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GEOCHEMISTRY

Potassium Feldspar from Vein Systems and Their Aureoles at the Epithermal Asachin Gold–Silver Deposit, Southern Kamchatka

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Potassium feldspars are typical of propylite and gangue mineral assemblages of epithermal low-sulfide and sulfide gold–silver deposits in Kamchatka, Japan, New Zealand, Indonesia, Papua New Guinea, Eastern Australia, the western coast of the United States, and other regions of the Pacific metallogenic belt. It is generally considered that K-feldspars at these deposits are mainly represented by adularia. According to the modern classification of alkali feldspars, adularia is a water-transparent low-temperature K-feldspar with a low content of isomorphous admixtures of any structural modifications, including sanidine, orthoclase, and microcline [1]. Recent decades have been marked by the publication of numerous works devoted to triclinic and monoclinic varieties of adularia [2, 3], including sanidine [4–6], orthoclase [7], and microclines [8] determined by structural methods. However, adularia is traditionally referred to monoclinic feldspars or intermediate microclines with insignificant deviation from monoclinic symmetry [1]. K-feldspars of unknown structure are often conditionally termed adularia. At the majority of the aforementioned deposits, adularias have been distinguished only based on morphological features. At the same time, the determination of structural modification of K-feldspars (Si/Al ordering) is important for reconstruction of their geological evolution.

In this paper, we report a detailed structural study of potassium feldspars from the epithermal Asachin gold–silver deposit (southern Kamchatka) ascribed to the low-sulfide quartz–adularia type [9].

The gold–silver mineralization of the Asachin deposit is mainly localized in veins, with subordinate significance of associated stockwork–disseminated zones.

To identify macrozones of K-metasomatism in specimens and core samples cut parallel to the long axis, we applied during field documentation a slightly modified technique of specific K-feldspar coloration, which was previously developed for studying thin sections [10]. This method allowed us to outline roughly the distribution areas and to highlight the details of the K-metasomatism zone. Adularias from vein rocks and their aureoles (60 samples) were identified with X-ray and IR spectroscopy.

The Al–Si–O framework of K-feldspar consists of four types of tetrahedra: T_1O, T_1m, T_2O, and T_2m. Because of the nonequivalent position of tetrahedra relative to the K cation, site T_1O is more favorable for Al. In the completely ordered structures (maximum microcline), Al occupies site T_1O, while Si is allocated in sites T_1m, T_2O, and T_2m. Statistically uniform arrangement of Al and Si over all four sites corresponds to the extremely disordered state (high sanidine). In this case, we can distinguish only two sites (T_1 and T_2), because sites T_1O and T_2O do not differ from sites T_1m and T_2m, respectively. The degree of structural ordering of K-feldspar is quantitatively described by the Thompson coefficients X, Y, and Z [11, 12]. In monoclinic K-feldspars, $X = Y = 0$ (because sites O and m are indistinguishable). Recent structural refinements showed that the parameter $X \to 0$ even in the triclinic feldspars and can be omitted. The coefficient Y depends on allocation of Al between T_1O and T_1m, which defines the degree of triclinic ordering.

Figure 1 demonstrates XRD patterns of two typical quartz–feldspar vein aggregates from the Asachin deposit. K-feldspar is represented by high orthoclase in sample 228 (Fig. 1a) and maximum microcline in sample 476 (Fig. 1b). The degree of triclinic ordering (Δp)

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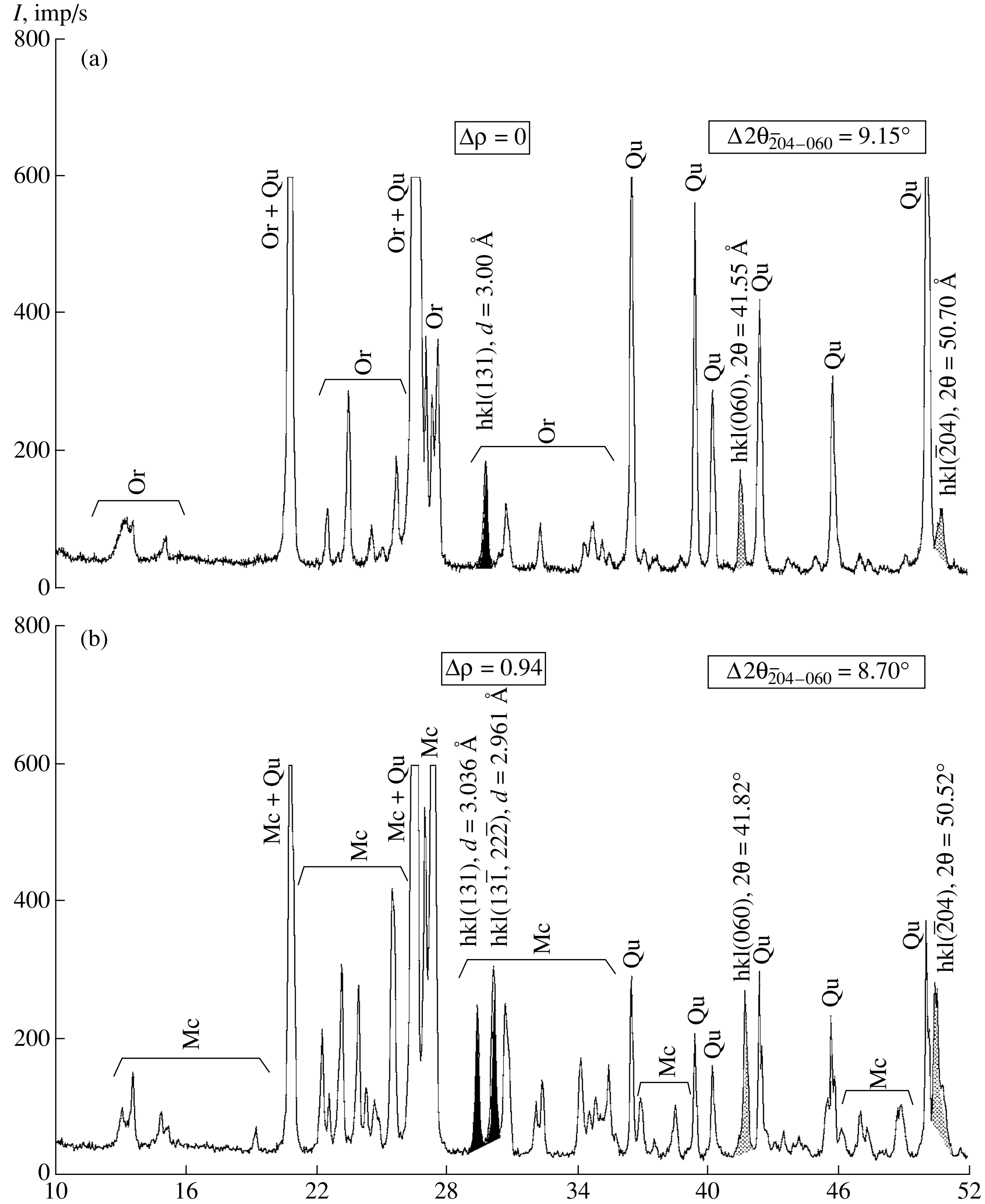

XRD patterns: (a) sample 228 (quartz–orthoclase aggregate), (b) sample 476 (quartz–microcline aggregate). Degrees are shown along the x-axis. (Or) orthoclase, (Mc) microcline, (Qu) quartz; Δρ the degree of X-ray triclinic ordering.

was experimentally determined from splitting of diffraction maximums with indices hkl = 131 and $1\bar{3}1$, which are located in the diagnostic angle region of 2θ = 28°–31° (CuK_{α} radiation), where θ° is the Wolf–Bragg angle. $\Delta p = 12.5\ (d_{131} - d_{131})$, where d is the interplanar spacing of the corresponding lines. Monoclinic potassium feldspars have $\Delta p = 0$ ($Y = 0$), while the completely ordered microclines have $\Delta p = 1$ ($Y = 1$). The coefficient Z (degree of monoclinic ordering) is calculated from the formula $Z = 1.39(9.42 - 2\theta^{\circ}_{204-060})$ [12]. The diagnostic area in the XRD pattern is the region 40°–52° (2θ°), which contains two reflections with hkl = $\bar{2}04$ and 060 (Fig. 1). The change in degree of Si and Al ordering in the K-feldspar lattice is reflected in the IR spectra. The quantitative estimate of IR ordering is calculated from the formula $Q = 0.05\ (\Delta\nu - 90)$ in the range from 0 to 1 [13]. The value $\Delta\nu = \nu_1 - \nu_2$ is determined as the difference between frequencies of the absorption band max-

Al distribution over tetrahedral sites of K-feldspars, Thompson variables (X, Y, Z), 2θ reflections 204 and 060, and $\Delta\rho$

Feldspar	Al $T_{1(O)}$	Al $T_{1(m)}$	Al $T_{2(O)}$	Al $T_{2(m)}$	Al $T_{1(O)}$ + + Al $T_{1(m)}$	X	Y	Z	$2\theta_{204-060}$	ρ
Sanidine (annealed Spencer C)	**0.26**	**0.26**	**0.22**	**0.22**	**0.52**	**0**	**0**	**0.08**	**9.35**	**0**
Orthoclase (Spencer C)	**0.345**	**0.345**	**0.125**	**0.125**	**0.69**	**0**	**0**	**0.44**	**9.07**	**0**
Orthoclase (sample 228)	0.335	0.335	0.148	0.148	0.67	0	0	0.38	9.15	0
Orthoclase (sample 599)	0.365	0.365	0.135	0.135	0.73	0	0	0.46	9.08	0
Orthoclase (sample 584)	0.38	0.38	0.13	0.13	0.76	0	0	0.50	9.06	0
Orthoclase (sample 260)	0.39	0.39	0.12	0.12	0.78	0	0	0.54	9.03	0
Orthoclase (Sample 615)	*0.385*	*0.385*	*0.095*	*0.095*	*0.77*	*0*	*0*	*0.58*	*9.00*	*0*
Adularia (Spencer B)	**0.405**	**0.405**	**0.08**	**0.08**	**0.81**	**0**	**0**	**0.65**	**8.90**	**0**
Intermediate microcline (Spencer U)	**0.63**	**0.235**	**0.045**	**0.03**	**0.865**	**0.015**	**0.395**	**0.79**	**8.83**	**0.35**
Intermediate microcline (sample 477)	0.835	0.095	0.035	0.035	0.93	0	0.74	0.86	8.78	0.74
Maximum microcline (Pellotsalo)	**0.97**	**0.015**	**–0.1**	**0**	**0.985**	**–0.01**	**0.955**	**0.97**	**8.78**	**0.97**
Maximum microcline (sample 476)	0.97	0.03	0	0	1.0	0	0.94	1.0	8.70	0.94

Note: (Sample 228) vein, borehole 74 111, depth 146.0–147.0 m; (sample 599) vein, borehole 74116, depth 192 m; (sample 584) vein, borehole 7402, depth 86.3 m; (sample 260) vein, borehole 7436, depth 118.5 m; (sample 615) adularia metasomatite, borehole 74116, depth 29.5 m; (sample 477) vein, borehole 7437, depth 109.0 m; (sample 476) vein, borehole 7437, depth 108 m. Standard feldspar from the reference book is shown in bold [11]. Adularia from potassium metasomatites are italicized.

imums in the regions of 600–650 cm^{-1} (ν_1) and 500–550 cm^{-1} (ν_2). With a decreasing degree of ordering, the maximums of bands ν_1 and ν_2 become closer and $\Delta\nu$ regularly decreases from microclines to sanidines. The degree of IR ordering (Q) is 0.8–1 for microclines, 0.1–0.8 for orthoclases, and 0–0.1 for sanidines. Unfortunately, in this region, the frequencies of some bands of analyzed K-feldspars are overlapped by bands of quartz closely intergrown with K-feldspar. Nonetheless, a significantly lower degree of K-feldspar ordering (sample 228) was recorded from the low-frequency shift of the maximum of the band ν_1, the sharp decrease in the occurrence of fine structure of bands in the region of 650–520 cm^{-1}, and their widening. The Q value for K-feldspar from sample 476 is 1 (i.e., maximum for microclines) and only ~0.2 (orthoclase) for K-feldspar from sample 228, which is quite consistent with XRD data.

K-feldspar is present in the propylite assemblages of hydrothermally altered rocks, which accompany vein bodies, veins, and stockworks. We can distinguish the following structural types of metasomatites: massive adularia zones, K-metasomatites with rare spots of unaltered rhyolites, areas of successive alternation of adularia zones and host rocks, and local zones of near-fissure adularization. The Au-bearing veins of the Asachin deposit are armored by aureoles of adularia metasomatites up to 300–400 m thick and traced to a depth of 200 m. The outer contact zones of veins are often accompanied by microspherulite adularia metasomatites (up to 3–5 m thick), which are indirect evidence for elevated gold potential. Individual spherulites (1–5 mm across, occasionally up to 10 mm) have a concentric-zonal structure related to alternation of milky white quartz and adularia rims with fine-grained ore in the core. The northern and southern flanks of the main ore zone are characterized by a decrease in the intensity of K-metasomatism and local appearance of near-fissure adularization zones, which are replaced by zones of intense argillic alteration along the strike.

The K-metasomatites consist of quartz, albite, and adularia with an admixture of mixed-layer illite–smectite, 1M mica (muscovite type), and chlorite. The products of argillic alteration are made up of a mixture of quartz, adularia, and 1M mica, which confirm previously published data [14]. All the aforementioned varieties of K-feldspars from vein aureoles have stable crystallographic parameters (table), which correspond to the Spencer B-type adularia standard [11].

The textural–structural features of veins are conformable to the contact surface. They are represented by drusy, sheaflike, comb-shaped, concentric-banded, cockade, colloform, radial-spherical, and cryptocrystalline types similar to those described in northern Queensland, Australia [15]. Cryptocrystalline ore minerals (gold–naumannite–selenopolybasite assemblage) developed as very fine dust, small spherical aggregates, and rare crystals are mainly confined to the boundaries of individual rhythms. The ore minerals emphasize structural–textural features of vein aggregates. K-feldspars from gangue assemblages show drastic compositional variations along the dip of high-angle ore bodies and make up the following continuous series: high orthoclase → intermediate orthoclase → intermediate microcline → maximum microcline (table). This series corresponds to the increase in triclinic degree and, correspondingly, Si/Al ordering. Similar tendencies are also observed across veins, in which the degree of K-feldspar ordering decreases from selvage to the central parts of the veins.

The intensity of gold–silver mineralization shows positive correlation with the K-feldspar content. Ore zones enriched in noble metals are mainly composed of K-feldspar aggregates. In particular, Au-rich central parts of the main ore zone of the Asachin deposit contain domains with up to 80–85% tabular pelitic unhatched microcline from 0.1–0.15 to 0.4–0.5 mm in size. The tabular microcline grades into equant or xenomorphic grains in some places. Quartz–microcline zones are confined to the central parts of the veins, while their peripheral areas are made up of quartz–orthoclase aggregates. The latter are dominated by fine-grained xenomorphic orthoclase and quartz grains up to 0.01–0.02 mm in size, among which water-transparent rhombohedral orthoclase crystals up to 0.5–0.1 mm in size occur. Individual areas contain coarser grained orthoclase-rich aggregates with grain size up to 1.0 mm. In texture and crystallographic appearance, the aforementioned varieties of gangue orthoclase and microcline differ sharply from the microglobular metasomatic adularia. The quartz–orthoclase and quartz–microcline veins are replaced along the dip into barren quartz–prehnite veins, with quartz–epidote–orthoclase vein aggregates in the transitional zones.

Thus, K-feldspars from the productive veins make up a continuous series from orthoclase to maximum microcline with increase in crystallochemical ordering. According to ^{39}Ar/^{40}Ar data obtained at the Analytical Center of the Institute of Geology and Mineralogy of the Siberian Division, Russian Academy of Sciences (A.V. Travin, analyst), the isochron age of quartz–orthoclase veins (sample 240) is estimated at 3.2 ± 0.2 Ma, while the quartz–microcline vein (sample 476) reveals evidence of superposition of the younger mineralization with an age no older than 1.1 ± 0.3 Ma. Judging from age spectra of the studied K-feldspars, the ores were formed in several stages. The quartz–microcline aggregate is relatively young and presumably represents the recrystallization product of quartz–orthoclase rocks.

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