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GEOCHEMISTRY

Duration of Migmatite Formation in the Granulite-Facies Metamorphism Zone of Svecofennides of the Ladoga Region, Southeastern Baltic Shield

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High-temperature metamorphism zone is characterized by partial melting of rocks and the generation of diverse migmatite leucosomes in the course of rock deformations leading to the structural and morphological diversity of rocks. Therefore, polymigmatites represent a unique rock assemblage, in which separate members of the evolution series related to the successive generation (crystallization) of leucosomes retain, to variable extent, characteristics of the evolving environment of mineral formation. Isotope dating of different-aged (with respect to geological relationships) leucosomes makes it possible to estimate the timing of ultrametamorphic events and respective deformations. The duration of metamorphism can also be determined with the highest precision. We solved this type of problem for polymigmatites that dominate in the Early Proterozoic metamorphic zone of the northern Ladoga region.

The Svecofennian polymigmatite complex of the Ladoga region is a member of the Svecofennian accretionary orogen that occupies the southern and southwestern parts of the Baltic Shield. The polymigmatites include as much as seven to eight generations of vein material with diverse petrological and geochemical characteristics [1–3].

The leucosomes are developed in the garnet–biotite, garnet–hypersthene, and garnet–cordierite–sillimanite–K-feldspar gneisses on a small island in Lake Ladoga. The migmatized gneisses occupy a large area of the island. Gneissosity and banding of these rocks are oriented in the submeridional or northwestern direction, while the dip is nearly vertical. In the eastern area of the island, the gneisses are crosscut by a small pluton of pinky red two-feldspar granites. The granites and gneisses show a distinct injection contact that fosters the development of injection migmatites in the thin outer contact zone.

Based on the contact type and relative age at the exposure, one can identify five generations of leucocratic veins (Fig. 1) with specific compositions, morphologies, and structures. The oldest veins in the gneisses occur as fragments of granite veins and veinlets up to 1–2 cm thick. In some fragments, one can see that these veins include at least two generations of leucosomes (generations 1 and 2). The total content of leucosomes of these generations does not exceed 10–15 vol % of the whole migmatized rock. Leucosomes of generation 3 make up patchy veins that resemble shadow granites in some places. Veins of generation 3 are up to dozens of centimeters thick. Leucosomes of this generation are most widespread at the exposure. They are probably

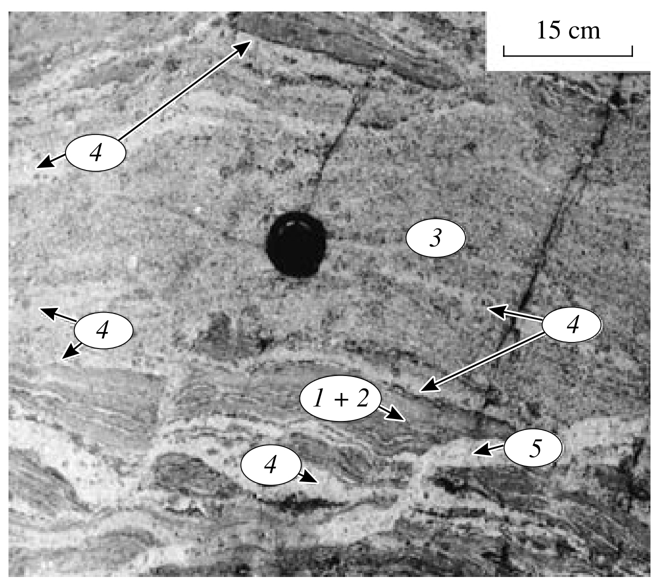

Fig. 1. Photomicrograph of a fragment of the exposure of polymigmatites. Vein material of the gneisses includes no less than five generations (numbers in the ellipses).

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Results of the U–Pb isotopic study of monazite from different-aged leucosomes and boudinaged dike

Ord. no.	Fraction, μm	$^{206}Pb^{a}/^{204}Pb$	$^{207}Pb^{b}/^{206}Pb$	$^{208}Pb^{b}/^{206}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	Th/U	*Rho*	Age, Ma				MSWD/*P*
									$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Concordant age	
No. B-02-78/10 (boudinaged dike, orthogneiss)													
1	Whole-rock	3665	0.11402	6.1209	5.286	0.3362	17	0.92	1868.4	1866.5	1864.5	1865.0 ± 1.5	0.61/0.43
2	Whole-rock	19050	0.11421	5.8883	5.298	0.3364	16	0.93	1869.6	1868.5	1867.4	1868.0 ± 2.9	0.13/0.72
No. B-02-78/11 (vein of generation 3)													
3	>150	11020	0.11448	4.0293	5.343	0.3385	11	0.98	1879.5	1875.8	1871.6	1872.2 ± 1.7	3.3/0.07
4	100–150	11980	0.11440	4.3313	5.331	0.3380	12	0.97	1876.9	1873.8	1870.5	1870.9 ± 2.1	2.4/0.12
No. B-02-78/12 (vein of generation 4)													
5	Whole-rock	3615	0.11436	7.3601	5.304	0.3364	20	0.95	1869.1	1869.5	1869.8	1869.7 ± 2.5	0.01/0.93
No. B-02-78/13 (vein of generation 5)													
6	Large (>50–80)	1654	0.11366	7.9390	5.257	0.3355	22	0.94	1864.8	1861.9	1858.8	1859.9 ± 2.7	1.4/0.23
7	Fine (<50)	3443	0.11354	8.2531	5.199	0.3321	23	0.94	1848.7	1852.5	1856.8	1855.4 ± 2.7	3.3/0.07

Note: (a) Isotope ratios are corrected for the fractionation and common Pb; (b) isotope ratios are corrected for the fractionation, procedure blank, and common Pb; (*P*) probability of concordance. Mineral decomposition and separation of Pb and U were carried out following the Krogh technique [10]. The procedure blank was no more than 0.1 ng for Pb and 0.01 ng for U. The Pb and U isotopic measurements were performed on an MAT-261 mass spectrometer. Measurement error of Pb/U isotopic ratios was 0.5% (2σ). All calculations were performed with the Ludwig program [11, 12].

related to maximal melting in situ. This is indicated, for example, by the dependence of mineral and chemical compositions of the veins on the composition of host gneisses. Leucosomes of generation 3 are crosscut by coarse-grained garnet-rich veins of generation 4. These veins extend along the strike over 3–6 m. Leucosomes of generations 1–4 are folded and conformal relative to the enclosing gneisses. The youngest, obliquely cutting pegmatite–granite veins of generation 5 extend over tens of meters and vary in thickness from 2–3 to 20–30 cm.

The exposure also includes small (up to 1–3 m) melanocratic orthogneiss boudins with abundant biotite, amphibole, and hypersthene. The deformed and migmatized boudins are conformal with the enclosing gneisses.

The mineral composition of all leucosomes is rather simple. They mainly differ in terms of the proportion of the major minerals (biotite, garnet, K-feldspar, plagioclase, and quartz).

Thermobarometric estimates based on the composition of coexisting minerals [2, 4] indicate that leucosomes of generation 1 in the polymigmatic complex of the Ladoga region formed at ~800–900°C and 5–6 kbar. The high *PT* stage of metamorphism is marked by the appearance of Grt–Opx ± Kfs-, Cpx–Opx-, Grt + Cdr + Kfs assemblages* in gneisses that enclose the oldest leucosomes. Petrographic observations suggest that the younger leucosomes are coeval with the development of cordierite in garnets of the substrate. Redistribution of Fe and Mg between garnets and the newly formed cordierite indicates the formation of leucosomes at 800–600°C [2]. Analysis of gneisses and veins based on the garnet–biotite geothermometer indicates that the temperature of the enclosing rocks was 650–500°C during the formation of the youngest granite veins [2].

Data on CO_2-rich inclusions in leucosomes [2, 5] show that the pressure remained stable at ~4–6 kbar at initial stages of ultrametamorphism. The pressure dropped to 2–4 kbar during the formation of late veins, suggesting the cooling of rocks in the course of decompression.

In order to minimize the contamination of sample with the protolith material, we took samples from the largest and well-isolated leucosomes of generations 3–5 (samples B-02-78/11, B-02-78/12, and B-02-78/13). In addition, we investigated a sample of migmatized orthogneiss boudin.

* Mineral abbreviations: (Crd) cordierite, (Cpx) clinopyroxene, (Grt) garnet, (Kfs) K-feldspar, and (Opx) orthopyroxene (hypersthene).

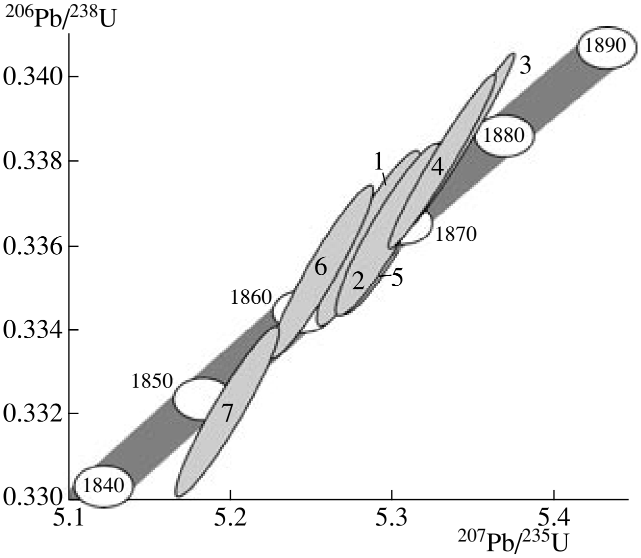

Fig. 2. Diagram with the Wetherill's concordia for monazites from leucosomes and veins of various generations. Numbers in the ellipses correspond to those of analyzed samples in the table.

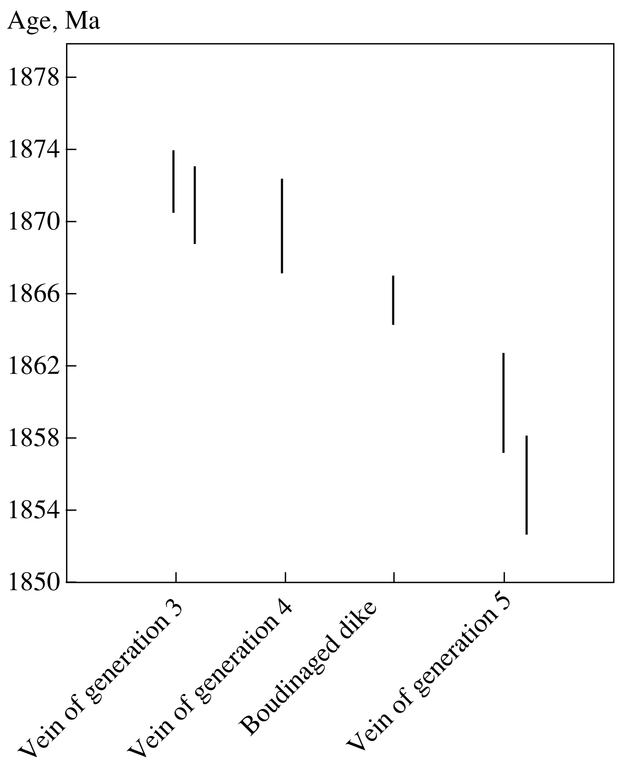

Fig. 3. Sequence of the formation of vein material in polymigmatites based on the U–Pb monazite dating. Age ranges are shown with the consideration of 2σ error (error of the determination of half-decay period was ignored).

Monazite samples were extracted from the leucosomes. If the samples contained different grain sizes, they were divided into the coarse (50–80 μm or more) and fine (< μm) fractions. The results obtained are shown in the table.

Leucosome no. 3 (B-02-78/11) yielded two monazite fractions with a similar U–Pb date of 1871.7 ± 1.3 Ma (MSWD = 0.93, probability = 0.34).

Leucosome no. 4 (B-02-78/12) yielded the concordant U–Pb monazite date of 1869.7 ± 2.5 Ma (MSWD = 0.01, probability = 0.93).

Leucosome no. 5 (B-02-78/13) contains two monazite fractions. The coarse fraction yielded the U–Pb monazite date of 1859.9 ± 2.7 Ma, while the fine fraction is slightly younger (1855.4 ± 2.7 Ma).

The orthogneiss sample (B-02-78/10) also contains two monazite fractions with an average age of 1865.6 ± 1.3 Ma (MSWD = 1.4, probability = 0.07).

In the Vezerilla plot (Fig. 2), all data points of the monazite samples fall into or near the concordia line, suggesting a good preservation of the U–Pb isotope system in the mineral. The minor but steady discrepancy observed between the coarse and fine fractions can be explained by a later closure of the U–Pb isotope system in fine monazite grains, according to the 3D diffusion model [6].

Data presented in this paper indicate that the duration of the formation of different generations of leucosome, including the latest granite veins, is no less than 10–15 Ma (Fig. 3). If one takes into consideration the fact that the oldest leucosomes appeared at the peak of metamorphism (~1880 Ma ago [7]), the total duration of the formation of leucocratic veins in the ultrametamorphism zone of the Ladoga region amounts to ~20 ± 5 Ma. This estimate is in good agreement with the estimate of duration of the main stage of plutonic metamorphism in the studied part of Svecofennides. In particular, results of the isotopic–geochronological study of plutons demonstrate that the plutonic metamorphism was constrained by an age boundary of 1880–1860 Ma [7, 8]. The results obtained are also consistent with results of the U–Pb and Sm–Nd investigation of minerals from the leucosome sequence of plagiomigmatites in Svecofennides of Finland [9].

Thus, results of the dating of leucosomes indicate that the sequence of polymigmatite formation can be considered a prolonged event with a duration of no less than 20 Ma. Initial stages of ultrametamorphism are related to the peak of plutonometamorphic activity in Svecofennides and the development of numerous anatectic melts. The consequent decrease in temperature, consolidation of rocks, and development of primarily brittle strains promoted the injection of melts from the lower horizons and the formation of the youngest granite veins.

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