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GEOLOGY

# Feldspar Thermometry of Ultrahigh-Temperature (≥1000°C) Metapelites from the Voronezh Crystalline Massif (Kursk–Besedino Granulite Block)

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The Kursk–Besedino block confined to the central part of the Kursk magnetic anomaly is one of two granulite blocks of the Voronezh crystalline massif (VCM). It is made up of Archean granulite-facies rocks (magnetite quartzites, Fe–Al-rich rocks, metabasites, metaultrabasites, and metapelites) that are preserved as relicts among migmatites and gneisses of the undivided Oboyan Complex metamorphosed in the prograde amphibolite facies. The Mesoarchean age (3277 ± 33 Ma) of the rocks of the granulite block was confirmed by U–Pb zircon dating on gneissose plagiogranite [1] cutting across magnetite quartzites. The magnetite quartzites of the region contain unique ortho- and clinopyroxenes with exsolution lamellae, which made it possible for the first time to determine the ultrahigh temperatures of peak metamorphism at ≥1000°C [2]. In associated metapelites, all mineralogical evidence (for instance, sapphirine–quartz assemblages) of this metamorphism was obliterated by intense retrograde metamorphism. However, these rocks contain feldspars with exsolution lamellae, which are indicative of a high crystallization temperature.

The studied metapelites were taken in five boreholes. They are represented by light gray and gray migmatized gneisses with massive or vaguely banded medium to coarse-grained rocks. The texture is granoblastic, lepidogranoblastic, and porphyroblastic (owing to garnet grains up to 1 cm in size), with signs of partial melting. Samples taken from the borehole core were studied in the polished thin sections using a Jeol 6380 LV electron microprobe at Voronezh State University and a CamScan 2300 Microprobe at the Institute of Experimental Mineralogy, Russian Academy of Sciences. The mineral composition was determined using an INCA 250 energy dispersive microprobe. The acceleration voltage, probe current, and beam size were, respectively, 20 kV, 10 nA, and 1–3 μm. The analysis accuracy was systematically controlled using natural and synthetic standards. In some cases, low (10 kV) acceleration voltages with the electron beam focused within an area of 50 nm were applied. The area of host mineral and exsolution lamellae was determined by analysis of high-contrast BSE images (Program Atlas, Tescan inc.).

Seven samples (on average 40, occasionally 120, points in each sample) were analyzed. Metapelites consist of the following mineral assemblages[1]: Qtz + Grt + Kfs + Crd + Sil + Spl + Bt + Mag (occasionally with Pl, Ilm, and Py) and Qtz + Grt + Kfs + Opx + Spl + Crd + Bt + Py + Mag. Minerals show diverse reaction relations. Feldspars as equant or more rarely irregular grains 10–500 μm in size are often localized among the cordierite–quartz matrix. Most grains contain exsolution lamellae: (1) antiperthites (K-feldspar lamellae in plagioclase matrix) (Fig. 1a); (2) perthites (plagioclase lamellae of different morphology in the K-feldspar matrix) (Fig. 1b); (3) mesoperthites (plagioclase and K-feldspar lamellae in almost equal proportions) (Fig. 1c).

Mesoperthites contain a unique multistage exsolution (Fig. 1d), similar to that previously found in orthopyroxenes from magnetite quartzites of the region [2]. In feldspar rims, the exsolution lamellae change their morphology and decrease in the abundance.

The composition of primary feldspar was simultaneously determined (reintegrated) by two methods: (1) scanning microprobe analysis and (2) calculation of proportions (and compositions from point energy dispersive analysis) of the host mineral and exsolution lamellae over the area in each grain.

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[1] Mineral abbreviations after [3].

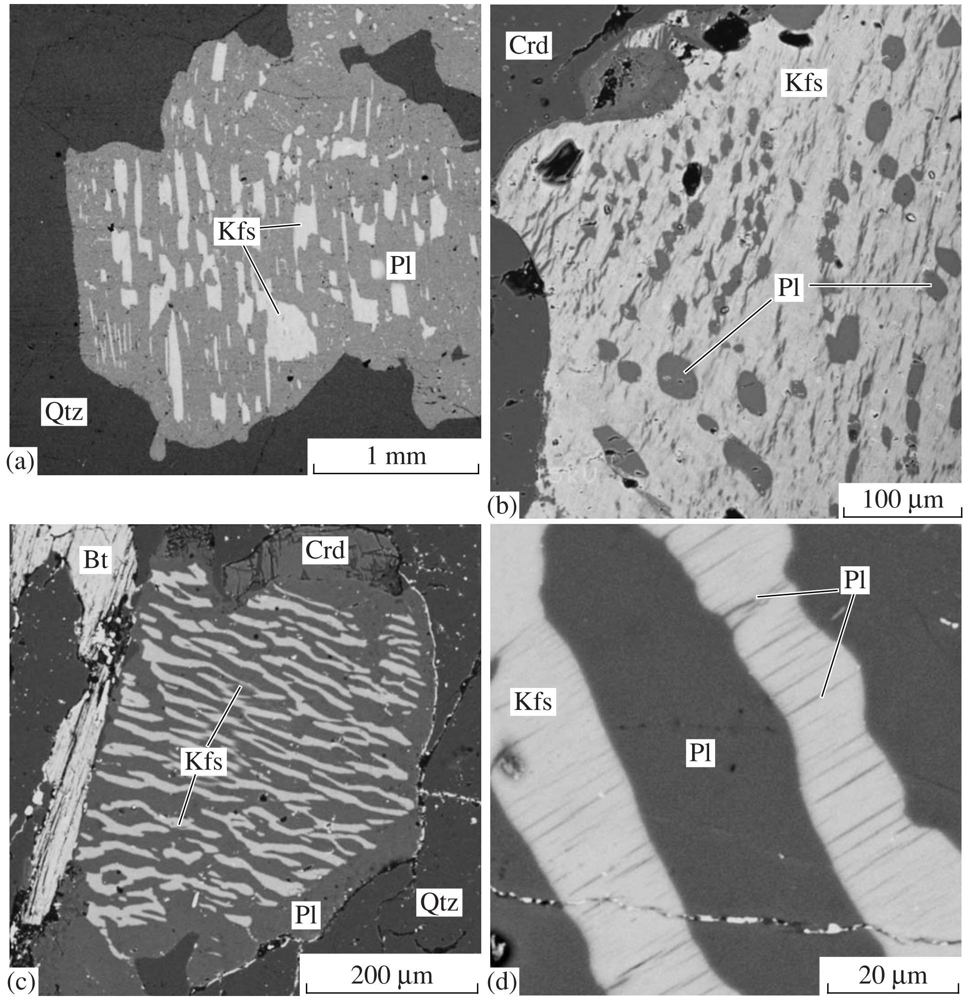


**Fig. 1.** Exsolution lamellae of feldspar solid solutions: (a) antiperthites, (b) perthites, (c) mesoperthites, (d) unique multistage exsolution in mesoperthites (K-feldspar lamellae are exsolved into plagioclase lamellae).

Feldspar grains analyzed by the first method were practically completely overlapped by scanning fields, each 50 × 50 μm in size. The obtained results were averaged. In the second analysis (calculation of area), each grain was analyzed in 40 to 80 points. Low-voltage (10–15 kV) operation was used to reduce the absorption from light elements and to improve the measurement accuracy. Areas were calculated using high contrast BSE images of mineral grains obtained by electron scanning. The areas of different mineral phases corresponded to the integral number of single spots (pixels) of similar contrast. It was found that the feldspar exsolution products (both lamellae and matrix) are homogeneous in composition, with the maximum difference no more than 1–2 mol %. K-feldspars typically contain an insignificant (≤1.5 wt %) admixture of BaO. The composition of reintegrated feldspars is represented in the table. It is seen that both methods yield close results, with the maximal differences no more than 5–7 mol % for averaged minerals. At the same time, the first method gives somewhat underestimated relative contents of Ca and Na in perthite feldspars and K in the antiperthite and mesoperthite feldspars (with a corresponding increase of the K content in the former varieties and Ca, Na, in the latter). This can be related both to systematic matrix-effect errors [4, 5] and insufficient representativeness of lamellae exposed to X-ray analysis, which leads to disturbance of the true proportions of exsolution products in the minerals [2].

The crystallization temperature of feldspar was estimated using the two-feldspar thermometer of Fuhrman and Lindsley [6], which was recommended in [7] as the most appropriate for products of high-grade metamorphism. The diagram (Fig. 2) for pressure of 8 kbar demonstrates the compositions of reintegrated feldspars and their exsolution products (table). It is seen that different techniques yield close stability temperatures for primary feldspars: ≥1050°C for antiperthites, ≥1000°C for mesoperthites, and ≥960°C for perthites. Since each of the studied samples contains only one feldspar with perthite, antiperthite, or mesoperthite exsolution lamellae, the obtained temperatures correspond to the mini-

Chemical composition (wt %) of exsolution products of feldspars from metapelite granulites of VCM

| Component | Sample 167, antiperthite feldspar | | | | Sample 143, perthite feldspar | | | | Sample 165, mesoperthite feldspar | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HM, $S = 70$ | Lamellae, $S = 30$ | R**, $S = 100$ | RSM*** | HM, $S = 72$ | Lamellae, $S = 28$ | P, $S = 100$ | RSM | HM, $S = 58$ | Lamellae, $S = 42$ | P, $S = 100$ | RSM |
| | Pl | Kfs | Pl + Kfs | Pl + Kfs | Kfs | Pl | Kfs + Pl | Kfs + Pl | Pl | Kfs | Pl + Kfs | Pl + Kfs |
| $SiO_2$ | 60.32 | 64.92 | 61.70 | 61.36 | 64.55 | 62.93 | 64.1 | 64.75 | 64.55 | 64.38 | 64.48 | 64.16 |
| $Al_2O_3$ | 25.39 | 19.15 | 23.51 | 22.96 | 18.63 | 22.51 | 19.71 | 18.98 | 22.62 | 18.84 | 21.03 | 21.10 |
| FeO | 0.26 | 0.66 | 0.38 | 0.26 | 0 | 0 | 0 | 0 | 0.12 | 0.56 | 0.31 | 0.32 |
| CaO | 6.99 | 0.04 | 4.9 | 5.28 | 0.1 | 4.09 | 1.22 | 0.79 | 3.56 | 0.14 | 2.12 | 2.23 |
| $Na_2O$ | 7.15 | 0.41 | 5.13 | 5.72 | 0.92 | 9.42 | 3.3 | 2.97 | 8.85 | 0.5 | 5.34 | 5.97 |
| $K_2O$ | 0.22 | 15.17 | 4.7 | 3.49 | 15.22 | 0.12 | 10.99 | 12.2 | 0 | 15.26 | 6.41 | 5.23 |
| Total | 100.33 | 100.35 | 100.32 | 99.07 | 99.42 | 99.07 | 99.42 | 99.69 | 99.70 | 99.68 | 99.69 | 99.01 |
| Si | 2.69 | 3.00 | 2.78 | 2.79 | 2.99 | 2.8 | 2.94 | 2.96 | 2.87 | 2.99 | 2.92 | 2.92 |
| Al | 1.33 | 1.04 | 1.25 | 1.23 | 1.02 | 1.18 | 1.06 | 1.02 | 1.19 | 1.03 | 1.12 | 1.13 |
| Fe | 0.01 | 0.03 | 0.01 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0.02 | 0.01 | 0.01 |
| Ca | 0.33 | 0.00 | 0.24 | 0.26 | 0 | 0.2 | 0.06 | 0.04 | 0.17 | 0.01 | 0.10 | 0.11 |
| Na | 0.62 | 0.04 | 0.45 | 0.50 | 0.08 | 0.81 | 0.29 | 0.26 | 0.76 | 0.05 | 0.47 | 0.53 |
| K | 0.01 | 0.89 | 0.27 | 0.20 | 0.9 | 0.01 | 0.64 | 0.71 | 0.00 | 0.9 | 0.37 | 0.30 |
| An, mol % | 35 | 0 | 25 | 27 | 1 | 19 | 6 | 4 | 18 | 1 | 11 | 12 |
| Ab, mol % | 64 | 4 | 47 | 52 | 8 | 80 | 29 | 26 | 82 | 5 | 50 | 56 |
| Or, mol % | 1 | 96 | 28 | 21 | 91 | 1 | 65 | 70 | 0 | 94 | 39 | 32 |

Note: Averaged areas (*S*, %) and composition of exsolution products are shown for each of the eight mineral grains studied. (HM) host mineral; (R) reintegrated, (RSM) reintegrated by scanning method.

mum crystallization temperatures of primary minerals [7]. The pressure effect on the feldspar stability curves in the diagram of Fuhrman and Lindsley [6] is insignificant, and no correction is required for the temperatures found (Fig. 2) within the pressure range of 8–15 kbar. The compositions of exsolved feldspars (perthite, antiperthite, and mesoperthite) (table) reflect a retrograde path of rock cooling up to temperatures ≤700°C (Fig. 2).

The obtained crystallization temperatures of feldspars from metapelites of VCM practically coincide with those obtained for associated magnetite quartzites [2] and confirm ultrahigh temperature conditions of peak metamorphism of the Mesoarchean volcanosedimentary complex of the region. At the subsequent low-temperature metamorphic stages, all rocks, especially metapelites, underwent cardinal retrograde reworking. Owing to this process, the signs of ultrahigh temperature metamorphism preserved only in rare and relatively unique relicts, for instance, in pyroxenes with exsolution lamellae in magnetite quartzites and in the above described feldspars from metapelites.

The feldspar exsolution products crystallized with decreasing temperature (≤700°C) at the final stages of metamorphic transformations. Changes in the morphology and the decrease in lamellae abundance observed in the marginal parts of feldspars, as well as multistage exsolution in the mesoperthite feldspars, occurred even at lower temperatures.

Similarly high peak temperatures of regional metamorphism were previously well established only in two regions: Scouri, Scotland [8], and Enderby Land, Antarctica [9, 10]. The perthitic, antiperthitic, and mesoper-

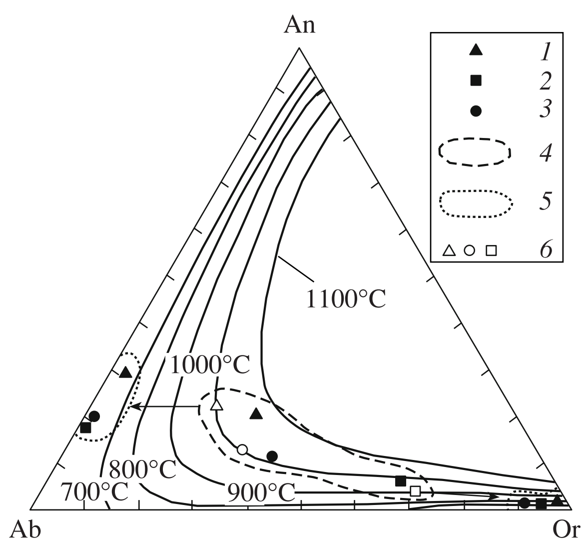


**Fig. 2.** Diagram [6] of metamorphic conditions of reintegrated feldspars and their exsolution lamellae. (*1*) antiperthites, (*2*) perthites, (*3*) mesoperthites; (*4*) reintegrated compositions; (*5*) melted feldspars, (*6*) composition reintegrated by method of scanning fields

thitic feldspars, similar to those of VCM, with close crystallization temperatures (≥1000–1110°C) were found in the metapelites of the Napir Complex, Enderby Land, where they also associate with iron banded formations [7].

The peak temperatures obtained for the first time at VCM place this complex together with other relatively unique regions of high-temperature high-pressure metamorphism that were discovered in the last two decades. These data require revision of the geological (tectonothermal (metamorphic), geodynamic, and magmatic) evolution of the region.

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