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GEOCHEMISTRY

Oxygen and Hydrogen Isotopic Composition of the Fluid during Formation of Anthophyllite Metaultramafic Rocks in the Sysert Metamorphic Complex, Central Urals

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Abstract—The oxygen ($\delta^{18}O$) and hydrogen (δD) isotopic composition of H_2O-bearing minerals was studied for the ore-bearing amphibole metaultramafic rocks, which are the products of the early regional (435 ± 44 Ma) and late local (260 ± 6 Ma) silicic metasomatose in the Sysert metamorphic complex. The gold–sulfide mineralization of the Karas'evogorskoe deposit and anthophyllite–asbestos bodies of the Tersut deposit are related to the regional and local metasomatose combined with plagiogranitization and potassium granitization, respectively. The H_2O-bearing minerals of metasomatites (anthophyllite, tremolite, talc) of the Karas'evogorskoe and Tersut deposits are characterized by heavier $\delta^{18}O$ (9.8 to 12.2 and 7.6 to 9.4‰, respectively) and lighter δD (87 to –91 and –56 to –67‰, respectively) values. The calculated isotopic composition of the fluid in equilibrium with these minerals indicates a heterogeneous source of water for the fluids related to the formation of metasomatites and the metamorphic origin of fluids. During the regional metasomatose, this fluid was a result of equilibrium of the deep fluid with volcanosedimentary rocks enriched in the heavy oxygen isotope. At the local metasomatose, the metamorphic fluid was formed by interaction of magmatic water produced by potassium granitization with ultramafic rocks.

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The studied metaultramafic rocks are considered by most researchers as a component of the ophiolite association [1–3]. They are presumably of Riphean age and are localized in the schist framework of the Archean–Proterozoic gneiss–migmatite cores of some metamorphic complexes of the Urals (Ufalei, Sysert, Vishnevogorsk–Ilmenogorsk). The long-term tectonic, magmatic, metamorphic, and metasomatic processes during formation of these complexes strongly transformed the mafic–ultramafic rocks into anthophyllite rocks with gold–sulfide mineralization and economic bodies of anthophyllite–asbestos [4].

The metaultramafic anthophyllite rocks in the Sysert metamorphic complex were formed during the regional and local silicic metasomatose synchronously with plagiogranitization (435 ± 44 Ma) and potassium granitic magmatism (260 ± 6 Ma) [2, 5], respectively.

The silicic metasomatose was preceded by zonal regional dynamothermal metamorphism, which resulted in formation of enstatite–olivine, talc–olivine, olivine–antigorite, and antigorite metaultramafic rocks.

The silicic metamorphic metasomatites of the regional stage (anthophyllite, tremolite–anthophyllite, anthophyllite–chlorite–talc–tremolite, and talc rocks) host gold–sulfide mineralization. The local silicic metasomatose resulted in transformation of metaultramafic rocks into talc–carbonate–anthophyllite rocks with veinlike anthophyllite–asbestos areas.

This study presents the first data on the oxygen and hydrogen isotopic composition of minerals of anthophyllite rocks, which indicates the metamorphic origin of silicic ore-bearing fluids and their isotopic reservoirs.

The anthophyllite rocks of the Karas'evogorskoe gold–copper and Tersut anthophyllite–asbestos deposits were the objects of study. These deposits are localized in the Tashkul zone of metamorphic schists of the Middle Riphean Igish and Saitovo formations, which frames the Shumikha gneiss–migmatite structure from the west (Fig. 1). The rocks of the zone include biotite and muscovite–biotite plagioschists, amphibolites, quartzites, and metaultramafic rocks, which transit into gneisses, granitic gneisses, and amphibolites of the Early Proterozoic Chernovskaya Formation. The complex of metamorphic rocks hosts bodies and dikes of palyngenic–anathectic potassium granites of various thicknesses, which intrude all the rocks including metaultramafic ones.

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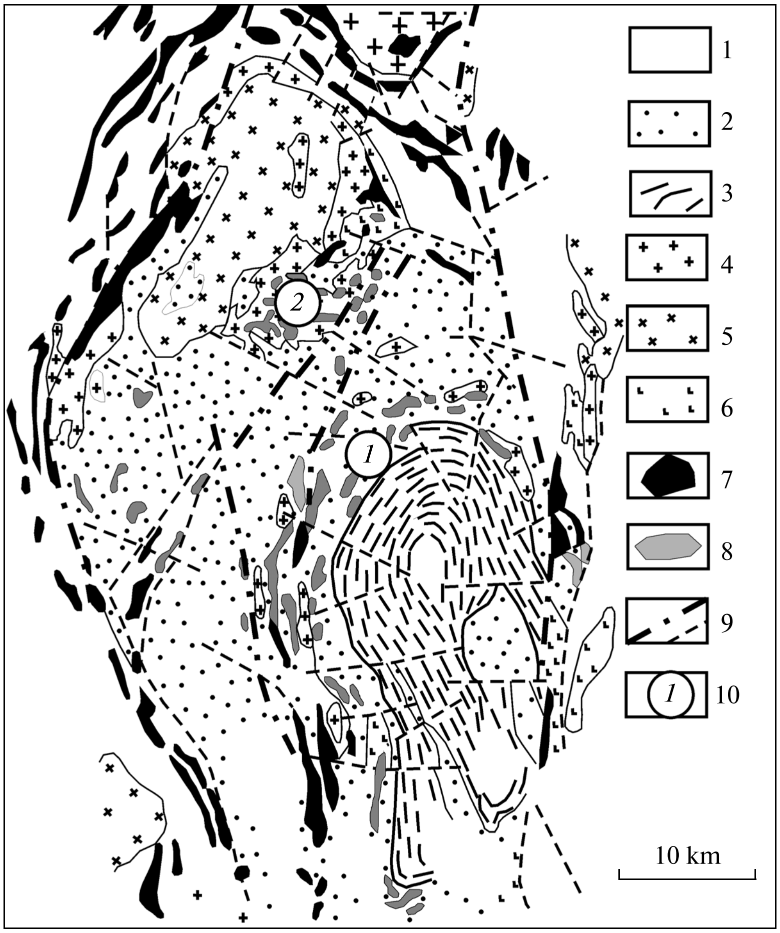

Fig. 1. Position of the studied objects on a geological scheme of the northern part of the Sysert–Vishnevogorsk metamorphic complex, simplified after G.A. Keil'man and G.A. Glushkova. (1) Lower to Middle Paleozoic volcanosedimentary rocks; (2) Riphean metamorphic rocks (graphitic quartzite, amphibolite, amphibole and biotite–amphibole gneiss); (3) Archean–Proterozoic gneiss–migmatite complexes (gneiss, granitic gneiss, migmatite); (4) granite; (5) plagiogranite, quartz diorite, granodiorite; (6) amphibolite after gabbro, gabbro; (7) serpentinite, talc–carbonate rock; (8) anthophyllite rock; (9) faults; (10) deposits: (*1*) Karas'evogorskoe, (*2*) Tersut.

The gold–copper mineralization of the Karas'evogorskoe deposit includes massive and disseminated ores in anthophyllite and tremolite–anthophyllite metasomatites with minor carbonate, chlorite, talc, and sulfides. The geochemical spectrum of ores (Fe, Cu, Ni, Co, Ti, P, Zn, Au, Ag, Bi, U, Mo, Te, Se) is a combination of elements of ultramafic, mafic, and granitic profiles [6]. The minerals of the productive stage (chlorite, siderite, Cu, Fe, Ni, and Co sulfides, Bi and Ag tellurides and selenides, native bismuth and gold, and uraninite) were deposited after anthophyllite and finish the transformation of the ultramafic rocks into amphibole metasomatites. The study of fluid inclusions in minerals from anthophyllite metasomatites allowed us to conclude that sulfide ores were formed from the fluid of the regressive stage of plagiogranitization and regional silicic metasomatose with dominant Na over K (Na/K = 8) [7]. At the same time, both amphibole metasomatites and sulfide ores were metamorphosed under the influence of late granitic dikes.

The Tersut anthophyllite–asbestos deposit is located in the southeastern contact of the Sysert granitic pluton (Fig. 1). The structure of the asbestos-bearing ultramafic bodies is zonal [8] with secondary enstatite and olivine–enstatite rocks in the central parts, enstatite–anthophyllite and talc–carbonate–anthophyllite rocks in the intermediate zone, and significantly talc rocks in the marginal zones. The anthophyllite–asbestos areas are mostly confined to the intermediate zone. The ultramafic bodies exposed by the open pits during exploration of anthophyllite–asbestos host numerous dikes of muscovite–biotite granites, aplites, and pegmatites with contact-metasomatic rims composed of phlogopite, chlorite, talc, and talc–carbonate zones.

We analyzed the oxygen and hydrogen isotopic composition of H_2O-bearing minerals of metasomatites and calculated the isotopic composition of water

Oxygen and hydrogen isotopic composition of minerals and calculated water isotopic composition of the fluid during formation of ores from the Karas'evogorskoe deposit and anthophyllite–asbestos of the Tersut deposit

Sample number	Rock	Minerals	Isotopic composition of minerals, ‰ (SMOW)		Isotopic composition of the fluid water at different temperatures (°C)									
					400		500		600		700		800	
			$\delta^{18}O$	δD	$\delta^{18}O$	δD	$\delta^{18}O$	δD	$\delta^{18}O$	δD	$\delta^{18}O$	δD	$\delta^{18}O$	δD
Karas'evogorskoe deposit														
555	Subore amphibole metasomatite	Anthophyllite	12.2	−87.1	13.4	−42	13.9	−55	14.1	−64	–	–	–	–
550	Supraore amphibole metasomatite	Tremolite	9.8	−90.6	11.0	−46	11.5	−59	11.7	−67	–	–	–	–
Tersut deposit														
1710	Carbonate–talc–anthophyllite rock	Talc	8.4	−65.7	7.5	−33.5	8.3	−35.5	8.8	−36.8	9.1	−37.8	–	–
1716	Talc–anthophyllite rock	Anthophyllite	9.4	−66.2	10.6	−21	11.1	−31.1	11.3	−42.7	11.3	−48.9	–	–
		Talc	9.3	−56.2	8.3	−24.0	9.2	−26.0	9.7	−27.3	10.0	−28.3	–	–
1709	Carbonate–talc–chlorite–anthophyllite rock	Anthophyllite	7.6	−59.8	8.8	−15.0	9.3	−27.7	9.5	−36.3	9.5	−42.5	–	–
		Talc	8.3	−66.8	7.2	−34.6	8.2	−36.6	8.7	−37.9	9.0	−38.9	–	–
1717	Schlieren of biotite from granitic gneiss	Biotite	7.4	−82.1	–	–	–	–	9.9	−51.4	9.9	−56.8	9.6	−60.8

The analyses were carried out in the Analytical Center of the Far East Geological Institute, Far East Branch, Russian Academy of Sciences (analyst T.A. Velivetskaya). The accuracy of determination (1σ) is $\delta^{18}O \pm 0.1‰$, $\delta D \pm 1‰$.

of the fluid in equilibrium with minerals (table). The latter was calculated using an isotope calculator [9] for the temperature range of formation of amphiboles of the Karas'evogorskoe deposit of 400–600°C at the regressive branch of amphibole facies of metamorphism. The same range expanded to 700°C was accepted for the temperature conditions of anthophyllitization with the formation of anthophyllite–asbestos estimated by different authors as 420–500°C [10] and 600–700°C [8]. The temperature range of 600–800°C was accepted for calculation of the water isotopic composition in equilibrium with biotite of granitic gneiss. The calculation of the oxygen ($\delta^{18}O_{H_2O}$) and hydrogen ($\delta^{18}D_{H_2O}$) isotopic composition of water is based on reactions of isotopic equilibrium of anthophyllite, tremolite, talc, and biotite with water [11–13] and hornblende, biotite, and chlorite with water [14, 15], respectively.

The H_2O-bearing minerals of the studied deposits are distinct in isotopic composition: amphiboles of the Karas'evogorskoe deposit are characterized by higher $\delta^{18}O$ and lower δD values relative to anthophyllite and talc of the Tersut deposit (table).

The calculated data of the oxygen and hydrogen isotopic composition of the fluid ($\delta^{18}O_{fl}$ and δD_{fl}, respectively) in formation of metasomatites and gold–copper ores of the Karas'evogorskoe deposit indicate a metamorphic character of the fluid (Fig. 2). The δD_{fl} values for all temperatures correspond to the values of the juvenile water ($\delta D_{fl} = -48 \pm 20$‰), whereas $\delta^{18}O_{fl}$ values are significantly heavier relative to both juvenile ($\delta^{18}O_{fl}$ = 6–7‰) and magmatic ($\delta^{18}O_{fl}$ = 6–10‰) water. We suggest that metamorphic fluid for gold–copper mineralization was a result of equilibrium of juvenile or magmatic water of the plagiogranitization stage with silicic sedimentary rocks of the ophiolite substrate enriched in isotopically heavy oxygen. This model corresponds to the regional character of silicic metasomatose, which embraces both ultramafic and country rocks.

The hydrogen and oxygen isotopic composition of the fluid in equilibrium with biotite of the granitic gneiss of the Tersut deposit corresponds to the magmatic water in contrast to metamorphic water for the fluid in equilibrium with anthophyllite and talc of asbestos bodies. The $\delta^{18}O_{fl}$ value of metamorphic water is similar to that of magmatic water; however, it is characterized by a heavier hydrogen isotopic composition. The reservoir of isotopically heavier hydrogen is unclear. The participation of seawater in these processes is problematic. An ultramafic source of water is also unlikely because of anthophillitization of water-free olivine–enstatite rocks. It may be suggested that the isotopic composition of magmatic water became heavier due to fractionation of hydrogen isotopes upon hydration of olivine and enstatite accompanied by extraction of free hydrogen.

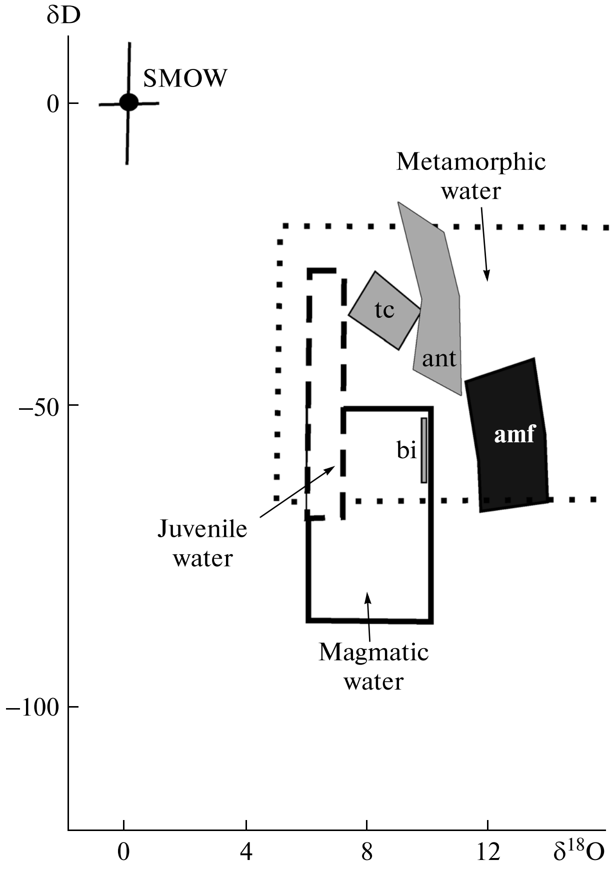

Fig. 2. Calculated oxygen and hydrogen isotopic composition of water (‰ SMOW) in equilibrium with amphibole (amf) of the Karas'evogorskoe gold–sulfide deposit and with talc (tc), anthophyllite (ant), and biotite (bi) of the Tersut deposit of anthophyllite–asbestos deposit.

Thus, the fluids that produced anthophyllite metasomatites were characterized by a heterogeneous source of water and were metamorphic in origin. During the regional silicic metasomatose, this fluid was a result of equilibrium of the deep fluid and volcanosedimenatry rocks enriched in the heavy oxygen isotope. At the local silicic metasomatose, the metamorphic fluid was formed after interaction of magmatic water produced by the potassium granitization with ultramafic rocks.

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