagioclase from hornblende after websterite; (c) inclusion of liquid CO₂ in orthopyroxene from plagioclase–hornblende pyroxenite.

Table 1. Results of freezing study of fluid inclusions from rocks of the Kuvalrog pluton

Sample	Rock	Composition of inclusions	Host mineral	$T_{\text{hom}}, ^\circ\text{C}$	$T_{\text{melt}}, ^\circ\text{C}$
s1-17/1-1	Hornblende plagiopyroxenite	CO ₂	Plagioclase	-22.5	-59.6
s1-17/1-2	"	"	"	-21.1	-59.8
s1-17/1-3	"	"	"	-21.0	-
s1-17/1-4	"	"	"	-25.0	-
s1-17/1-5	"	H ₂ O-CO ₂ **	"	+8.8	-59.2
s1-17/1-6	"	CO ₂	"	-30.4	-61.9
s1-17/1-7	"	"	"	+15.6	-59.0
s1-17/1-8	"	"	"	-30.7	-
s1-17/2-1	"	"	Orthopyroxene	-6.2	-57.2
s1-17/2-2	"	"	"	-11.4	-58.0
s1-17/2-3	"	"	"	-12.8	-
s1-17/2-4	"	"	"	-12.2	-57.3
s1-17/2-5***	"	"	"	-4.5	-57.3
s5-34-1	Plagiorhornblendite	H ₂ O-CO ₂	Orthopyroxene	+22.3*	-57.7
s5-34-2	"	"	"	+12.6*	-56.8
s5-34-3	"	"	"	+12.0	-
s5-34-5	"	"	"	+10.7	-
s5-10/2-1	Hornblende gabbro-norite	CO ₂	"	-1.4	-
s5-10/2-2	"	"	"	-6.2	-
s5-10/2-3	"	"	"	-8.4	-
s5-10/2-4	"	H ₂ O-CO ₂	"	-9.2	-59.7
s5-10/2-5	"	CO ₂	"	-9.0	-
s5-10/2-6	"	"	"	-12.8	-58.6
s5-10/2-7	"	H ₂ O-CO ₂	"	+21.2	-57.3
s5-10/2-8	"	"	"	-9.5	-59.2
s5-10/2-9	"	"	"	-8.0	-
s5-10/2-10	"	N ₂ -CH ₄	"	-14.3	-
s5-10/2-11	"	H ₂ O-CO ₂	"	+24.7	-58.2
s5-10/2-12	"	"	"	+11.8	-
s5-10/2-13	"	"	"	-4.4	-60.8
s5-10/2-14	"	"	"	-6.0	-
s5-36-1	Hornblende norite	"	"	+20.0*	-57.7

Notes: * Homogenization into gas; the remaining FIs homogenized into liquid.

** The homogenization temperature of CO₂ is indicated for H₂O-CO₂ FIs.

*** Secondary FI.

melting temperature, while the salinity was estimated from the final ice melting temperature and presented as wt % NaCl equivalent. Thiéry diagrams (Thiéry et al., 1994) were used to estimate the amount of admixtures in the CO₂ component. Fluid density, molar volumes, and molar ratios were calculated taking into account homogenization temperature and fluid composition with the package FLUIDS 1 (Bakker, 2003) using equations of state taken from (Duan et al., 1996; Thiéry et al., 1994) for CO₂ inclusions and from (Wagner and Pruss, 1993) for aqueous and aqueous-salt inclusions.

The FLUIDS 1 package and equations of state from (Duan et al., 1996; Bodnar and Vityk, 1994; Knight and Bodnar, 1989) were used to calculate isochores in *PT* coordinates.

After the microthermometric study, the major types of FIs were investigated with Raman spectroscopy in the regime of continuous scanning with a Renishaw RM 1000 spectrometer equipped with a Leica DMLM microscope. The average time to obtain one spectrum was about 100 s. Raman spectra were excited by the

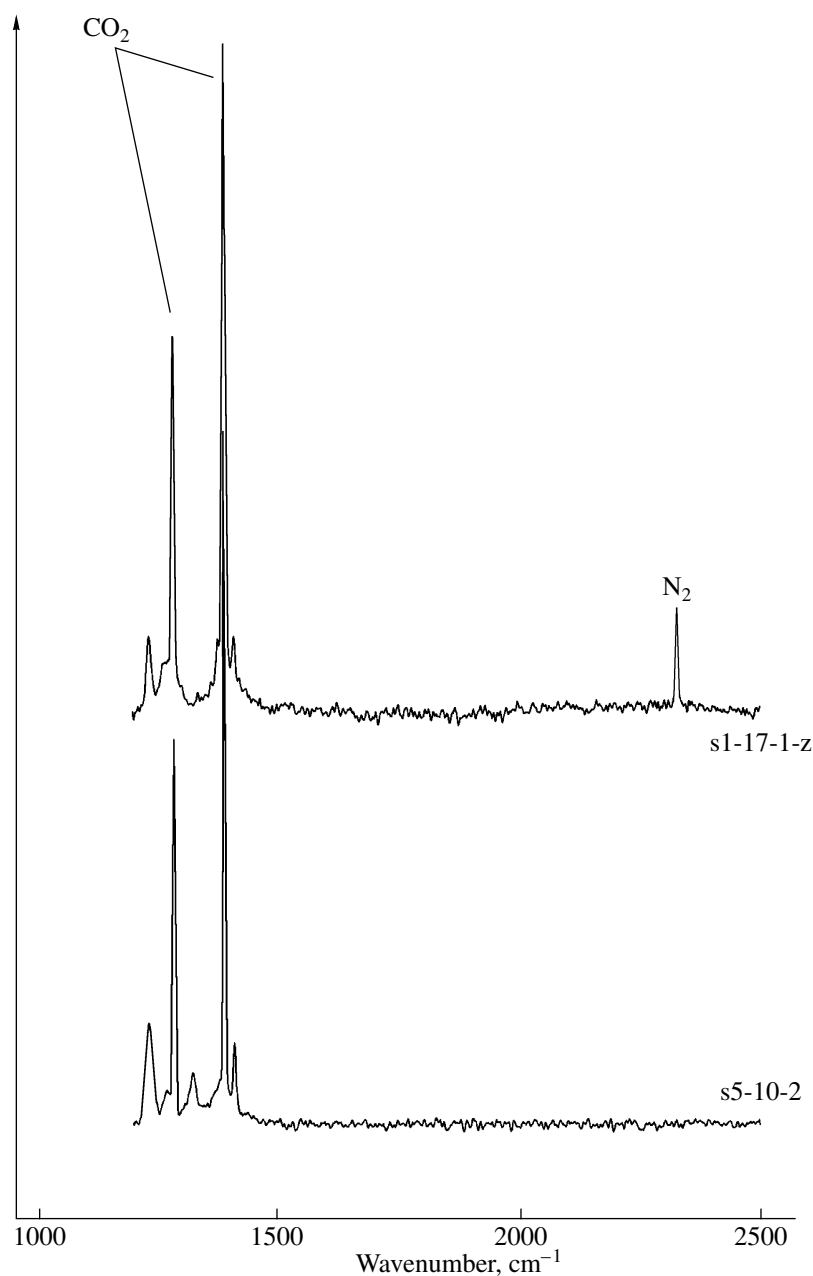


Fig. 3. Raman spectra of fluid inclusions from cortlandite (s1-17-1-z) and gabbronorite (s5-10-2) of the Kuvalrog pluton.

514.5-nm band of a Melles Griot argon ion laser. These spectra were corrected for the spectral sensitivity of the equipment. The gas composition in FIs was estimated in qualitative terms using the Raman spectra.

RESULTS

The studied FIs from the Kuvalrog and Shanuch plutons are mainly hosted in intercumulus minerals from norite and cortlandite as linear chains along healed fractures that do not extend beyond host plagioclase or quartz. Inclusions in orthopyroxene are rare

because this mineral is commonly replaced by amphibole (cummingtonite and tremolite) pseudomorphs.

The FIs from ultramafic rocks of the Kuvalrog pluton are largely filled with CO₂ (Fig. 2; Table 1). These inclusions from plagioclase vary from 3 to 15 μm in size and frequently are closely associated with sulfide grains. The inclusions are usually rounded in shape. According to the freezing study, the homogenization temperature (T_{hom}) ranges from –30.7 to +15.6°C; the melt temperature (T_{melt}) varies from –61.9 to –59.0°C. Inclusions in orthopyroxene are smaller (0.5–8 μm) and slightly elongated; their T_{hom} and T_{melt} range from –12.8

Table 2. Initial data for calculation of inclusion isochores

Sample	T_{hom} CO ₂	T_{melt} CO ₂	T_{hom} H ₂ O	N ₂ , wt %	D , g/cm ³
s1-17/1	-25.0	-59.7		24	0.820
s1-17/2	-12.8	-58.0		7	0.932
s5-10/2	-12.8	-58.6		14	0.888
sh-28			130.0		0.935
sh-05			174.0		0.893

Note: Data are given for the most dense individual inclusions from a studied sample.

to -6.2 and from -58.0 to -57.3°C , respectively. The temperature of ice melting is lower than for pure CO₂ (-56.6°C), indicating the presence of other gases. The

Raman spectroscopy of inclusions from sample s1-17-1-z detected an admixture of nitrogen (Fig. 3) in amount of about 24 wt %. According to Thiéry diagrams (Thiéry et al., 1994), inclusions in pyroxene from plagioclase-bearing hornblende pyroxenite (sample s1-17/2) contain up to 7 wt % N₂ (Table 2).

In contrast to the inclusions from cortlandite, FIs from norite are filled with CO₂ and CO₂-H₂O with a variable but, as a rule, low H₂O/CO₂ ratio. The H₂O-CO₂ inclusions are less dense and, according to the Raman spectroscopy, do not contain nitrogen (Table 1; Fig. 3, sample s5-10-2). Their homogenization temperature ranges from -9.2 to $+24.7^{\circ}\text{C}$. In one case, a N₂-CH₄ inclusion was observed in the sulfide-bearing rock (Table 1). This inclusion is dark and opaque at room temperature and becomes heterogeneous upon cooling to -149°C ; the phase interface disappears at -143°C .

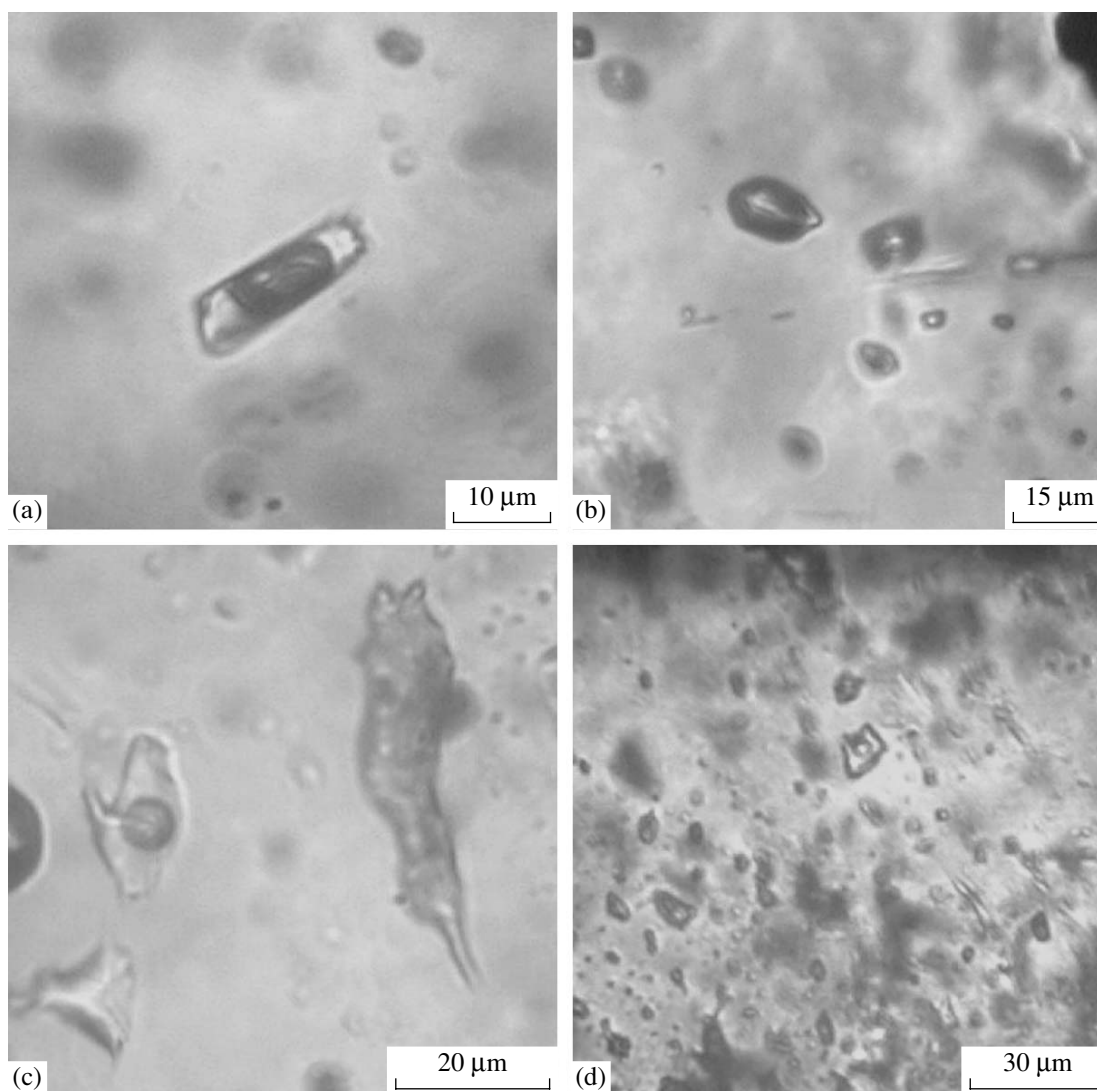


Fig. 4. Fluid inclusions in rocks from the Shanuch Ni-bearing pluton. (a) N₂-CH₄-CO₂ inclusion in quartz from sulfide-bearing amphibolized pyroxenite (sample sh05); (b) CH₄-CO₂ inclusion in quartz from the same sample; (c) aqueous-salt inclusion in quartz from massive sulfide ore (sample sh28); (d) abundant FIs in quartz segregations from the Shanuch sulfide ore.

Table 3. Results of freezing study of secondary fluid inclusions in quartz from rocks of the Shanuch Ni-bearing pluton

Sample	Rock	Composition of inclusions	$T_{\text{hom}}, ^\circ\text{C}$	$T_{\text{melt}}, ^\circ\text{C}$
SSH 2-1	Amphibolized pyroxenite	H ₂ O	–	0
SSH 2-2	"	"	–	–0.4
Sh 28-2	Massive sulfide ore	"	–	–1.2
Sh 28-3	"	"	–	–0.2
Sh 28-6	"	H ₂ O–CO ₂	+15.0	–59.6
Sh 28-8	"	H ₂ O	+130	–
Sh 08-3	Stringer–disseminated ore	"	–	–1.4
Sh 05-2*	Quartz–amphibole rock	"	+134	–
Sh 05-3	"	"	+174	–
Sh 05-4	"	"	+180	–

Note: The freezing results are given only for aqueous FIs because CH₄–CO₂ inclusions are not frozen even at –196°C.

* Metastable FI.

At the Shanuch nickel–sulfide deposit, FIs were studied from hydrothermally altered ultramafic rock (orthopyroxenite altered to tremolite–cummingtonite schist) that hosts disseminated and massive sulfide ores. This rock commonly contains interstitial quartz; quartz veinlets and pockets with abundant secondary inclusions 20–30 μm in size occur in massive sulfide ore. Two groups of FIs have been identified in the Shanuch pluton. According to their localization in the same fractures, inclusions of both groups were entrapped simultaneously.

FIs of group I are the most abundant. They are practically opaque and gas-dominant (Figs. 4a, 4b). Occasionally these inclusions contain a small amount of CO₂. No visible phase transformations except sporadic melting of CO₂ have been detected in these inclusions within the temperature range from –170 to +300°C. The Raman spectroscopy indicates that FIs belonging to this group consist of CO₂ and CH₄ with an admixture of N₂ (Fig. 5a, sample sh05-1-2). The inclusions that are widespread in the quartz pockets hosted in the massive ore are similar to the above inclusions (Fig. 5b). The proportions of gases can be approximately estimated from the intensity of peaks in Raman spectra at 79% CO₂, 12% CH₄, and 9% N₂. The semiquantitative estimates of the composition of gas mixtures in FIs from the Shanuch pluton were obtained using scattering coefficients (Burke, 2001).

FIs of the second group are completely transparent and irregular in shape and show a higher liquid/gas ratio (Figs. 4c, 4d). These inclusions are substantially aqueous (Fig. 5a, sample sh05-1-1) and frequently without a gas bubble. The salinity of these inclusions is not higher than 2 wt % NaCl equivalent because ice melting occurs within the temperature interval from 0 to –1.4°C (Table 3). Two-phase FIs homogenize into gas at a temperature ranging from +134 to +180°C. H₂O–CO₂ inclusions containing up to 20–25% H₂O are occasional.

The density has been determined and isochores drawn using the aforementioned software for inclusions from samples s1-17/1, s1-17/2, s5-10, sh28, and sh05 (Table 2; Fig. 6). On the basis of the results obtained and the known total pressure (on average, 7 kbar) during the formation of plutons, the entrapment temperature could be calculated. The entrapment temperatures of the CO₂ inclusions from points 4 and 5 are obviously overestimated because the temperatures of the pyroxene solidus in this pluton estimated from thermobarometric data are much lower and range from 950 to 1150°C (Shcheka and Chubarov, 1987). Such high entrapment temperatures could have resulted either from a total pressure drop by the moment of the inclusion entrapment time or from complete water leakage from inclusions. Both phenomena are plausible. The entrapment temperature of the H₂O–CO₂ inclusions (~1030°C, point 3) appears to be close to the actual value of this parameter in the rocks of the Kuvalrog pluton. The relatively low entrapment temperature of the CH₄-bearing inclusions from the Shanuch pluton likely corresponds to the subsolidus temperature of sulfide melts, which falls within an interval from 400 to 600°C at most Cu–Ni sulfide deposits (Gorbunov, 1968).

DISCUSSION

As follows from the results obtained, FIs from the Kuvalrog and Shanuch plutons differ in their compositions. The prevalence of methane-bearing inclusions in Shanuch pluton is the main distinction. As is known, ore-bearing mafic–ultramafic intrusions are commonly characterized by elevated concentrations of methane and hydrogen in the fluid phase (see, for example, (Neruchev and Prasolov, 1995)). On the basis of gas chromatography, these authors established the enrichment of taxitic and picritic gabbrodolerite from the Noril'sk intrusions in reduced gases, particularly, in H₂ and CH₄. Chashchin (1996), having studied the gas

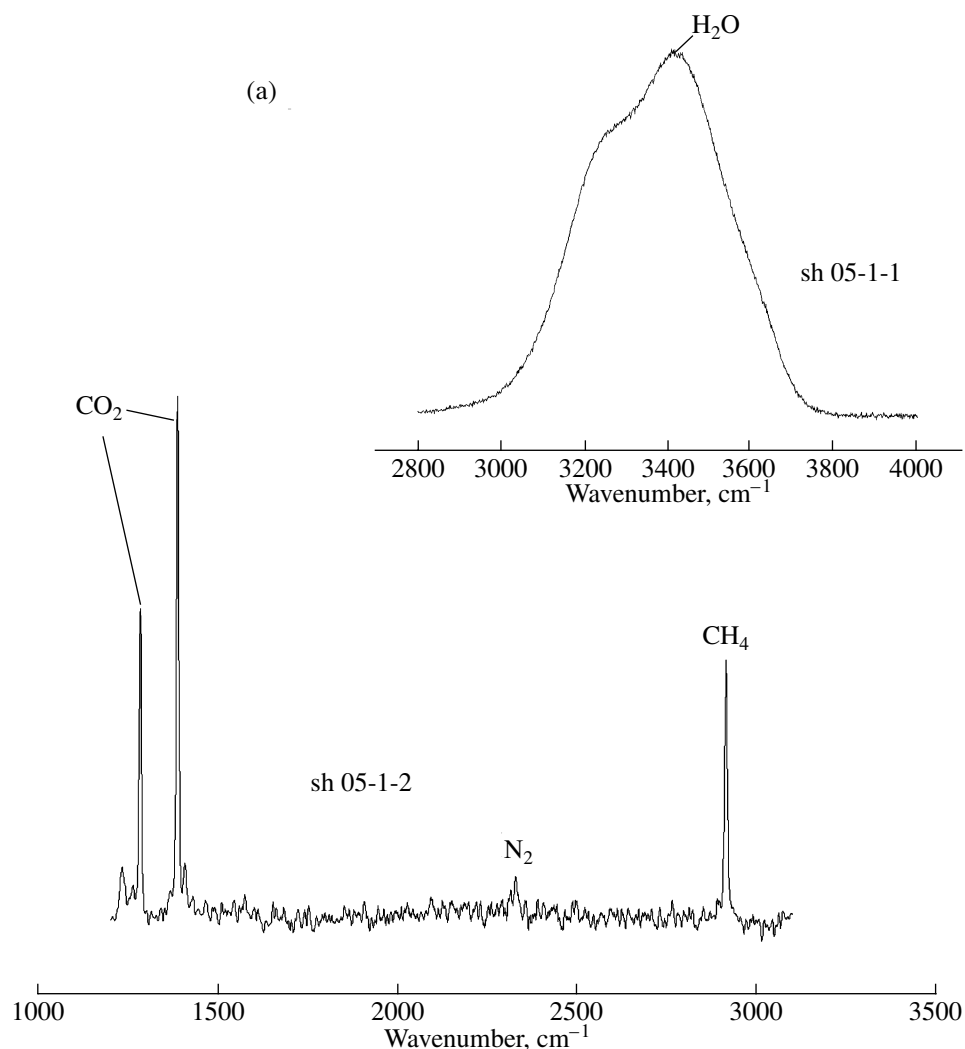


Fig. 5. Raman spectra: (a) N₂–CH₄–CO₂ (sample sh05-1-2) and aqueous (sh05-1-1) inclusions in quartz from amphibolized orthopyroxenite; (b) N₂–CH₄–CO₂ inclusions in quartz from massive ore (sh28-8 and sh28-9). The Shanuch pluton.

composition of Cu–Ni deposits in the Kola Peninsula, showed that enrichment in CH₄, H₂, and N₂ is characteristic of most sulfide deposits in this region. Taking these data into account, the presence of methane in FIs from rocks of the Shanuch pluton can be regarded as evidence for its enrichment in sulfides in comparison with rocks of the Kuvalrog pluton, where mainly FIs from barren rocks were studied. Nevertheless, rare CH₄-bearing inclusions from these rocks are closely related to sulfides. These FIs are located near sulfide grains and are hosted in the fractures radiating from these grains (Fig. 2a).

Such an arrangement of inclusions indicates that they mark the release of volatiles from a sulfide drop. Numerous FIs have been detected in monomineral quartz lenses hosted in the massive sulfide ore from the Shanuch pluton (Fig. 4d). These lenses are completely incorporated into the sulfide matrix and are broken by a system of fractures that control the localization of both

FIs and sulfide veinlets. Therefore, it may be assumed that sulfide melt was a source of volatiles that fill FIs.

In our opinion, the empirical relationship between the fluid regime of mafic–ultramafic intrusions and magmatic sulfide mineralization, which has been recognized previously and confirmed by this study, may be interpreted as follows.

In contrast to the traditional view, sulfide melt, like silicate magma, may dissolve a great amount of volatiles. The opinion on the “dryness” of sulfide melt, i.e., the absence of dissolved fluid in it, became firmly established after the experimental study of water solubility in it by Naldrett and Richardson (1967). Experiments have shown that no appreciable amounts of water are soluble in sulfide liquid. However, the experimental results are inconsistent with geological observations. In studying Cu–Ni deposits, geologists pointed out long ago that sulfide bodies are accompanied by wide halos of hydrothermal alteration (Polferov, 1966; Gor-

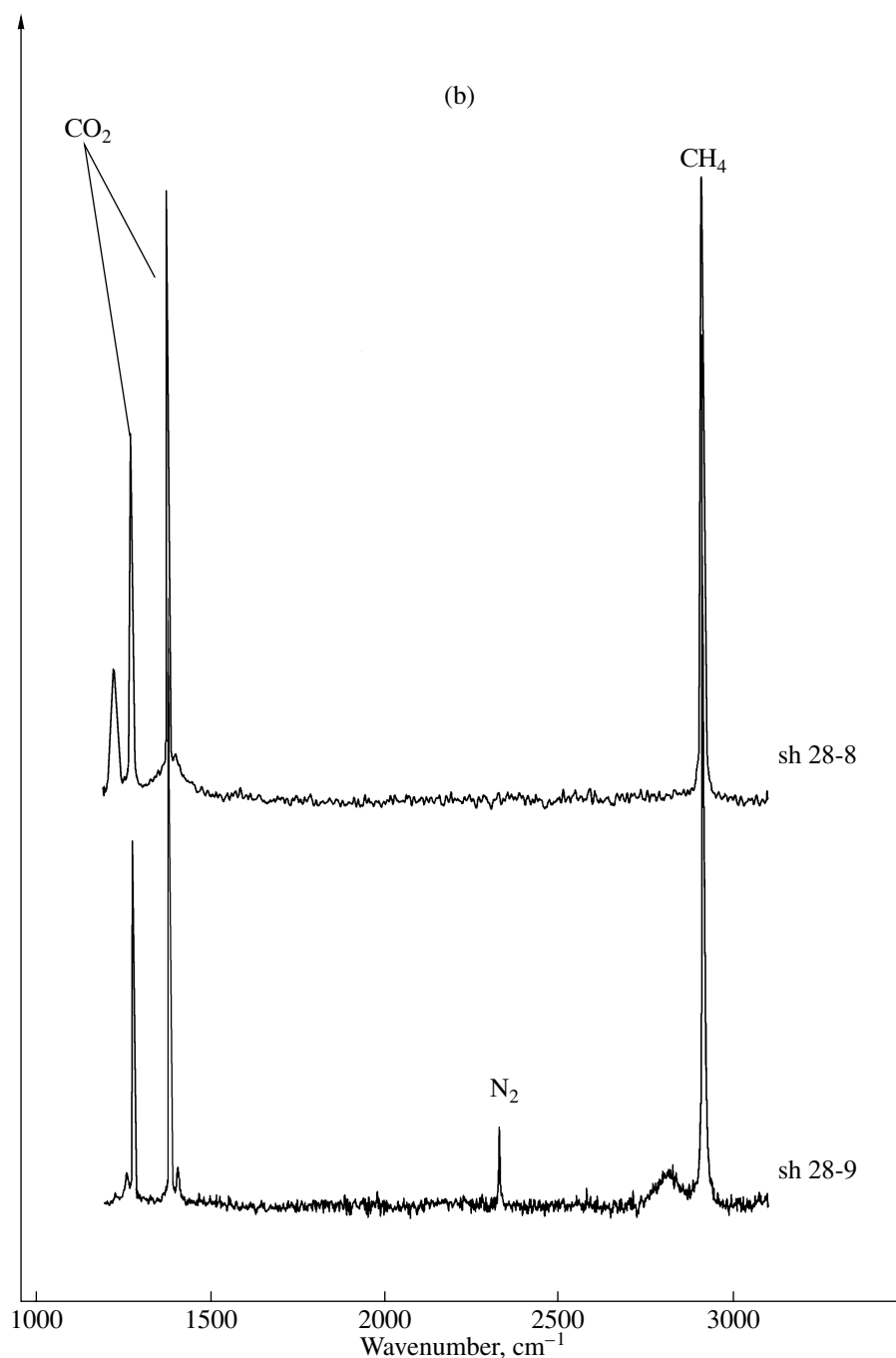


Fig. 5. (Contd.)

bunov, 1968). Genkin et al. (1979) described caps of hydroxyl-bearing minerals above sulfide segregations in taxitic gabbrodolerite of the Noril'sk intrusions. These facts unambiguously indicate a high concentration of fluids in sulfide liquids responsible for the formation of Cu–Ni ores. Inconsistence between the low crystallization temperature of sulfide ore estimated from paleothermometry (400–600°C, after Gorbunov, 1968) and the higher crystallization temperature of “dry” sul-

fide melts established in experiments (850–1050°C, after Craig et al., 1967) also supports a high fluid concentration in sulfide liquid. In addition, new experimental data demonstrate a high capacity of sulfide melts in respect to oxidized fluids (Konnikov et al., 2004; Wykes and Mavrogenes, 2005).

As follows from gas chromatography and mass spectrometry of gases extracted from pores and FIs of Cu–Ni sulfide ore (Neruchev and Prasolov, 1995),

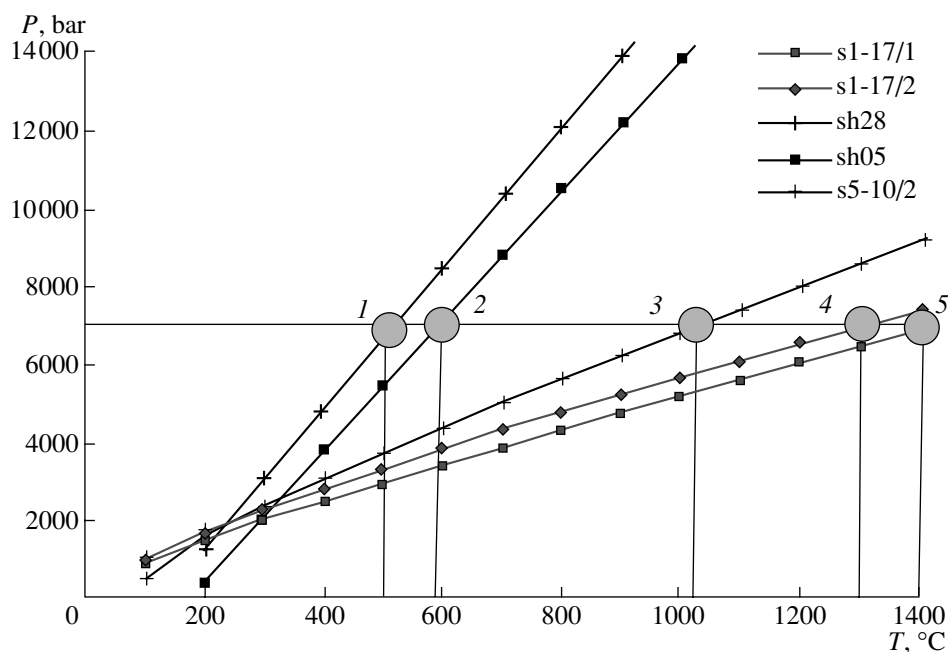


Fig. 6. Isochores calculated with the package FLUIDS 1 (Bakker, 2003) for pseudosecondary inclusions from the Kuvalrog (s1-17/1, s1-17/2, and s5-10/2) and Shanuch plutons (sh5 and sh28).

reduced gases and hydrocarbons, including methane, predominate among fluids dissolved in sulfide melts. Unfortunately, no experimental data on the solubility of reduced gases in sulfide melt are available to date. However, as judged from the solubility of a $\text{H}_2\text{O}-\text{CO}_2$ mixture (Konnikov et al., 2004), it may be assumed that H_2 , CH_4 , and CO concentrations in sulfide liquid should be higher than those in coexisting silicate melt. If this is the case, then the fluid phase released after crystallization of sulfide-bearing magma should be enriched in reduced gases, including methane. We suggest that this late magmatic fluid is recorded in the composition of pseudosecondary and secondary inclusions hosted in minerals at the Shanuch deposit. Intense serpentinization of olivine in cortlandite and replacement of pyroxene with amphibole, biotite, and quartz are probable related to this fluid.

Thus, the correlation between the gas composition and the sulfide content in rocks from the Kamchatka norite–cortlandite complex established by FI study corroborates the relationship between endogenetic mineralization in mafic–ultramafic complexes and mantle-derived flows of H_2 , CH_4 , and carbon (Lutz, 1980; Tomson et al., 2003).

CONCLUSIONS

(1) The composition of FIs from igneous rocks of the Kuvalrog and Shanuch plutons as typical representatives of the norite–cortlandite complex of Kamchatka has been established for the first time.

(2) These plutons differ in the composition of fluids associated with sulfide deposition. CO_2 and less frequent $\text{H}_2\text{O}-\text{CO}_2$ FIs with a small admixture of nitrogen prevail in the Kuvalrog pluton, whereas the Shanuch pluton is characterized by more abundant low-salinity $\text{CO}_2-\text{CH}_4-\text{N}_2$ and H_2O inclusions.

(3) Taking into account the predominant role of methane in ore-bearing intrusions at many sulfide deposits, the composition of FIs is suggested to be a criterion for estimation of the resource potential of the norite–cortlandite complex in Kamchatka with respect to the nickel sulfide mineralization.

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REFERENCES

1. R. J. Bakker, "Package FLUIDS 1. Computer Programs for Analysis of Fluid Inclusion Data and for Modeling Bulk Fluid Properties," *Chem. Geol.* **194**, 3–23 (2003).
2. R. Y. Bodnar and M. O. Vityk, "Interpretation of Microthermometric Data for $\text{H}_2\text{O}-\text{NaCl}$ Fluid Inclusions," in *Fluid Inclusions in Minerals: Methods and Applications. Short Course* (IMA, 1994), pp. 117–130.

3. E. A. J. Burke, "Raman Microspectrometry of Fluid Inclusion," *Lithos* **55**, 139–158 (2001).
4. J. R. Craig, A. J. Naldrett, and G. Kullerud, *Succession of Mineral Assemblages in Pyrrhotite-Rich Ores* (Carnegie Inst., Washington, 1967), pp. 431–435.
5. Z. Duan, N. Moller, and J. H. Weare, "A General Equation of State for Supercritical Fluid Mixtures and Molecular Dynamics Simulation of Mixture PVTX Properties," *Geochim. Cosmochim. Acta* **60**, 1209–1216 (1996).
6. A. D. Genkin, A. A. Filimonova, and V. S. Maslov, "Formation Mechanism of Veins and Deposits of Massive Noril'sk Copper–Nickel Ores," in *Main Parameters of Natural Processes of Endogenic Ore Formation* (Nauka, Novosibirsk, 1979), Vol. 1, pp. 118–128 [in Russian].
7. G. I. Gorbunov, *Geology and Origin of the Pechenga Sulfide Copper–Nickel Deposits* (Nedra, Moscow, 1968) [in Russian].
8. C. L. Knight and R. J. Bodnar, "Synthetic Fluid Inclusions: IX. Critical PVTX Properties of NaCl–H₂O Solutions," *Geochim. Cosmochim. Acta* **53**, 3–8 (1989).
9. E. G. Konnikov, E. M. Prosolov, and D. A. Orsoev, "Fluid Regime of Ni-Bearing Gabbro–Cortlandite Intrusives in the Southwestern Sredinny Range, Kamchatka," *Dokl. Akad. Nauk* **402** (4), 519–523 (2005) [*Dokl. Earth Sci.* **402** (4), 632–635 (2005)].
10. E. G. Konnikov, W. P. Meurer, S. S. Neruchev, et al., "Fluid Regime of Platinum Group Elements (PGE) and Gold-Bearing Reef Formation in the Dovyren Mafic–Ultramafic Layered Complex, Eastern Siberia, Russia," *Miner. Deposita* **35**, 526–532 (2000).
11. E. G. Konnikov, G. A. Pal'yanova, W. P. Meurer, et al., "Experimental and Theoretic Study of the Fluid Regime of Sulfide Cu–Ni–PGM Mineralization," in *Experimental Mineralogy: Some Results on the Turn of Centuries* (Nauka, Moscow, 2004), Vol. 1, pp. 315–326 [in Russian].
12. E. G. Konnikov, S. G. Simakin, D. A. Orsoev, et al., "Geochemistry and Formation Conditions of Nickel-Bearing Gabbro–Cortlandite Complex in Kamchatka," *Geol. Geofiz* **47** (12), 1287–1295 (2006).
13. E. G. Konnikov, V. M. Chubarov, V. A. Travin, et al., "Formation Time of the Ni-Bearing Norite–Cortlandite Association of East Asia," *Geokhimiya* **44** (5), 564–570 (2006) [*Geochem. Intern.* **44** (5), 508–515 (2006)].
14. B. G. Lutz, *Geochemistry of Oceanic and Continental Magmatism* (Nedra, Moscow, 1980) [in Russian].
15. A. J. Naldrett and S. W. Richardson, *Effect of Water on the Melting of Pyrrhotite–Magnetite Assemblages* (Carnegie Inst., Washington, 1967), pp. 429–431.
16. S. S. Neruchev and E. M. Prasolov, "Fluid–Geochemical Model of PGE Deposits Associated with Trap Magmatism," in *Platinum of Russia* (Geoinformmark, Moscow, 1995), Vol. II, Book 1, pp. 94–101 [in Russian].
17. V. A. Nivin and V. V. Chashchin, "Gas Component of Nickel-Bearing Mafic–Ultramafic Complexes of the Kola Peninsula in Context of Their Nickel Potential," *Geol. Rudn. Mestorozhd.* **38** (4), 378–380 (1996) [*Geol. Ore Deposits* **38** (4), 338–340 (1996)].
18. V. A. Poletaev, Candidate's Dissertation in Geology and Mineralogy (Moscow, 2004).
19. D. V. Polferov, "Sulfide/Silicate Ratio in Copper–Nickel Ores," *Geol. Rudn. Mestorozhd.* **8** (3), 49–62 (1966).
20. E. Roedder, *Fluid Inclusions in Minerals* (Reviews in Mineralogy, Mineral. Soc. Amer., 1984, Vol. 12; Mir, Moscow, 1987).
21. S. A. Shcheka and V. M. Chubarov, "Nickel-Bearing Cortlandites of Kamchatka," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 12, 50–61 (1987).
22. R. Thiéry, A. M. van den Kerkhof, and J. Dubessy, "VX Properties of CH₄–CO₂ and CO₂–N₂ Fluid Inclusions: Modeling for $T < 31^{\circ}\text{C}$ and $P < 400$ Bars," *Eur. J. Mineral.* **6**, 753–771 (1994).
23. I. N. Tomson, O. P. Polyakova, and T. A. Alekseeva, "Aureoles of Carbonaceous Metasomatism as Indicators of Ore Fields," *Dokl. Akad. Nauk* **393** (5), 656–658 (2003) [*Dokl. Earth Sci.* **393A** (9), 1239–1240 (2003)].
24. W. Wagner and A. Pruss, "International Equations for the Saturation Properties of Ordinary Water Substances. Revised According to the International Temperature Scale of 1990," Addendum to *J. Phys. Chem. Reference Data* **16**, 783–787 (1993).
25. J. Wykes and J. A. Mavrogenes, "Hydrous Sulfide Melting: Experimental Evidence for the Solubility of H₂O in Sulfide Melts," *Econ. Geol.* **100**, 157–164 (2005).
26. S. S. Zimin, *Nickel-Bearing Association of Hornblende Basic Rocks in the Far East* (Nauka, Novosibirsk, 1973) [in Russian].