

Metamorphic grade of the Madan unit in the southern part of the Central Rhodopes, Bulgaria

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Abstract. The objective points of the study are orthogneisses, paragneisses and amphibolites from the Madan unit, that crop out along the Arda river valley in the southern part of the Central Rhodope and accommodate syn- to postkinematic granite bodies. The interpretation of the metamorphic grade is based on field and microstructural observations, X-ray diffraction data on K-feldspars structural state and conventional geothermobarometry. The equilibrium garnet-plagioclase-biotite assemblage of paragneisses situated in the western part of the unit define *P-T* range of 600-670°C/0.9-1.2 GPa. The amphibole-plagioclase equilibrium pairs from amphibolites situated in the eastern part of the unit yield 640-720°C/0.6-1.0 GPa. The calculated temperatures cluster together around the water-saturated granite solidus in accordance with the field observations of initial stage of migmatization, microstructural features of amphibolite facies ductile deformation and orthoclase structure of K-feldspars in ortho- and paragneisses.

Key words: metamorphism, geothermobarometry, ductile deformation, microstructures, Madan unit, Central Rhodopes

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Емилия Раева, Златка Чернева. Степен на метаморфизъм в Маданската единица от южната част на Централните Родопи, България

Резюме. Предмет на изследване са отрогнайси, парагнайси и амфиболити от Маданската единица, разкриващи се по долината на р. Арда в южната част на Централните Родопи и вместващи син- до посткинематични гранитни тела. Интерпретацията за степенът на метаморфизъм се основава на теренни и микроструктурни наблюдения, рентгено-структурни изследвания за структурното състояние на К-фелдшпати и конвенционална геотермобарометрия. Гранат-плагиоклаз-биотитовата равновесна минерална асоциация в парагнайсите, разположени в западната част на единицата, определя 600-670°C/0,9-1,2 GPa. Резултатите от равновесните двойки амфибол-плагиоклаз от амфиболитите, разположени в източната част на единицата, показват 640-720°C/0,6-1,0 GPa. Изчислените температури се групират около водонаситения гранитен солидус в съгласие с теренните наблюдения на мигматизация от метатекситов тип, с микроструктурните особености на пластична деформация в амфиболитов фациес и с ортоклазовата структура на К-фелдшпати от орто- и парагнайсите.

Introduction

Modern approach to metamorphic grade evaluation requires quantitative pressure and temperature estimates, obtained from conventional thermobarometry and/or pseudosections based on combination of whole rock and mineral chemistry. The metamorphic petrology gives preferences to metapelitic and metabasitic rocks, because their mineral assemblages are more sensitive to changing metamorphic conditions and could draw the almost overall pattern of P - T metamorphic path. The quartz-feldspathic rocks and their uniform mineral assemblages, composed of feldspar, quartz, biotite \pm hornblende \pm white mica are stable at large P - T variation and cannot give complete information on the metamorphic evolution. On the other hand gneissic rocks yield abundant information on small-scale synmetamorphic deformation structures.

The most widespread rocks in the Central Rhodopes, Bulgaria are quartz-feldspar gneisses (metagranitoids predominantly). Metabasic and metasedimentary rocks although limited, crop out at different levels of the metamorphic section. Earlier estimates of metamorphic grade are based on petrographic observations of equilibrium mineral assemblages in metapelitic and metabasitic rocks mainly. Numerous studies have contributed to the conclusion of a general Barrovian style of metamorphism and transition from upper amphibolite facies accompanied by partial melting in deeper levels towards lower amphibolite to greenschist facies in the upper structural levels (Dimitrov 1955; Vergilov 1960; Vergilov et al. 1963; Kozhoukharov 1968, 1984; Kozhoukharova & Kozhoukharov 1980; Ivanov et al. 1979, 1980, 1984). The occurrence and sequential formation of Al-Si polymorphs (kyanite \rightarrow sillimanite \rightarrow andalusite) in the upper amphibolite facies section has given evidence for a general P - T path trajectory (Kostov et al. 1986) that is consistent with an orogenic geological setting.

Thermobarometric data available on the Central Rhodopes metamorphic rocks reveal decompressional P - T -path and enable suggestions about peak metamorphic conditions. Our study focuses attention on the poorly studied southernmost part that crops out along the upper course of the Arda river and straddles the Bulgarian-Greek border. The study area (Fig. 1) corresponds to the southern fragment of the Madan lithotectonic unit (Ivanov 1998; Ivanov et al. 2000; Sarov et al. 2005). A combination of results including conventional thermobarometry, microstructural indicators of synmetamorphic deformation and structural state of K-feldspar provide documentation on the metamorphic evolution of the rocks.

Geological setting

The Madan unit is a part of a metamorphic core complex in the Central Rhodopes (Fig.1) that comprises several tectonic units bounded by brittle-ductile shear zones (Ivanov et al. 2000; Sarov et al. 2004). The dome core (Arda unit) consists of high-grade amphibolite facies rocks affected by advanced melting (diatexis). The intermediate plate of the dome (Madan and Startsevo units) has undergone high-grade amphibolite facies metamorphism and initial stage of migmatization (metatexis). The non migmatic uppermost plate of the dome comprises Asenitsa unit to the north, as well as Borovitsa and Kardjali units to the east (not shown on Fig. 1) that keep record of lower amphibolite to greenschist facies metamorphism. The Madan unit crops out in two separate fragments (Fig. 1): one to the North, along the Vacha river valley; and another to the South-West, along the Arda river valley.

The orthogneisses are the most widespread rocks in the Central Rhodopean Dome. Their protoliths belong to two age groups of granitoids: late Paleozoic in the Arda unit (Arnaudov et al. 1990a; Arkadakskiy et al. 2000, 2003; Peytcheva et al. 2000, 2004; Ovtcharova et al. 2002); and late Jurassic ones

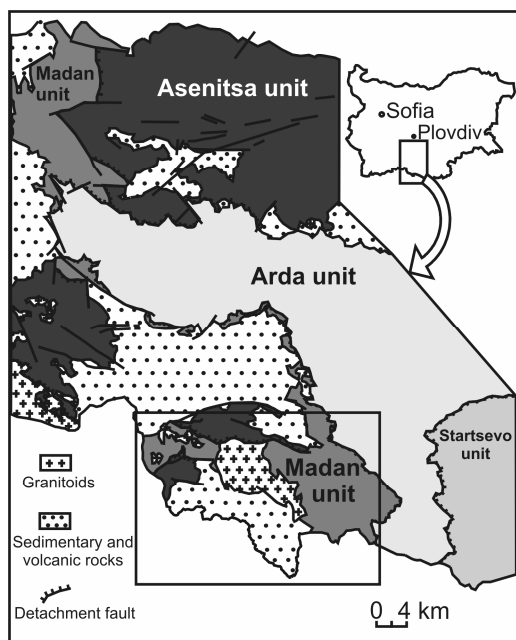


Fig. 1. Simplified geological map of the Central Rhodopean Dome (after Ivanov et al. 2000)

in the Startsevo, Borovitza, Asenitza, and the Madan unit fragment along the Arda river valley (Ovtcharova 2004; von Quadt et al. 2006; Raeva et al. 2008b). Metasedimentary rocks are also present in all the units in association with metabasic rocks usually. Retrogressed eclogites have been found among the latter in the Arda and Startzevo units (Kolcheva et al. 1986), Kardzhali unit (Ovtcharova et al. 2004), and in the Asenitza unit (Ichev 1994). Limited data on the Arda unit eclogites indicate participation of Neoproterozoic oceanic crust remnants (540-610 Ma magmatic protoliths) in the Central Rhodope metamorphic complex (Arkadakskiy et al. 2003). The age of the HP metamorphic event/events is yet unknown. The moderate-pressure regional metamorphism span more than 20 Ma, from ~56 Ma to ~35 Ma, including partial melts crystallization in the migmatitic units, syn- to post kinematic granite emplacement, and sequential cooling (Arnaudov et al. 1990a, b; Arkadakskiy et al. 2000; Kaiser-Rohrmeier

2005; Ovtcharova et al. 2002, 2003; Peytcheva et al. 2000, 2004; von Quadt et al. 2006).

The decompression path of the metamorphic evolution is relatively well defined by conventional thermobarometry of metabasic and metapelitic rocks mainly. Assuming late Cretaceous to early Tertiary HP event (like in the Greek Central Rhodope, Liati 2005) one could complete the decompression path of the Arda unit based of thermobarometric results available: HT eclogite metamorphism at 780°C/2 GPa (Kolcheva et al. 1986); HP granulite facies melting during decompression in the range 700-850°C/0.9-1.9 GPa (Cherneva et al. 2008; Cherneva & Georgieva 2007; Georgieva et al. 2007); final migmatite melt crystallization at 650-700°C/0.65-0.8 GPa (Cherneva et al. 1997; Kostov et al. 1986) and subsequent decompression cooling to 550-600°C/0.5 GPa (Cherneva et al. 1997; Georgieva et al. 2002, 2007).

The Startsevo unit peak conditions of eclogite facies metamorphism are estimated as ~800°C/1.7-1.8 GPa, followed by granulite overprint at temperatures greater than ~700°C/~1.0-1.3 GPa (Carrigan et al. 2006). The corresponding estimates of Machev & Kolcheva (2008) are 730-770°C/2.0-2.2 GPa for the HP event, 850-880°C at lower pressure for the granulite facies, and amphibolite facies equilibration at 655-736°C/0.8-1.2 GPa. Gneisses and schists from the same unit give the range 600-660°C/0.7-0.9 GPa and a transition through 550-580°C/0.6-0.4 GPa to 440-550°C/0.2-0.3 GPa (Ovtcharova 2004). The thermobarometric estimates on metabasic rocks 540-600°C/0.6 GPa (Pristavova 1995) overlap some of the above results.

The Madan unit along the Vacha river valley have had similar metamorphic evolution in the stage of amphibolite facies decompression like the Startsevo unit: from 650-670°C/0.7-0.8 GPa in the lower structural level to 625°C/0.6-0.7 GPa in the higher structural level of the tectonic unit (Cherneva et al. 1995).

The Asenitsa unit pelitic schists yield peak metamorphic conditions at ~550°C/1.35

GPa (Guiraud et al. 1992). Data on structural state of K-feldspar (Arnaudova et al. 1990) support the results of the Asenitsa unit lower metamorphic grade. The latter study makes a general distinction based on the K-feldspar structural state: orthoclase in migmatitic units; and microcline in not affected by magmatization ones.

The study area coincides with the Madan unit that crops out along the Arda river valley (Figs. 1, 2). The dominant rocks are migmatitic biotite orthogneisses (Sarov et al. 2005; Raeva et al. 2008a) of late Jurassic protolith age (160 Ma, Raeva et al. 2008b). Mica schists, paragneisses, and marbles crop out mostly in the north-western parts of the unit, whereas amphibolites occur predominantly in the south-western parts (Katskov et al. 1962; Belmustakova 1995; Kozhoukharov et al. 1989). The metamorphic grade is supposed to correspond to upper amphibolite facies, based on common petrographic observations. Syn- to post-

kinematic granite bodies intruded the orthogneisses. A strike-slip shear zone controlled granite emplacement (Sarov et al. 2005; Naydenov et al. 2005) that happened in a short time span from 43 Ma for the synkinematic bodies to 41 Ma for the post-kinematic Smilian pluton (Ovtcharova et al. 2003; Kaiser-Rohrmeier 2004; Raeva et al. 2008b). The Madan unit continuation to the South corresponds to the so called Upper unit on the territory of Greece (Papanikolaou & Panagopoulos 1981), whose metamorphic evolution has focused attention recently with regard to UHP metamorphic relics (Schmidt et al. 2009 and references therein).

The dominant Madan unit orthogneisses have unclear foliation, massive structure, round to lens-shaped former feldspar porphyroclasts as well as elongated fine-grained melanocratic enclaves, parallel to the gneiss foliation (Raeva et al. 2008a). Evidence of *in situ* migmatization

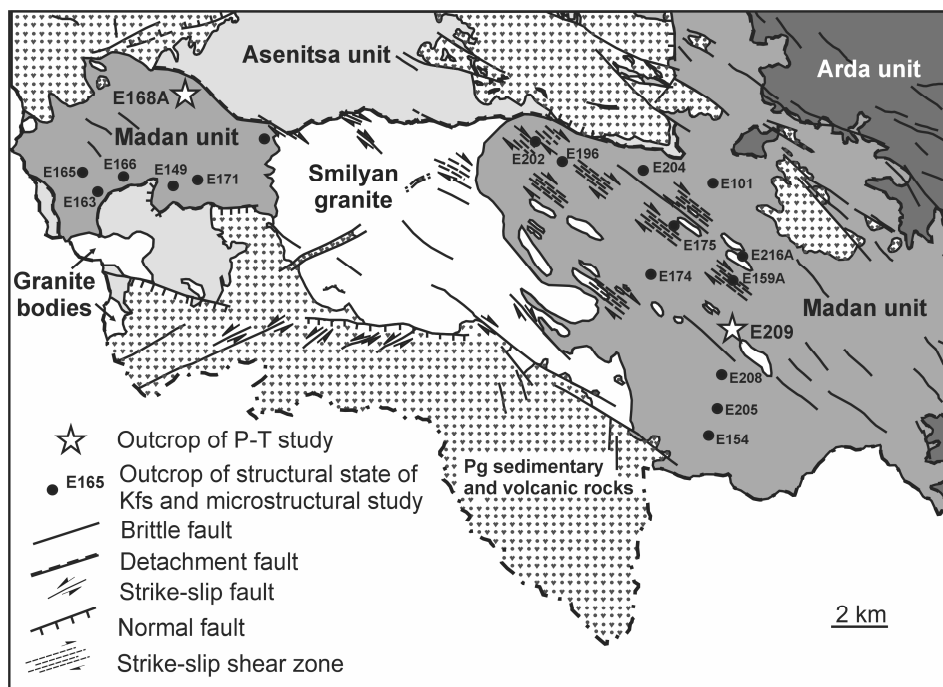


Fig. 2. Tectonic sketch map of the study area (after Sarov et al. 2005)

is present as concordant with the foliation discontinuous leucosome bands, ~3–4 mm to 1–1.5 cm thick. Ptigmatic leucosomes although rare, occur as well as leucosomes filling local ductile shear zones across the gneiss foliation.

Minor paragneisses form discontinuous bands among the orthogneisses near the Asenitsa unit marbles (Fig. 2, E168A). These are brownish-grey, fine-grained, fine-foliated, garnet- and tourmaline-bearing biotite gneisses. Thin non penetrative leucosomes occur locally in the paragneisses concordant to the gneiss foliation, completing the field features of initial stage of metatexite type of migmatization in the study area.

The metabasic rocks among the orthogneisses represent metric to tens- metric scale lens-like bodies. The amphibolites are dark-greenish, fine-grained, and clearly foliated metamorphic rocks.

Abundant granite, aplite and pegmatite veins penetrate the Madan unit rocks (Sarov et al. 2005). Pre-, and/or syn-, and postmetamorphic injections could be distinguished among the veins. The first two groups of veins are concordant to or pass across the gneiss foliation, producing small offsets along the foliation planes and diffuse contacts with migmatitic leucosomes. Their generation could be related to the gneiss protoliths or to the melt migration during migmatization. Postmetamorphic aplite and pegmatite veins have clear and sharp contacts and crosscut both the gneiss foliation and the synmetamorphic veins.

Materials and methods

Selected samples of orthogneisses, paragneisses and amphibolites from the Madan unit are studied. The orthogneiss samples (black points on Fig. 2) represent the dominant rocks to the East and to the West of the Smilyan granite. The studied paragneisses crop out in the north-western part of the Madan unit (sample E168A, N41°31'13", E24°37'37"). The amphibolite samples represent metric scaled lens-shaped body among the orthogneisses to the east of the Smilyan granite (sample E209,

N41°26'49", E24°51'17").

Popular microstructural indicators are used to characterize synmetamorphic deformation and corresponding thermal conditions of mineral recrystallization: undulose to prismatic extinction in quartz, and patchy undulose extinction in feldspars, due to subgrain formation, refer to low-temperature microstructures below ca. 600°C (Fitz Gerald & Stunitz 1993; Passchier & Trouw 1996; Kruhl 1996); 'chessboard' pattern in quartz and 'core-mantle' structures in feldspars indicate high-temperature conditions above ca. 620–650°C (Passchier & Trouw 1996; Kruhl 1996; Albertz 2006).

The structural state of K-feldspars from ortho- and paragneisses is an indicator of the cooling history of the rocks. K-feldspar fractions, obtained by routine procedure of mineral separation, have been used for X-ray diffraction analysis of the K-feldspar structural state. The structural types were determined from measurements of the $\bar{2}04$, 060 and 131 ($\bar{1}\bar{3}1$ resp.) reflections on powder diffractograms, following the method of the three reflections of Wright (1968). K-feldspar analyses are implemented with TUR M62 X-Ray Diffractometer at the Sofia University.

Chemical compositions of rock forming minerals in selected samples were used for thermobarometric calculations. Microprobe analyses were performed using Jeol Superprobe 733 electron microprobe at the Geological Institute of the Bulgarian Academy of Sciences and Jeol JSM-6310 electron microscope at the University of Graz, Austria, with 15 kV accelerating voltage and 100 s counting time.

The mineral abbreviations used are according to Siivola & Schmid (2007).

Petrography and microstructural relations

Orthogneisses

The major minerals are plagioclase, K-feldspar, quartz and biotite. The accessory mineral assemblage includes apatite, zircon, allanite,

titanite and magnetite and rarely garnet. The orthogneiss texture is lepidogranoblastic to granoblastic.

Biotite flakes form discontinuous foliation planes and surround feldspar grains (Fig. 3a). Biotite (<1.5-2 mm) is pleochroitic from dark brown to straw yellow. Elongated sub-parallel quartz aggregates envelop feldspar porphyroblasts (Fig. 3b). Quartz grains show undulose to prismatic extinction (Fig. 3c). A clear 'chessboard' pattern is developed in rare large quartz grains (Fig. 3d).

Subhedral to anhedral, rounded to lens-shaped plagioclase grains (<2-3 mm) have uniform to undulose extinction. There is subgrain formation on the periphery of some of them forming "core-mantle" textures. A wedge-shaped plagioclase twinning appears in response of deformation (Fig. 3e). Antiperthitic exsolutions of rectangular or irregular shapes occur in larger plagioclase grain cores (Fig. 3e). The exsolution clusters in the plagioclase cores suggest former normal compositional zoning of original plagioclase in the magmatic protolith. Myrmekitic plagioclase peripheries and myrmekitic plagioclase inclusions occur on the contact with K-feldspar grains (Fig. 3c) that together with antiperthites indicate subsolidus and lower temperature re-equilibration.

Large, subhedral to anhedral, round to lens-shaped K-feldspar crystals (~1-1.5 mm) display usually undulose extinction. A weak to apparent cross-hatched microcline twinning occurs in some K-feldspar grains close to subgrain and grain boundaries and along microcracks (Fig. 3c). Belmustakova (1995) has described cross-hatched microcline twinning in K-feldspars as a typical feature of the gneisses in the area. According to our observations the cross-hatched twinning is not ubiquitous and it is more frequent in the Smilyan shear zone area. This indicates causal connection between observed cross-hatched twinning in K-feldspars and intensity of ductile deformation in the gneisses.

Microstructural indicators refer to deformation at high-grade metamorphic conditions in amphibolite facies ca. 600-650°C:

rounded, subhedral to lens-shaped plagioclase crystals surrounded by fine-grained, re-crystallized quartz and biotite (Fig. 3b); 'chessboard' pattern in quartz (Fig. 3d); wedge-shaped plagioclase twinning (Fig. 3e); 'core-mantle' plagioclase textures (Fitz Gerald & Stunitz 1993; Kruhl 1996; Stipp et al. 2002). The 'chessboard' pattern in quartz occurs especially in gneisses from the Smilyan shear zone area. Fine-flaked white mica and/or fine-grained feldspars filling plagioclase microcracks and subgrain boundaries suggest initial stage of partial melting (Mehnert et al. 1973; Jurewicz & Watson 1984; Sawyer 1999). Plagioclase cracks filled with quartz, biotite and K-feldspar (Fig. 3f) indicate former melt presence (Blumenfeld & Bouchez 1988; Bouchez et al. 1992) in consistence with field observation of initial stage of migmatization (metatexis).

Paragneisses

The major mineral assemblage includes biotite, plagioclase, K-feldspar and quartz, and minor garnet. The accessory minerals are apatite, zircon, magnetite, tourmaline, titanite and epidote. The paragneiss texture is lepidogranoblastic.

Reddish-brown elongated biotite flakes (1-1.5 mm) construct continuous foliation planes, surrounding plagioclase grains (Fig. 4a). Dynamically re-crystallized quartz grains show undulose to prismatic extinction (Fig. 4b) forming discontinuous bands parallel to the foliation.

Anhedral to subhedral, rounded to lens-shaped plagioclase grains (<1 mm) are arranged also parallel to the common foliation (Fig. 4c, d). Rare larger subhedral plagioclase grains (~1-1.5 mm) display patchy undulose extinction in response to subgrain formation. "Core-mantle" textures occur when subgrains are developed on large plagioclase grain peripheries (Fig. 4c). Some plagioclase grains show wedge-shaped twinning (Fig. 4e).

Minor amount of K-feldspar (<0.5 mm) take place in pressure shadows of plagioclase grains (Fig. 4d). Rare larger K-feldspar grains

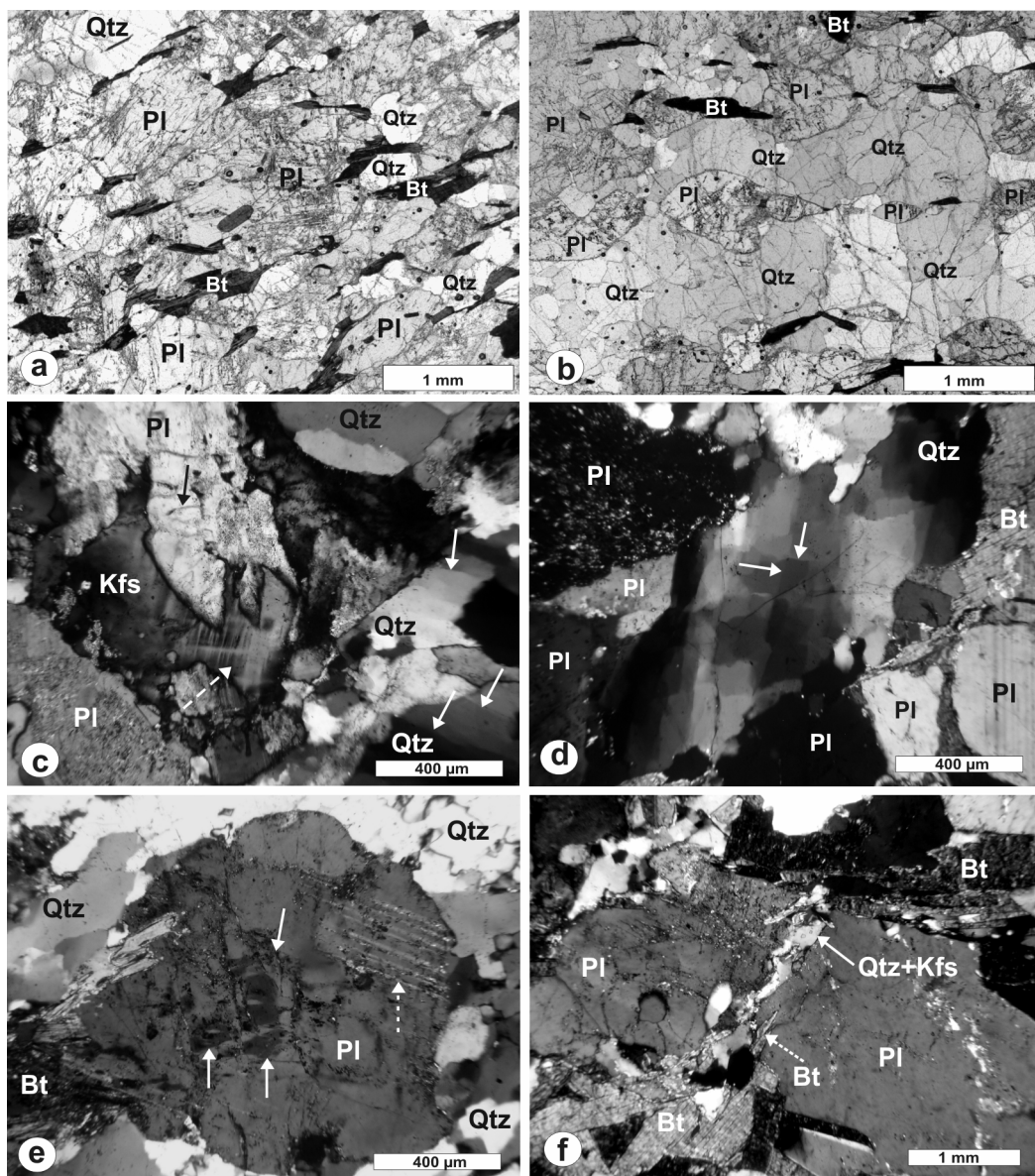


Fig. 3. Microstructural relations of rock-forming minerals in orthogneiss samples E216A, E205A, E196, E166, E202: a) curved and thinner biotite flakes, PPL; b) lens-shaped plagioclase grains surrounded by recrystallized quartz, PPL; c) prismatic extinction in quartz (white arrows), myrmekitic plagioclase (black arrow) and cross-hatched microcline twinning in anherdal K-feldspar (dashed arrow), CPL; d) 'chessboard' pattern in quartz (arrows), CPL; e) rounded plagioclase grain with wedge-shaped plagioclase twinning (dashed arrow) and irregular-shaped antiperthites (white arrows), CPL; f) plagioclase cracks filled with quartz, K-feldspar (arrow) and biotite (dashed arrow), CPL

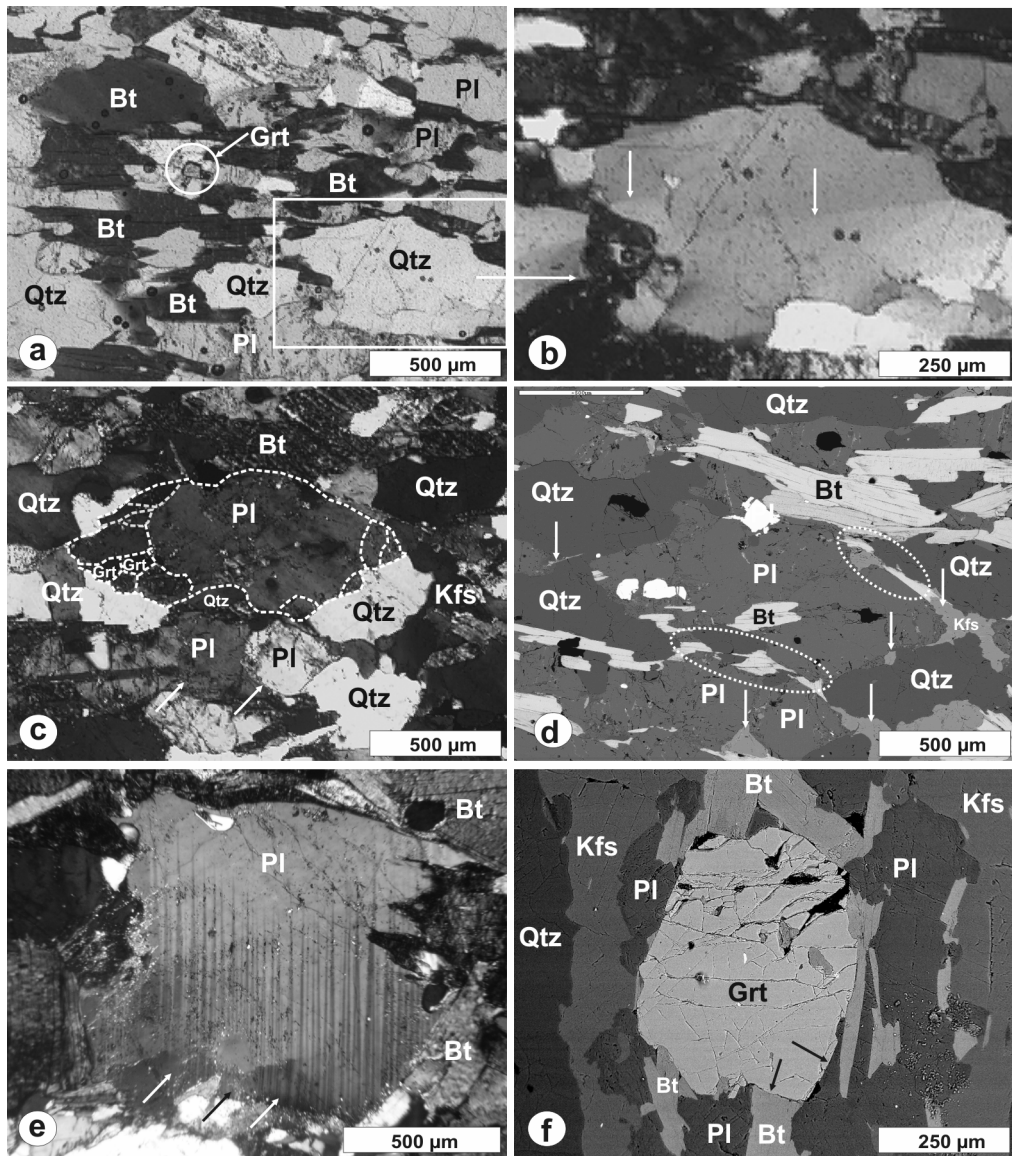


Fig. 4. Microstructural relations of rock-forming minerals in paragneiss sample E168A: a) elongated and extended biotite flakes forming continuous foliation, PPL; b) prismatic extinction in quartz, CPL; c) 'core-mantle' structure in plagioclase (dashed lines) and small rounded plagioclase grains (arrows), CPL; d) interstitial and in pressure shadows K-feldspar (white arrows); dynamic recrystallized fine-grained quartz, biotite and K-feldspar round large plagioclase grains (dashed ellipses), BSE; e) wedge-shaped plagioclase twinning and subgrains (arrows), CPL; f) euhedral garnet grain and sharp and clean boundaries with plagioclase and biotite (arrows), BSE

(~0.5 mm) are elongated, parallel to the general foliation (Fig. 4f) and display undulose extinction. Some of them partially or completely include small plagioclase grains full of myrmekites.

Garnet grains are small (up to 1 mm), euhedral to subhedral, slightly rounded (Fig. 4f). They occur predominantly near biotite flakes which in some cases penetrate into garnet cracks.

Microstructures reflect deformation at high-grade amphibolite facies metamorphism ca. 600°C: undulose to prismatic extinction in quartz (Fig. 4b); ‘core-mantle’ textures in plagioclase (Fig. 4c); wedge-shaped plagioclase twinning (Fig. 4e) (Passchier & Trouw 1996; Kruhl 1996). Dynamically re-crystallized fine-grained quartz and/or K-feldspar and plagioclase occur along plagioclase grain boundaries (Fig. 4d) and support an interpretation of partial melting processes influence (Mehnert et al. 1973; Jurewicz & Watson 1984; Sawyer 1999). These features coincide with field observation of initial stage of migmatization in paragneisses.

Garnet, plagioclase and biotite grain contacts testify for equilibrium relations with each other. The contact lines are sharp and smooth and show no evidence of replacement of one mineral by another or new phase crystallization (Fig. 4f). The mentioned microstructure criteria imply for a simultaneous coexistence of chemically compatible minerals (Vernon 1977).

Amphibolites

The major mineral assemblage consists of amphibole and plagioclase. There is also minor quartz and secondary biotite. The accessory minerals are titanite, magnetite, apatite and zircon. The term “amphibolite” is used in accordance with the mineral composition and macroscopic characteristics, without, as far as possible, any genetic connotation as recommended by Coutinho et al. (2007).

Amphibole (<1.5-2 mm) is subhedral to anhedral, exhibiting dark green to light green

pleochroism. Larger plagioclase grains (1-1.5 mm) are subhedral with undulose extinction, while smaller grains (~0.5-1 mm) are anhedral, rounded to lens-shaped. Some large amphibole and plagioclase grains contain inclusions of euhedral plagioclase and amphibole respectively (Fig. 5).

Elongated quartz aggregates occur parallel to the foliation. Rare anhedral interstitial quartz grains display weak undulose extinction.

Biotite (< 1 mm) with dark brown to light yellow pleochroism is rare. The biotite contacts with amphibole grains are sharp and smooth,

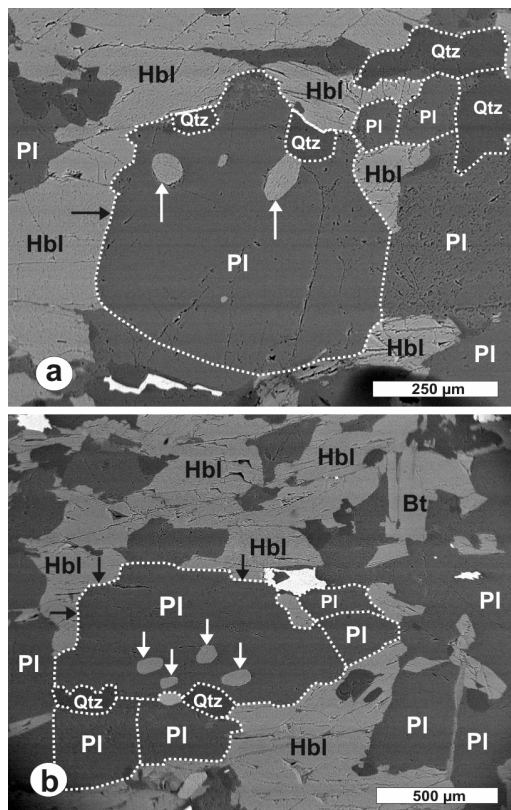


Fig. 5. Microstructural relations between rock-forming minerals in metabasite sample E209: a) and b) subhedral plagioclase with small euhedral amphibole inclusions (white arrow); sharp and new-phase-free boundaries between Pl and Hbl (black arrow), BSE

but near plagioclase and quartz biotite flakes are irregular and ragged in shape.

The microstructural relations refer to deformation at amphibolite facies conditions (Vernon 1975; Voll 1976; Tullis 1983), namely: plagioclase undulose extinction due to microcracks and subgrain formation; and wedge-shaped plagioclase twinning. Triple junctions of polygonal plagioclase crystals reflect plagioclase re-crystallization by means of complete consumption of parental larger crystals at static conditions (Srivastava & Mitra 1996).

Plagioclase-amphibole boundaries are usually sharp and smooth showing no evidence of mutual replacement or new phase crystallization (Fig. 5). These microstructural features suggest simultaneous coexistence of compatible plagioclase and amphibole (Vernon 1977).

Mineral chemistry

The orthogneisses have homogeneous plagioclases of oligoclase-andesine composition (An_{28-33} ; Appendix: Table 1). K-feldspar grains show normal compositional zoning from Or_{86} in the core to Or_{91} in the rim and Or_{89-92} in smaller grains (Appendix: Table 2).

Biotite is Fe-rich with high $Fe/(Fe+Mg)$ ratio value (0.53-0.60) and low Al^{IV} contents (2.36-2.52 *apfu*) corresponding to annite component enrichment (Appendix: Table 3). The content of TiO_2 in biotite varies from 2.9 to 4.5% and correlates positively with $Fe/(Fe+Mg)$ ratio values. The biotites studied have similar compositions with these from biotite gneisses of the Startsevo unit (Egri dere) and Madan unit along the Vacha river valley (Cherneva et al. 1997).

The paragneisses contain homogeneous plagioclase grains of oligoclase-andesine composition (An_{27-32}), which Ca contents increase (An_{35-39}) close to adjacent garnet grains (sample E168A, from points 5'l-g to 14l-g; Appendix: Table 1), due to Ca diffusion re-equilibration between garnet and plagioclase. Minor amount of interstitial and pressure shadowed K-feldspars as well as larger K-feldspar grains have high Or-

component (Or_{86-90}) and low Ab-component (Ab_{13-09} ; Appendix Table 2).

Biotite compositions have $Fe/(Fe+Mg)$ ratio values (0.51-0.60) similar to biotite in orthogneisses, and larger Al^{IV} variation (2.36-2.62 *apfu*, Appendix: Table 3). There is not systematic compositional distinction between large and small (recrystallized) biotite grains. The content of TiO_2 (1.7-3.3 %) is lower than TiO_2 in orthogneiss biotite. The paragneiss biotite resembles biotite composition of Kanarata shear zone metapelites (Georgieva et al. 2002) situated between Arda and Startsevo units.

Garnet composition is almandine dominated with relatively high and constant spessartine component (XSps 0.13-0.18) (Appendix: Table 4). The grossular component increases from core to rim (XGr from 0.09 to 0.25) while the almandine and pyrope components decrease (XAlm from 0.63 to 0.53 and XPrp from 0.12 to 0.06). The $Fe/(Fe+Mg)$ ratio values increase in the same direction (from 0.84 to 0.90) or keep constant values (Appendix: Table 4). The garnet rim next to biotite is poorer in Fe and Mg- and richer in Ca when compared with garnet rims close to plagioclase grains. The explanation refers to experimental results of slower Ca diffusion during retrograde re-equilibration (Vielzeuf et al. 2007).

The amphibolites comprise homogeneous plagioclase grains of andesine composition (An_{34-37} ; Appendix: Table 1). Plagioclase rims near rare biotite flakes show decrease of An-component (to An_{01}). Very small, anhedral K-feldspar grains (Or_{96} , Ab_{04}) occur between acid plagioclase and biotite suggesting local re-equilibration related to biotite formation.

Biotites from amphibolites differ with lower $Fe/(Fe+Mg)$ ratio values (from 0.40 to 0.43) and higher Al^{IV} contents (2.66-2.67 *apfu*; Appendix: Table 3) when compared with biotites from ortho- and paragneisses.

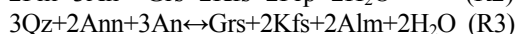
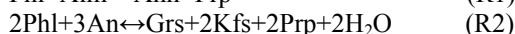
Amphibole has tschermakite composition according to the nomenclature of Leake et al. (1997, 2003). The large crystals display core to rim decrease of Ti (0.13 to 0.08 *apfu*) and small increase of Na (0.36 to 0.44 *apfu*), K (0.09 to 0.14 *apfu*), and Al (2.10 to 2.22 *apfu*)

(Appendix: Table 5). Amphibole inclusions in plagioclase have similar contents of Si, Al, Ti, Mn, Ca and Fe²⁺ like large amphibole cores. The enrichment of Na and K in amphibole rims is due to faster diffusion of alkali elements through crystal lattice during diffusion re-equilibration.

Thermobarometry of paragneisses

The *paragneiss* mineral assemblage is appropriate to determine the *P-T* metamorphic conditions using garnet-plagioclase and garnet-biotite equilibrium pairs whose relations suit the requirements of equilibrium mineral assemblage according to metamorphic petrology microstructural criteria (Vernon 1977; Bucher & Frey 2002; Vernon & Clarke 2008). Selected biotite flakes have ‘clean’ peripheries and cleavage system. The garnet, plagioclase and biotite contacts are smooth and ‘clean’, with no evidence of minerals interaction and replacement or new phase formation showing metamorphic conditions in equilibrium (Fig. 4f).

The TWQ software calculations of Mg, Fe and Ca equilibrium distribution between garnet, biotite and plagioclase offer the following reactions:



The intersection points of R1, R2 and R3 reaction curves correspond to *P-T* values in the temperature interval 630–655°C at pressures from 0.88 to 0.96 GPa for equilibrium assemblage composed of garnet rims, and adjacent large biotite and plagioclase grains (Fig. 6). The participation of smaller biotite and plagioclase grains in association with garnet rims yield higher *P-T* values above 720–740°C at ~1 GPa.

The above reactions allow an application of conventional thermobarometry based on Mg-Fe exchange between garnet and biotite and Ca-exchange between garnet and plagioclase. The popular Fe-Mg exchange garnet-biotite thermometers put some limits regarding mineral chemistry of the pairs,

namely: (Ca+Mn)/(Ca+Mn+Fe+Mg) ratio values up to ~0.2 in garnet and (Al^{VI}+Ti)/(Al^{VI}+Ti+Fe+Mg) up to ~0.15 in biotite (Ferry & Spear 1978); (XGr)³ > 0.03 in garnet and Al^{VI}/(Al^{VI}+Ti+Fe+Mg) > 0.03 in biotite (Wu et al. 2004). Our data meet the requirements of several thermometers (Hodges & Spear 1982; Dasgupta et al. 1991; Thompson 1976; Perchuk & Lavrent'eva 1983; Holdaway & Lee 1977). We have used also the geothermometer of Caddick & Thompson (2008) for pressure estimates.

The garnet-biotite-plagioclase thermobarometer of Caddick & Thompson (2008) defines a temperature range of 630–670°C at pressures from 0.99 to 1.23 GPa (Table 6; Fig. 9). Similar temperature values in the range of 600–660°C yield the garnet-biotite thermometers of Hodges & Spear (1982) and Dasgupta et al. (1991) at given pressures from 0.99 to 1.23 GPa (Table 6; Fig. 9). The temperature estimates obtained from the other garnet-biotite thermometers are close to or below 600°C (Table 6; Thompson 1976; Perchuk & Lavrent'eva 1983; Holdaway & Lee 1977).

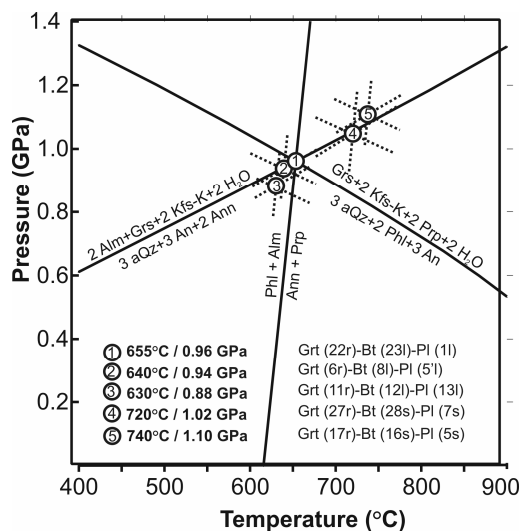


Fig. 6. Thermobarometric estimates using TWQ software (Berman 1991) and thermodynamic database of Berman (1992) with equilibrium reactions

Table 6. *Thermobarometric estimates of selected garnet-plagioclase and garnet-biotite pairs*

Pairs	Garnet	22 r	17 r	27 r	6 r	11 r
	Plagioclase	1 l	5 s	7 s	5 l	13 l
	Biotite	23 l	16 s	28 s	8 l	12 l
P (GPa) after Caddick & Thompson (2008)	600°C	1.03	1.02	0.96	1.04	0.91
	650°C	1.16	1.15	1.08	1.17	1.04
	700°C	1.29	1.28	1.21	1.30	1.17
T (°C) after Caddick & Thompson (2008)	0.9 GPa	649	763	755	633	623
	1.1 GPa	661	775	767	645	635
	1.3 GPa	673	787	779	657	647
T (°C) after Hodges & Spear (1982)	0.9 GPa	643	763	755	633	620
	1.1 GPa	650	771	763	640	627
	1.3 GPa	657	779	771	646	633
T (°C) after Dasgupta et al. (1991)	0.9 GPa	643	770	731	609	598
	1.1 GPa	652	780	742	618	607
	1.3 GPa	661	790	752	627	616
T (°C) after Thompson (1976)	0.9 GPa	613	689	696	585	587
	1.1 GPa	627	704	711	599	601
	1.3 GPa	641	720	726	613	614
T (°C) after Perchuk & Lavrent'eva (1983)	0.9 GPa	586	638	642	567	568
	1.1 GPa	591	643	648	572	573
	1.3 GPa	596	649	654	577	578
T (°C) after Holdaway & Lee (1977)	0.9 GPa	582	647	653	559	560
	1.1 GPa	589	654	660	565	567
	1.3 GPa	595	661	667	572	573

Thermobarometry of amphibolites

The *amphibolite* mineral assemblage offer a possibility to define *P-T* conditions based on Ca-Al-Si exchange between amphibole and plagioclase. Selected pairs represent three types of relations: 1) between subhedral amphibole and plagioclase rims, 2) between subhedral amphibole and plagioclase cores and 3) small euhedral amphibole inclusions and host subhedral plagioclase. The grain contacts are smooth and 'clean' in the three cases (Fig. 5).

The Al/Si ratio values in amphibole-plagioclase pairs are pressure dependent (Fershtater 1990). The Al/Si ratio values in large subhedral amphibole grains as well as in small euhedral amphibole inclusions vary from 0.327 to 0.344 (Appendix: Table 5). The Al/Si ratio values in plagioclase vary from 0.511 to 0.526 (Appendix: Table 1). The Al/Si distribution between amphibole and plagioclase corresponds to

equilibrium at about 0.6 GPa (Fig. 7).

According to Al-in-amphibole geobarometers of Hammarstrom & Zen (1986), Hollister et al. (1987) and Schmidt (1992)

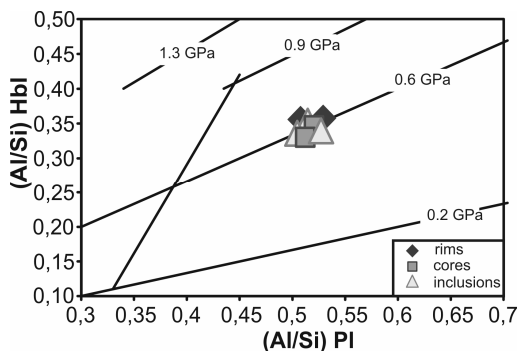


Fig. 7. Al/Si distribution between equilibrium coexisting amphibole and plagioclase from the amphibolite sample E209 after Fershtater (1990)

Table 7. *Thermobarometric estimates of selected amphibole-plagioclase pairs*

Pairs	Amphibole	No	3 r	7 r	4 c	6 c	5 i	11 i	12 i
	Plagioclase	No	2 r	8 r	1 c	9 c	1 c	10 ni	13 ni
P (GPa)	Schmidt (1992)		0.75	0.75	0.70	0.74	0.73	0.71	0.72
	Hammarstrom & Zen (1986)		0.71	0.72	0.67	0.71	0.70	0.68	0.65
	Hollister et al. (1987)		0.79	0.80	0.74	0.78	0.78	0.75	0.76
P (GPa)	Bhadra & Bhattacharya (2007)		0.78	0.57	0.69	0.72	0.69	0.43	0.32
	at 640°C		0.81	0.62	0.74	0.77	0.72	0.48	0.38
	Bhadra & Bhattacharya (2007)		0.99	0.81	0.88	0.93	0.90	0.66	0.59
	at 720°C		0.98	0.83	0.89	0.94	0.90	0.69	0.61
T°C	Holland & Blundy (1994)		683	637	682	659	676	658	630
	at P min		692	674	710	687	698	692	718
	Holland & Blundy (1994)		709	661	699	681	695	686	663
	at P max		700	684	711	695	703	697	721
	Holland & Blundy (1994)		673	640	676	649	669	673	651
	at P after Ferschtater (1990)		689	675	710	683	696	695	720

calculated pressures range from 0.65 to 0.80 GPa (Table 7). The Al-in-amphibole geobarometers although for magmatic rocks, are used here because the studied amphibolites are supposed to have magmatic protolith origin (Raeva 2009).

The garnet-free amphibolite mineral assemblage is appropriate for hornblende-plagioclase geobarometer of Bhada & Bhattacharya (2007) formulated for metamorphic pressure estimating of medium to high-grade metabasic rocks. The results expand the pressure range from 0.57 to 0.99 GPa (Table 7; Fig. 9). The pressures calculated below 0.5 GPa suppose disequilibrium amphibole-plagioclase pairs.

The temperature estimates of the amphibolites are calculated according to the amphibole-plagioclase geothermometer of Holland & Blundy (1994) with additional corrections recommended by Dale et al. (2000) at pressure values according to Fershtater (1990), Hammarstrom & Zen (1986), Hollister et al. (1987), Schmidt (1992) and Bhada & Bhattacharya (2007) (Table 7). The thermometric results range from 640 to 720°C at pressures from 0.57 to 0.99 GPa for all types of amphibole-plagioclase pairs (Fig. 9).

Two-feldspar thermometry

The orthogneiss mineral assemblage allows application of two-feldspar geothermometer. We have used the method of Fuhrman & Lindsley (1988) through SOLV CALC program package (Wen & Nekvasil 1994). The microstructural relations suggest several types of equilibrium pairs of plagioclase and K-feldspar: cores of large subhedral grains; rims of adjacent large subhedral grains; small anhedral adjacent grains; and large grain rims with adjacent small grains. The thermometric calculations at 0.3, 0.5 and 0.7 GPa yield equilibrium temperatures in the range of 524 to 592°C for large grains core-core pairs and 528–552°C for small anhedral grain pairs. The similarity of these results suggests common feldspar re-equilibration during post-migmatic ductile deformation. The temperatures obtained from the other pair types are even lower (445–510°C; Table 8).

Calculated compositions of equilibrium feldspar pairs differ from the real ones with higher Ab- and lower Or-component (both by 1 to 3.5%) in K-feldspar, and slightly higher (by 0.1 to 0.3%) Or-component in the plagioclase. The Ab-exsolution observed in K-feldspar

Table 8. *Temperature estimates of selected plagioclase-K-feldspar pairs from orthogneisses*

Sample	Pairs (Pl-Kfs)	3 GPa	5 GPa	7 GPa
E159A	9 c - 12 c	571	573	592
E171	4 c - 1 c	484	524	529
E171	14 s - 15 s	522	528	529
E171	21 s - 9 s	544	551	552
E171	3 r - 2 r	492	510	525
E173	9 r - 8 s	469	478	481
E166	2 r - 21 s	470	477	495
E166	2 r - 22 s	445	510	523

support an interpretation of deformational induced micropertite formation and retrogressive re-equilibration of feldspar compositions.

Structural state of K-feldspars

The results of X-ray diffraction analysis of K-feldspar mineral fractions from ortho- and paragneisses are shown in Table 9. The amount of Al in 2T1 sites in K-feldspar structure vary in the range from 0.78 to 0.81. Al proportions between T1 (o) and T1 (m) positions are equal with calculated triclinicity (Δp) of 0. There is slight increase of Al in T1 (o) position in limited number of samples, the triclinicity of which reaches up to 0.1 (Table 9, Fig. 8). The triclinicity values from 0 to 0.1 and the coefficient of order $((T1(o)-0.25)/0.75)$ from 0.19 to 0.27 correspond to orthoclase structure of K-feldspars (Wright 1968).

The orthoclase structural state of K-feldspars is characteristics for migmatitic units in the Central Rhodopes (the Arda and the Madan unit along the Vacha river valley) whereas K-feldspars from the lower-grade nonmigmatitic ones (Asenitsa unit) have dominantly microcline structures (Arnaudova et al. 1990). According to cited authors the orthoclase-microcline structural transition spans the temperature range 500-550°C in the Asenitsa unit metamorphic rocks. Irregular appearance of cross-hatched microcline twinning in K-feldspar from orthogneisses in the

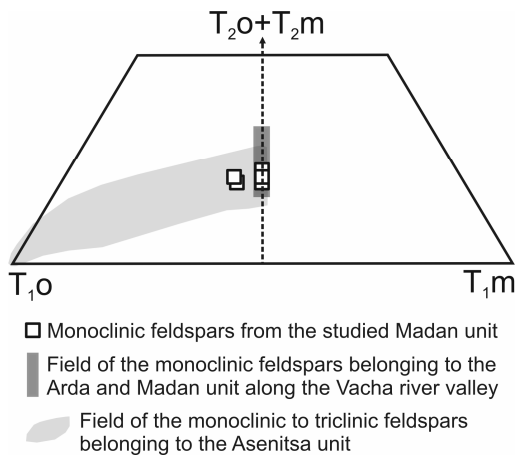


Fig. 8. Al occupancy of tetrahedral sites in alkali feldspars after Stewart & Wright (1974); data for K-feldspars from the Asenitsa, Arda and Madan unit along the Vacha river valley after Arnaudova et al. (1990)

region of the Smilyan shear zone refers to the influence of synmetamorphic subsolidus deformation processes at decreasing temperature. X-ray diffraction study of K-feldspars from the Smilyan pluton indicates orthoclase structural state of K-feldspars everywhere in the granite body with triclinicity values (Δp) equal to zero (Belmustakova 1995).

Table 9. *Al occupancy of tetrahedral sites in K-feldspars from the Madan unit orthogneisses and paragneiss E163 according to Wright (1968)*

Sample	Δp	T1(o)	T1(m)	T1(o)+ T1(m)	T2(o)= T2(m)
E163	0.00	0.40	0.40	0.79	0.10
E149	0.00	0.41	0.41	0.81	0.10
E165	0.00	0.41	0.41	0.81	0.10
E166	0.10	0.45	0.35	0.79	0.10
E171	0.10	0.46	0.36	0.81	0.10
E159A	0.00	0.39	0.39	0.78	0.11
E174	0.00	0.40	0.40	0.80	0.10
E175	0.00	0.40	0.40	0.81	0.10
E196	0.00	0.40	0.40	0.79	0.10
E216A	0.11	0.45	0.34	0.79	0.10

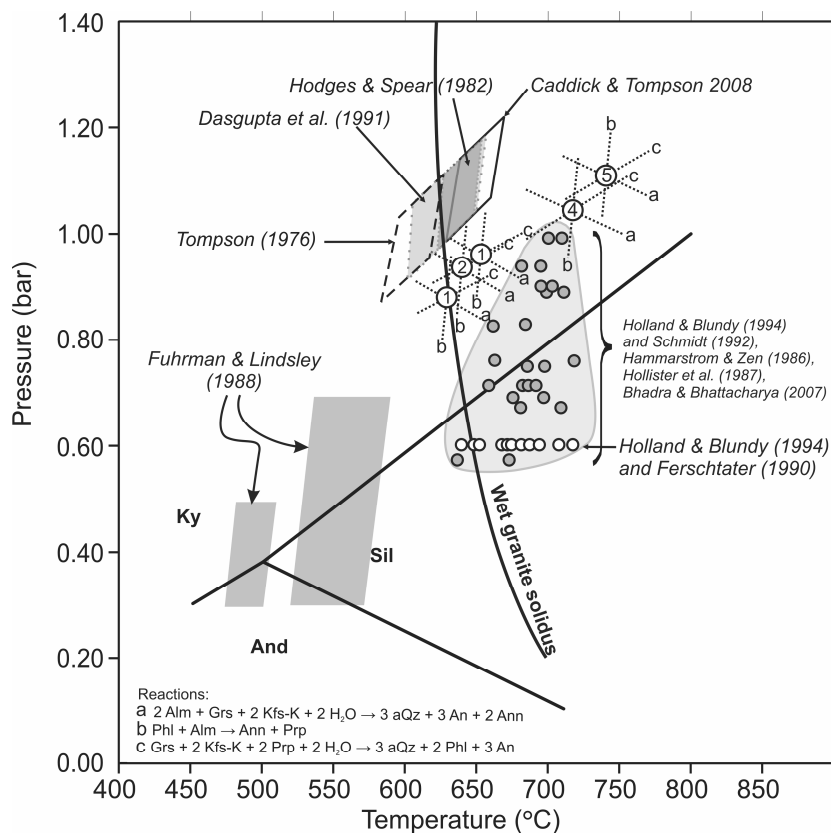


Fig. 9. Thermobarometric results for paragneisses and amphibolites; Ky-Sil-And stability fields after Holdway (1971); wet granite solidus after Johannes (1984); equilibrium triple points between Grt-Bt-Pl after TWQ software (Berman 1991)

Discussion

The thermobarometric results characterize the stage of mineral re-equilibration in orthogneisses, paragneisses and amphibolites during retrograde metamorphic path in the Madan unit along the Arda river valley.

Most of the temperature values for paragneisses cluster together around the water-saturated granite solidus (Fig 9) in conformity with field features of an initial stage of migmatization (metatexis) in the Madan unit gneisses. The temperature range of 600 to 670°C obtained from the geothermometers of Caddick & Thompson (2008), Hodges & Spear (1982), Dasgupta et al. (1991) and TWQ

software, characterize the most probable thermal equilibrium in the metamorphic rocks that crop out to the West of the Smilyan granite (Fig. 2). Higher temperature estimates above 700°C are calculated for pairs of garnet rim and small biotite grains (Figs. 6, 9).

Temperatures far above the wet granite solidus are not consistent with field and microstructural observations of metatexite type of migmatization due to initial stage of low-temperature melting. Some local compositional deviations in garnet (higher Mg and lower Mn) close to adjacent small biotite (Fe^{2+} lower than in large biotites) suggest incomplete equilibration in spite of microstructural evidence of compatible mineral coexistence.

The calculated temperature range of 640-720°C for the amphibolites is higher than that for the paragneisses. A thermal influence of syn- to postmetamorphic granite magma emplacement could be supposed for the eastern part of the Madan unit. The abundant small granite bodies and observed local transitional eastern contacts of the Smilian granite with the host metamorphic rocks support this interpretation.

The obtained metamorphic temperature conditions of the Madan unit along the Arda river valley are similar with these of the Startsevo and Madan unit along the Vacha river valley (Ovcharova 2004; Cherneva et al. 1995).

Microstructural features of the rocks reflect the thermal conditions of synmetamorphic deformation and corresponding mineral recrystallization. Sarov et al. (2005) consider subgrain formation in large K-feldspars, undulose extinction in plagioclase and thin quartz ribbons in orthogneisses of the same area as results of ductile deformation processes. The cited authors observe in local shear zones or in interstices fine-grained, thin aggregates of plagioclase, quartz and biotite controlled by orientated tension and suppose that its formation is due to a ductile deformation in a great depth and fluid presence.

Our observations of undulose to prismatic extinction and 'chessboard' pattern in quartz, 'core-mantle' structures in plagioclases and K-feldspars as well as undulose extinction in K-feldspars from ortho- and paragneisses suggest metamorphic conditions ca. 600-650°C close to the wet granite solidus in accordance with the indicators defined by Kruhl (1996), Passchier & Trouw (1996), Albertz (2006). The mentioned microstructures are typical for deformed and re-equilibrated rocks during retrograde cooling and correspond to the temperature estimate obtained from conventional thermometry.

The orthoclase structure of K-feldspars in ortho- and paragneisses correspond to the temperature range around the wet granite solidus. The local appearance of cross-hatched microcline twinning in K-feldspars from the orthogneisses in the Smilyan shear zone area

has microstructural evidence of deformation origin. The temperature range of 520-590°C and lower (450-510°C) for the orthogneisses obtained from the two-feldspar thermometer of Fuhrman & Lindsley (1988) overlap the orthoclase-microcline structural transition (Stewart & Wright 1974). The temperature results refer to thermal re-equilibration after orthoclase crystallization without destroying the mineral structure.

The pressure results for the paragneisses vary in the extended range from 0.88 to 1.23 GPa and differ from the pressure estimate in the range of 0.57-0.99 GPa for the amphibolites. The pressure variation could be an effect of different erosion levels, namely: lower level for paragneisses that crop out to the North-West of the Smilyan pluton; and higher level for amphibolites situated to the South-East of the pluton. The hypsometric difference between the two levels according to the calculated pressure estimates amounts to 7-11 km. The calculated pressure difference is acceptable having in mind the horizontal distance of about 20 km between paragneiss and amphibolite outcrops and the gneiss foliation dip of 25-30° (Fig. 2). Furthermore, the different types of rocks used for thermobarometry belong to different geochemical systems: K-Na-Ca-Al-Si for paragneisses and Fe-Mg-Ca-Al-Si for amphibolites. Good concomitant verification of the above hypothesis would be additional studies of metabasic rocks from the western part of the Madan unit.

Conclusions

The field relationships and the mineral assemblages of the Madan unit metamorphic rocks reveal a retrogressive regional metamorphic evolution during and after syn- to postkinematic granite magma emplacement. Conventional thermobarometry shows upper amphibolite facies *P-T* metamorphic conditions of 600-670°C/ 0.9-1.2 GPa for the paragneisses and 640-720°C/0.6-1.0 GPa for the amphibolites. The temperatures are in accordance with field observations of initial stage of

migmatization (metatexis), microstructural features and orthoclase structure of K-feldspars. Lower *P-T* conditions towards 520-590°C/0.3-0.7 GPa favoured subsolidus and solidus re-equilibration during synmetamorphic ductile deformation. The obtained thermobarometric results are similar with these for the Startsevo and Madan unit along the Vacha river valley.

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Appendix: Table 1. *Selected plagioclase analyses: (r) rim; (c) core; (s) small grains; (l) large grains; (g) near garnet; (i) inclusion*

Points	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	BaO	Total	X Ab	X An	X Or	X Cn	Al/Si
Orthogneiss E159A														
2 r	61.43	0.00	24.31	0.14	6.07	7.65	0.28	0.12	100.00	0.682	0.299	0.016	0.002	
9 c	61.58	0.00	24.41	0.00	5.93	7.45	0.38	0.14	99.89	0.677	0.298	0.023	0.003	
Orthogneiss E166														
2 r	60.89	0.00	25.46	0.15	5.73	7.42	0.32	0.00	99.98	0.687	0.293	0.020	0.000	
3 c	60.22	0.02	25.87	0.07	6.11	7.15	0.36	0.02	99.82	0.665	0.313	0.022	0.000	
6 c	61.34	0.05	25.18	0.13	5.36	7.55	0.39	0.00	100.00	0.701	0.275	0.024	0.000	
9 c	60.09	0.00	26.15	0.00	6.31	7.10	0.35	0.00	100.00	0.656	0.323	0.021	0.000	
Orthogneiss E171														
3 r	60.29	0.00	25.09	0.13	6.58	7.49	0.29	0.06	99.91	0.661	0.321	0.017	0.001	
4 c	60.95	0.06	24.66	0.11	6.42	7.37	0.34	0.09	99.99	0.661	0.318	0.020	0.002	
14 s	60.99	0.00	24.58	0.09	6.35	7.51	0.29	0.11	99.92	0.669	0.312	0.017	0.002	
21 s	60.65	0.04	24.89	0.04	6.56	7.13	0.36	0.09	99.76	0.648	0.329	0.022	0.002	
Orthogneiss E173														
2 r	61.83	0.00	24.41	0.07	5.76	7.41	0.33	0.02	99.83	0.685	0.294	0.020	0.000	
3 r	59.53	0.00	25.78	0.08	7.29	6.78	0.15	0.00	99.60	0.622	0.370	0.009	0.000	
9 r	62.89	0.05	23.40	0.05	4.86	8.14	0.32	0.00	99.72	0.738	0.243	0.019	0.000	
Paragneiss E168A														
10 l	59.67	0.06	24.89	0.08	6.16	8.17	0.44	0.00	99.55	0.689	0.287	0.024	0.000	
1 l	60.41	0.00	24.65	0.16	5.85	8.32	0.45	0.21	100.05	0.700	0.272	0.025	0.004	
5 s-g	58.46	0.00	26.63	0.17	7.58	7.22	0.15	0.00	100.21	0.627	0.364	0.009	0.000	
7 s	59.35	0.00	25.81	0.26	6.79	7.68	0.24	0.00	100.13	0.663	0.324	0.014	0.000	
9 s	59.12	0.00	25.09	0.09	6.62	8.29	0.22	0.00	99.43	0.686	0.303	0.012	0.000	
5' l-g	58.67	0.00	26.07	0.21	7.70	7.14	0.08	0.00	99.87	0.624	0.372	0.005	0.000	
4 l-g	58.51	0.27	25.94	0.18	7.84	7.02	0.31	0.00	100.07	0.607	0.375	0.018	0.000	
1' l-g	59.23	0.00	25.62	0.12	7.24	7.04	0.45	0.29	99.99	0.618	0.351	0.026	0.005	
13 l-g	58.13	0.03	26.48	0.23	8.11	6.95	0.07	0.00	100.00	0.606	0.390	0.004	0.000	
14 l-g	58.54	0.08	26.25	0.03	7.32	7.29	0.33	0.16	100.00	0.629	0.349	0.019	0.003	
Amphibolite E209														
2 r	58.98	0.00	25.69	0.09	7.69	7.49	0.09	0.10	100.13	0.634	0.360	0.005	0.002	0.514
8 r	58.56	0.00	26.11	0.36	7.38	7.50	0.10	0.16	100.17	0.642	0.349	0.006	0.003	0.526
1 c	59.22	0.00	25.91	0.11	7.21	7.49	0.20	0.45	100.59	0.640	0.341	0.011	0.008	0.516
9 c	59.39	0.00	26.30	0.00	7.63	7.09	0.12	0.29	100.82	0.620	0.368	0.007	0.005	0.522
10 i	59.53	0.08	25.82	0.04	7.52	7.37	0.09	0.00	100.45	0.636	0.359	0.005	0.000	0.511
13 i	58.70	0.13	26.13	0.18	7.64	6.96	0.13	0.14	100.01	0.616	0.374	0.008	0.003	0.525

Appendix: Table 2. *Selected K-feldspar analyses: (c) core; (r) rim; (s) small grains*

Points	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	BaO	Total	X Ab	X An	X Or	X Cn
Orthogneiss E159A													
12 c	65.20	0.00	18.17	0.00	0.15	1.37	14.36	0.58	99.83	0.125	0.008	0.857	0.011
13 r	65.10	0.10	18.19	0.04	0.09	1.21	14.65	0.50	99.89	0.110	0.005	0.876	0.009
16 r	65.22	0.04	18.21	0.01	0.00	0.89	14.87	0.66	99.90	0.082	0.000	0.905	0.012
11 s	65.01	0.00	18.10	0.01	0.09	0.84	15.40	0.54	100.00	0.075	0.004	0.910	0.010
Orthogneiss E166													
21 s	64.23	0.00	18.96	0.01	0.05	0.76	15.30	0.54	99.86	0.069	0.003	0.918	0.010
22 s	64.24	0.00	19.21	0.00	0.10	0.75	15.16	0.47	99.93	0.069	0.005	0.917	0.009
Orthogneiss E171													
1 s	65.10	0.04	18.45	0.05	0.07	1.03	14.91	0.35	100.00	0.094	0.004	0.896	0.007
2 s	64.82	0.00	18.06	0.06	0.08	0.80	15.57	0.57	99.97	0.072	0.004	0.914	0.010
9 s	65.02	0.03	18.21	0.04	0.09	1.13	14.95	0.35	99.83	0.102	0.005	0.887	0.006
15 s	64.73	0.13	18.31	0.10	0.11	0.98	15.12	0.44	99.91	0.089	0.005	0.898	0.008
Orthogneiss E173													
1 s	65.16	0.01	18.49	0.05	0.11	0.59	15.04	1.12	100.57	0.055	0.005	0.918	0.021
8 s	64.18	0.00	18.64	0.04	0.04	0.86	14.99	1.16	99.92	0.078	0.002	0.898	0.021
Paragneiss E163													
24 s	64.33	0.00	19.30	0.00	0.05	0.98	14.37	0.93	99.96	0.003	0.092	0.889	0.017
27 r	64.01	0.00	19.47	0.01	0.02	0.92	14.66	0.73	99.83	0.001	0.086	0.899	0.014
28 c	63.94	0.00	19.62	0.12	0.09	1.14	14.18	0.86	99.95	0.005	0.107	0.872	0.016
Paragneiss E168A													
6 r	65.51	0.00	18.33	0.08	0.00	1.46	14.32	0.30	100.00	0.134	0.000	0.861	0.005

Appendix: Table 3. *Selected biotite analyses from paragneisses, orthogneisses and amphibolites: (l) large; (s) small*

Rock type	Paragneiss										
Sample	E168A									E163	
Point	11 l	23 l	16 s	28 s	35 l	8 l	9 l	3 l	12 l	15 l	18 l
SiO ₂	37.44	34.86	36.22	36.39	36.28	36.87	36.99	36.57	37.13	35.46	36.55
TiO ₂	1.79	1.71	1.88	2.12	1.74	3.00	3.25	3.09	2.84	3.11	3.08
Al ₂ O ₃	16.56	16.55	16.79	16.69	16.96	16.49	16.05	16.17	16.44	19.07	19.39
FeO	21.44	22.74	21.16	20.74	20.92	21.44	21.89	21.00	21.88	18.12	18.37
MnO	0.36	0.46	0.37	0.70	0.52	0.56	0.58	0.50	0.87	0.32	0.29
MgO	10.20	9.48	10.68	9.41	10.08	8.73	8.36	9.10	8.98	9.40	9.83
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.01
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.49	0.00	0.10	0.10
K ₂ O	8.84	10.17	9.32	9.98	9.65	9.59	9.83	9.80	9.27	9.63	9.73
Total	96.63	95.97	96.42	96.03	96.15	96.68	96.95	96.72	97.41	95.31	97.36
<i>apfu at 22 O atoms</i>											
Si	5.64	5.42	5.50	5.57	5.53	5.60	5.62	5.56	5.60	5.38	5.41
Ti	0.20	0.20	0.21	0.24	0.20	0.34	0.37	0.35	0.32	0.35	0.34
Al ^{IV}	2.36	2.58	2.50	2.43	2.47	2.40	2.38	2.44	2.40	2.62	2.59
Al ^{VI}	0.59	0.45	0.51	0.58	0.58	0.55	0.50	0.46	0.52	0.79	0.79
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ⁺³	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ⁺²	2.70	2.96	2.69	2.65	2.67	2.72	2.78	2.67	2.76	2.30	2.27
Mn	0.05	0.06	0.05	0.09	0.07	0.07	0.07	0.06	0.11	0.04	0.04
Mg	2.29	2.20	2.42	2.15	2.29	1.97	1.89	2.06	2.02	2.12	2.17
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.03	0.03
K	1.70	2.02	1.81	1.95	1.88	1.86	1.91	1.90	1.78	1.86	1.84
Totals	15.53	15.88	15.68	15.66	15.68	15.51	15.52	15.66	15.51	15.51	15.49
Fe ²⁺ /(Fe ²⁺ + Mg)	0.54	0.57	0.53	0.55	0.54	0.58	0.60	0.56	0.58	0.52	0.51

Table 3. (continuation)

Rock type	Orthogneiss									Amphibolite	
Sample	E159A			E166		E171				E209	
Point	8	17	18	14	15	5	7	8	11	27	28
SiO ₂	35.54	35.51	36.26	36.69	36.00	35.86	36.02	36.16	36.16	35.57	36.11
TiO ₂	4.48	3.77	3.46	3.47	2.99	3.57	3.47	2.86	3.18	1.65	1.71
Al ₂ O ₃	15.89	16.68	16.32	17.17	16.59	15.19	14.99	15.55	15.33	19.99	20.12
FeO	20.98	20.30	21.47	20.37	19.91	20.55	19.59	20.44	21.09	16.48	15.47
MnO	0.57	0.56	0.53	0.43	0.44	0.34	0.38	0.32	0.29	0.08	0.11
MgO	7.89	8.03	7.96	9.79	10.04	8.96	9.24	9.71	9.71	12.18	13.03
CaO	0.02	0.07	0.00	0.01	0.04	0.03	0.11	0.05	0.00	0.00	0.00
Na ₂ O	0.06	0.13	0.07	0.06	0.10	0.03	0.04	0.09	0.04	0.00	0.00
K ₂ O	9.69	9.60	9.63	9.95	9.67	9.67	9.62	9.56	9.69	9.25	9.27
Total	95.12	94.63	95.69	97.94	95.76	94.21	93.46	94.73	95.48	95.20	95.82
<i>apfu</i> at 22 O atoms											
Si	5.51	5.50	5.58	5.48	5.50	5.59	5.64	5.59	5.57	5.33	5.34
Ti	0.52	0.44	0.40	0.39	0.34	0.42	0.41	0.33	0.37	0.19	0.19
Al ^{IV}	2.49	2.50	2.42	2.52	2.50	2.41	2.36	2.41	2.43	2.67	2.66
Al ^{VI}	0.41	0.55	0.53	0.50	0.48	0.39	0.41	0.43	0.36	0.86	0.85
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ⁺³	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ⁺²	2.72	2.63	2.76	2.54	2.54	2.68	2.56	2.65	2.72	2.06	1.91
Mn	0.07	0.07	0.07	0.05	0.06	0.05	0.05	0.04	0.04	0.01	0.01
Mg	1.82	1.86	1.82	2.18	2.28	2.08	2.16	2.24	2.23	2.72	2.87
Ca	0.00	0.01	0.00	0.00	0.01	0.00	0.02	0.01	0.00	0.00	0.00
Na	0.02	0.04	0.02	0.02	0.03	0.01	0.01	0.03	0.01	0.00	0.00
K	1.91	1.90	1.89	1.89	1.88	1.92	1.92	1.89	1.91	1.77	1.75
Totals	15.49	15.50	15.52	15.58	15.62	15.56	15.54	15.61	15.63	15.61	15.59
Fe ²⁺ /(Fe ²⁺ + Mg)	0.60	0.59	0.60	0.54	0.53	0.56	0.54	0.54	0.55	0.43	0.40

Appendix: Table 4. Selected garnet analyses from paragneiss sample E1684: (c) core; (r) rim; (b) near biotit., (p) near plagioclase

Point	12r-b	13r-p	14c	22r	20c	17r	18c	27r	29c	34r-b	36r-p	33c	6r	7c	2c	11r	10c
SiO ₂	39.06	38.83	38.05	35.59	37.35	38.18	38.08	37.94	38.49	37.84	36.87	37.11	36.98	37.03	36.93	37.29	37.45
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.15	0.31	0.00	0.00
Al ₂ O ₃	21.06	20.95	21.02	18.96	21.24	21.23	21.06	20.97	20.98	21.34	21.08	20.43	20.88	21.05	20.44	20.63	20.98
FeO	23.20	24.08	27.73	29.21	27.50	24.14	27.35	24.93	24.79	24.90	26.93	28.69	23.44	28.42	27.66	25.46	27.66
MnO	6.18	5.94	6.41	7.22	7.33	5.95	6.00	6.90	6.58	6.57	6.71	6.69	6.93	7.20	7.79	7.27	7.14
MgO	1.91	2.79	2.88	2.07	3.04	2.70	2.86	2.56	1.74	2.50	3.14	2.93	1.46	2.61	2.16	1.61	2.41
CaO	8.64	7.24	3.64	6.41	3.03	7.84	4.35	6.05	7.74	6.74	5.15	3.54	8.13	3.54	3.53	6.75	3.74
Total	100.05	99.83	99.73	99.46	99.49	100.04	99.70	99.25	100.32	99.89	99.88	99.43	97.87	100.00	98.82	99.01	99.38
<i>apfu at 12 O atoms</i>																	
Si	3.08	3.07	3.04	2.94	3.00	3.02	3.04	3.04	3.05	3.01	2.96	3.00	3.01	2.98	3.01	3.02	3.02
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00
Al	1.96	1.95	1.98	1.85	2.01	1.98	1.98	1.97	1.96	2.00	2.00	1.95	2.01	2.00	1.96	1.97	2.00
Fe ²⁺	1.53	1.59	1.85	2.02	1.85	1.60	1.83	1.67	1.65	1.66	1.81	1.94	1.60	1.91	1.89	1.73	1.87
Mn	0.41	0.40	0.43	0.51	0.50	0.40	0.41	0.47	0.44	0.44	0.46	0.46	0.48	0.49	0.54	0.50	0.49
Mg	0.23	0.33	0.34	0.26	0.36	0.32	0.34	0.31	0.21	0.30	0.38	0.35	0.18	0.31	0.26	0.19	0.29
Ca	0.73	0.61	0.31	0.57	0.26	0.67	0.37	0.52	0.66	0.58	0.44	0.31	0.71	0.31	0.31	0.59	0.32
Total	7.94	7.95	7.97	8.14	7.99	7.99	7.97	7.98	7.97	7.99	8.04	8.02	7.98	8.01	7.99	7.99	7.98
X Alm	0.53	0.54	0.63	0.60	0.62	0.54	0.62	0.56	0.56	0.56	0.59	0.63	0.54	0.63	0.63	0.57	0.63
X Prp	0.08	0.11	0.12	0.08	0.12	0.11	0.12	0.10	0.07	0.10	0.12	0.12	0.06	0.10	0.09	0.06	0.10
X Grs	0.25	0.21	0.11	0.17	0.09	0.22	0.13	0.18	0.22	0.19	0.14	0.10	0.24	0.10	0.10	0.20	0.11
X Sps	0.14	0.14	0.15	0.15	0.17	0.13	0.14	0.16	0.15	0.15	0.15	0.15	0.16	0.16	0.18	0.17	0.16
#Fe*	0.87	0.83	0.84	0.89	0.84	0.83	0.84	0.85	0.89	0.85	0.83	0.85	0.90	0.86	0.88	0.90	0.87

* #Fe = Fe²⁺ / (Fe²⁺ + Mg)

Appendix: Table 5. *Selected amphibole analyses from amphibolite sample E209: Fe³⁺ from 13-CNK, r - rim, c - core, i - inclusion*

Points	3 r	7 r	4 c	6 c	5 i	11 i	12 i
SiO ₂	43.23	43.49	43.45	43.84	42.98	43.50	42.74
TiO ₂	0.75	0.97	1.15	1.01	0.93	1.20	1.10
Al ₂ O ₃	12.57	12.68	12.06	12.57	12.35	12.20	12.10
FeO	16.28	16.30	17.28	16.34	16.60	15.44	15.89
MnO	0.58	0.48	0.53	0.30	0.48	0.49	0.24
MgO	10.01	9.71	9.68	10.04	9.75	10.47	10.29
CaO	11.41	11.86	11.56	11.69	11.42	11.65	11.99
Na ₂ O	1.43	1.52	1.26	1.39	1.48	1.62	1.60
K ₂ O	0.73	0.73	0.48	0.65	0.60	0.71	0.56
Total	96.99	97.74	97.45	97.83	96.59	97.28	96.51
<i>apfu</i> at 23 O atoms							
Si	6.413	6.448	6.429	6.454	6.418	6.447	6.412
Al [IV]	1.587	1.552	1.571	1.546	1.582	1.553	1.588
<i>T</i>	8	8	8	8	8	8	8
Al [VI]	0.610	0.664	0.532	0.635	0.592	0.578	0.551
Ti	0.084	0.108	0.128	0.112	0.104	0.134	0.124
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ³⁺	0.633	0.328	0.666	0.480	0.585	0.408	0.363
Fe ²⁺	1.386	1.693	1.472	1.532	1.488	1.505	1.630
Mn	0.073	0.060	0.066	0.037	0.061	0.062	0.030
Mg	2.214	2.146	2.135	2.204	2.171	2.313	2.301
<i>C</i>	5	5	5	5	5	5	5
Ca	1.813	1.884	1.833	1.844	1.827	1.850	1.927
Na	0.187	0.116	0.167	0.156	0.173	0.150	0.073
<i>B</i>	2	2	2	2	2	2	2
Na	0.225	0.321	0.194	0.241	0.255	0.315	0.392
K	0.138	0.138	0.091	0.122	0.114	0.134	0.107
<i>A</i>	0.363	0.459	0.285	0.363	0.370	0.449	0.499
T=13	13.18	13.09	13.19	13.14	13.17	13.12	13.10
Mg/(Mg+Fe ²⁺)	0.61	0.56	0.59	0.59	0.59	0.61	0.59
Al/Si	0.343	0.344	0.327	0.338	0.327	0.331	0.334

