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Kyanite eclogite xenolith from the orthogneiss terrane of the Tisza Megaunit, Jánoshalma area, crystalline basement of southern Hungary

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Abstract

New evidence for high-pressure, eclogite facies metamorphism in the crystalline basement of the Tisza Megaunit (southern Hungary) is reported. The retrogressed mafic eclogite forms a small lens in the orthogneiss and it was found in the borehole near Jánoshalma. The carbonated eclogite contains the peak metamorphic assemblage omphacite + garnet + phengite + kyanite + clinozoizite + rutile + K-feldspar + quartz. Omphacite ($Xjd_{0.40-0.41}Xdio_{0.52-0.53}Xhd_{0.05}Xaug_{1.55-2.85}$) occurs in the matrix and as inclusions in garnet ($Xpy_{0.37-0.38}Xgrs_{0.21-0.22}Xalm_{0.39-0.40}Xsps_{0-0.01}Xadr_{0-0.01}$) and kyanite. Thermobarometry based on net-transfer reactions between garnet, omphacite, kyanite and phengite yields *P–T* conditions of 710 ± 10 °C and 2.6 ± 0.75 GPa. Retrogression during decompression is manifested by formation of symplectites; the most typical are diopside + plagioclase after omphacite, corundum + spinel + plagioclase after kyanite and biotite + plagioclase after phengite. Carbonatization along the veins of the retrogressed eclogite was probably coeval with formation of these symplectites. At places where carbonate is absent the rock was completely hydrated and retrogressed down to the greenschist facies with the development of actinolite. Similar eclogites together with abundant orthogneisses occur mainly in the eastern parts of the Tisza Megaunit, suggesting the existence of an ancient (possibly Variscan) subduction/accretionary complex.
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Keywords: Eclogite; Carbonated veins; High-pressure metamorphism; Thermobarometry; Tisza Megaunit

1. Introduction

Metabasic eclogites are more useful to constraining the high-pressure metamorphism than their felsic gneiss host rocks. Peak mineral assemblages in the metabasites define a more restricted region of *P–T* space than those in the felsic rocks and metabasic eclogites contain records of incomplete transformation along the retrograde *P–T* path (coronas, symplectites) that allow this *P–T* path to be quantified (Rubie, 1990; Elvevold and Gilotti, 2000; Medaris et al., 2003). The felsic host rocks commonly completely re-equilibrate their mineral assemblages along the retrograde *P–T* path and hence have no memory of the earlier, peak high-pressure metamorphism (Wang and Liou, 1991; Carswell et al., 2000; Hirajima and Nakamura, 2003).

Eclogite facies metamorphism in the European Variscan belt verifies the important role played by subduction in evolution of the Variscan orogen (O'Brien

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et al., 1990). Although very rare, in Hungary eclogites occur in the metamorphic basement of the Tisza Megaunit, southern Hungary (Ravasz-Baranyai, 1969; M. Tóth, 1995, 1996, 1997a,b; Lelkes-Felvári et al., 2003, Zachar and M. Tóth, 2004) (Fig. 1). The Tisza Megaunit (Fig. 1) forms the crystalline basement of

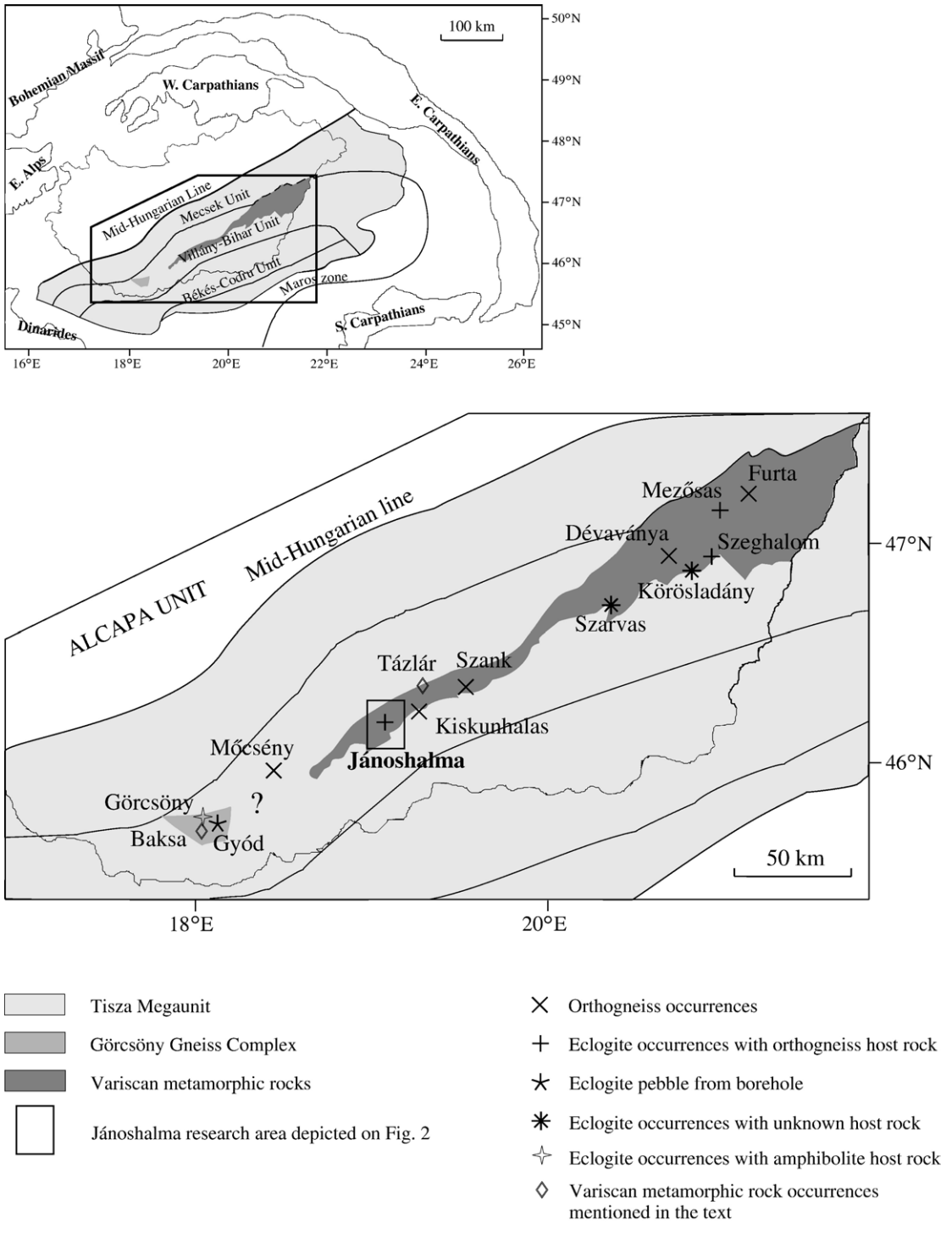


Fig. 1. Simplified geological map of the Tisza Megaunit in the Alpine–Carpathian–Dinaric system showing the position of the Jánoshalma and other crystalline basement highs within the Tisza Megaunit.

southern Hungary and it can be traced in northern Croatia, Serbia and western Transylvania (Szepesházy 1973, 1975, 1980; Jantsky 1979, 1980; Scheffer, 1963; Dank and Bodzay 1970; Cserepes Meszéna 1985, 1986; Szili 1985; Szili-Gyémánt, 1986; Balázs et al. 1985, 1986) (Fig. 1). According to the currently accepted model (Haas, 2004 and references therein), the Tisza Megaunit was detached from the northern, European margin of the Tethys in the late Jurassic (Bathian). It is located between the Mid-Hungarian Line and the Maros zone that separates it from the Southern Carpathians (Fig. 1). The Tisza Megaunit consists of Variscan crystalline metamorphic rocks covered by Tertiary and younger sediments of hundreds to, in the eastern part, of thousands of metres thickness. Therefore the investigation of the basement rocks of the Tisza Megaunit is possible only from boreholes. There are relatively well-known segments of the Tisza basement in the SW (Baksa, Görcsöny) and NE (Körös Complex) (Fig. 1), whereas the central parts are not well-understood. Based on occurrence of eclogites, the existence of a suture zone along Görcsöny Gneiss Complex and Körös Complex, possibly of Variscan age has been suggested (Szederkényi 1977, 1984; M. Tóth and Zachar 2002). Eclogite found recently in the Jánoshalma high (Fig. 2) plays an important role because it is relatively well-preserved, recording the peak high-pressure stage. It is located in the middle part of the crystalline basement of the Tisza Megaunit (Fig. 1).

In this paper we present the new mineralogical, petrological and geochemical data on the eclogite from Jánoshalma which constrain its metamorphic evolution. The eclogite facies mineral assemblage was observed along the veins of the completely hydrated greenschist facies metabasite where pervasive carbonatization occurred. The hydrated greenschist facies rock exhibits a symplectitic texture. On the basis of geothermobarometric calculations the *P–T* conditions of eclogite facies peak metamorphic stage are evaluated and relationships with the host gneisses are discussed. We attempt to correlate the eclogites and their country rocks within the Tisza Megaunit.

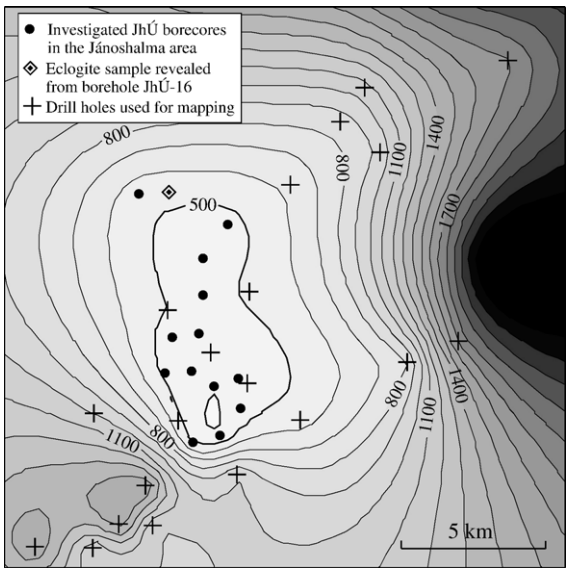


Fig. 2. Topographic map of the Jánoshalma crystalline high.

2. Geological background and former research

As a consequence of the Neogene evolution of the Pannonian Basin, the metamorphic basement of the Great Hungarian Plain consists mainly of deep basins separated by elevated crystalline highs. These highs are built mainly by gneisses and amphibolites; their structure is usually rather complex and characterised by adjacent blocks of different metamorphic evolution.

There are relatively well-known metamorphic terrains both to the SW (Baksa, Görgeteg Complexes) and NE from the Jánoshalma high (e.g. Fülöp, 1994). At the Tázlár and Kiskunhalas locations (Fig. 1), the nearest investigated areas to the N–NE of Jánoshalma, the low-grade quartz phyllites, carbonate-bearing phyllites, muscovite–biotite gneisses, mica-poor granites, granite gneisses and amphibolites dominate (Szepesházy, 1972; Cserepes Meszéna, 1978; Szederkényi, 1984). The Görcsöny area to the SW consists mainly of mica schists and gneisses of different metamorphic grades. Thick calc-silicate marble, thinner dolomite-marble and amphibolite layers are intercalated in the gneiss-rich units. The metamorphic terrane exhibits a continuous transition from chlorite up to the sillimanite zone (Szederkényi, 1976, 1977). Árkai et al. (1999) determined a clockwise *P–T* path from successive mineral parageneses in paragneisses of borehole Baksa-2. Two prograde and retrograde metamorphic events were identified. The first prograde event is characterised by the presence of kyanite and *P–T* conditions of 480±50 °C and 0.47±0.07 GPa, whereas the peak conditions of the second prograde one reached 660±25 °C and 0.75±0.05 GPa with the co-existence of kyanite and staurolite. The third, retrograde stage of metamorphism due to decompression is marked by the occurrence of sillimanite with *P–T* conditions of 650±40 °C and 0.44±0.02 GPa.

The Jánoshalma basement high is interpreted to be a uniform block of orthogneiss penetrated by granite veins and containing amphibole and garnet xenocrysts, and xenoliths of different rock types as eclogite, amphibolite.

Besides eclogite and amphibolite, felsic granulite, pyroxenite and serpentinite were observed from the same orthogneiss in the Mezősas and Furta area (Fig. 1) (Zachar and M. Tóth, 2003). The protolith of the orthogneiss was determined as granodiorite (Zachar and M. Tóth, 2003). Because of the different chemical composition and metamorphic evolution of the xenoliths embedded in the former granodiorite (now orthogneiss), those are presumably not unmelted residual nebulites in the granodiorite. According to previous investigations on the metamorphic evolution of the different xenoliths (M. Tóth and Zachar, 2003, 2006; Zachar and M. Tóth, 2004) we instead consider that granodiorite had sampled the xenocrysts and the high-, medium- and low-pressure rocks from the subduction melange in an ancient subduction-accretionary complex. If the whole orthogneiss body was subducted, all of these xenoliths should be affected by high-pressure metamorphism. This is not observed; therefore the former interpretation is preferred.

The fabric related to metamorphism of xenoliths (i.e. that transformed the mafic igneous protolith into eclogite) is termed D1, and predated the formation of the granodiorite intrusion. The granodiorite transformed into orthogneiss during a metamorphic event related to D2 that reached the sillimanite isograde, and resulted in the development of a garnet+biotite+sillimanite± muscovite assemblage in this body. The last D3 event resulted in an overprint with a well-developed foliation defined by biotite and/or muscovite (Zachar and M. Tóth, 2003) (Fig. 5f). Re-equilibrated rim of the amphibole xenocryst together with matrix plagioclase in the orthogneiss, yield temperature of approximately 600 °C for D3 (Zachar and M. Tóth, 2004). There is no clear evidence of HP phases in the orthogneiss, although rare occurrence of rutile inclusions in the very small amount of garnet, a single kyanite inclusion in S2 white mica and a few sillimanite pseudomorphs possibly after kyanite may indicate it.

It is still under debate whether there exists any connection between the metamorphic blocks of the Görcsöny and Körös areas within the Tisza Megaunit. One possible correlation point may be the sporadic occurrence of eclogites (Ravasz-Baranyai, 1969; M. Tóth, 1995, 1996, 1997a,b; Horváth et al., 2003, Lelkes-Felvári et al., 2003, Zachar and M. Tóth, 2004). It is typical mainly for the Körös Complex but two samples of eclogites have been found also in the Görcsöny area (Ravasz-Baranyai, 1969; Horváth et al., 2003). This indicates an ancient suture zone along the Görcsöny and Körös Complex areas (Fig. 1).

The first eclogite was described from the borehole Görcsöny-1 in the southwestern part of the Tisza Megaunit (Ravasz-Baranyai, 1969). M. Tóth (1995, 1997b) investigated retrogressed eclogites from the boreholes Körösladány-5, Szeghalom-2, Szeghalom-40 and Szarvas-16. However, except of tiny garnet grains of $Xpy_{0.29}Xgrs_{0.24}Xalm_{0.47}Xsps_{0}Xadr_{0}$ composition (Fig. 3), only symplectitic and corona textures suggesting the former high-pressure event, e.g. amphibole+plagioclase after pyroxene, tremolite+epidote+magnetite+albite+chlorite after crosstie (e.g. Brown, 1977; Yardley, 1982; Maruyama et al., 1986) have been found. In addition, the Szarvas-16 sample shows garnet ($Xpy_{0.35–0.40}Xgrs_{0.15–0.20}Xalm_{0.35–0.40}Xsps_{0–0.20}Xadr_{0–0.50}$) (Fig. 3) with relics of clinopyroxene ($Xjd_{0–0.3}Xdio_{0.70–0.75}Xhd_{0.25}$), kyanite and phengite. Because of the absence of stable eclogite facies mineral parageneses only a rough estimation of the peak conditions (600–650 °C; 1.0–1.2 GPa) was possible.

Lelkes-Felvári et al. (2003) found an exposure of retrogressed eclogite in the borehole Mezősas-2 (Fig. 1). This is the easternmost known eclogite occurrence within the Tisza Megaunit. The sample is strongly retrogressed, with only garnet and diopside+plagioclase symplectites (together inferred to have completely replaced omphacite) indicate a former eclogite facies metamorphism.

Horváth et al. (2003) found eclogite in the borehole Gyód-2. This eclogite occurs as a pebble in the Miocene conglomerates that cover the Variscan crystalline basement of the Tisza Megaunit in southwestern Hungary. Omphacitic pyroxene, garnet, rutile and quartz were determined as the peak assemblage. From this

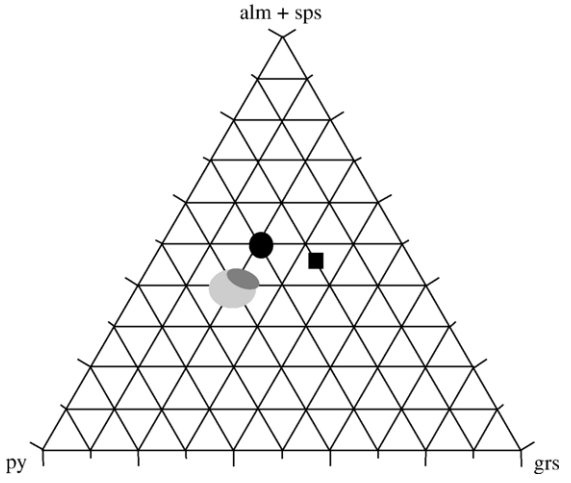


Fig. 3. Garnet composition from the different eclogite localities of the Tisza Megaunit. The (almandine+spessartine)–pyrope–grossular diagram after Coleman et al. (1965). Single black square: Görcsöny eclogite; light grey spot: Szarvas eclogite; black circle: Körösladány eclogite; dark grey spot: Jánoshalma eclogite.

paragenesis, the *P–T* conditions of 600–650 °C and 1.3–1.5 GPa were estimated for the metamorphic peak.

It is important to mention that all eclogitic samples were found in the boreholes and therefore there is only poor information on the extent and thickness of these eclogites. Only one drill hole has crosscut the eclogite body, revealing the eclogite size of only few tens of centimetres.

3. Analytical methods

Major and trace elements were measured by X-ray fluorescence method at the University of Veszprém, using a Philips PW 2404 spectrometer. Nuclear electron activation method was applied for determining the trace element composition, in the nuclear reactor of BME, Budapest. Mineral compositions were determined by a WDS analysis using a Cameca SX-100 electron microprobe at the Geological Survey (GÚDŠ) in Bratislava. Operating conditions were 15 kV acceleration Voltage and 15 nA sample current. Beam diameter was 2 μm for garnet and clinopyroxene, 10 μm for mica and 5 μm for amphibole, zoizite, K-feldspar and other minerals, using natural and synthetic standards.

4. Bulk rock chemistry

Major and trace element compositions of five eclogite samples (Tables 1 and 2) were measured. All eclogite samples are from borehole Jh-Ú-16 and belong to the same three-metre long bore core. Except of sample 1/3, extremely high values of LOI values are due to the carbonate that pervasively altered the amphibole-plagioclase symplectite matrix of the retrogressed eclogite. Because of the possible major element mobilization during metamorphism (particularly K_2O and Na_2O), the geochemical composition may not unavoidably represent protolith affinities.

Table 1
Major element compositions of the Jánoshalma eclogite samples

[wt.%]	Eclogite samples				
	1/1	1/2	1/3	1/4	1/5
SiO_2	42.89± 1.12	53.07± 1.38	51.87±1.35	47.29± 1.23	48.21± 1.25
TiO_2	0.84±0.05	0.97±0.06	0.77±0.04	0.96±0.06	0.75±0.04
Al_2O_3	15.52± 0.90	13.88± 0.81	17.43± 1.01	17.09± 0.99	15.44± 0.90
MgO	5.44±0.41	2.85±0.22	6.74±0.51	3.58±0.27	4.02±0.30
CaO	12.63± 1.02	9.94±0.81	7.19±0.58	5.31±0.43	6.71±0.54
MnO	0.31±0.04	0.11±0.01	0.09±0.01	0.12±0.01	0.10±0.01
Fe_2O_3	8.37±0.27	6.41±0.21	6.89±0.22	9.06±0.29	8.01±0.26
Na_2O	3.01±0.46	3.06±0.47	3.16±0.49	2.90±0.45	3.05±0.47
K_2O	0.78±0 02	0.88±0.03	1.70±0.05	1.83±0.06	1.28±0.04
P_2O_5	0.13±0.01	0.11±0.01	0.09±0.01	0.08±0.01	0.07±0.01
S	<0.001	<0.001	<0.001	<0.001	<0.001
LOI	9.32	7.48	3.22	10.75	10.71
Total	99.24	98.76	99.15	98.97	98.35

Table 2
Trace element compositions of the Jánoshalma eclogite

[ppm]	Eclogite samples				
	1/1	1/2	1/3	1/4	1/5
Cr	193±18	206±19	182±17	167±16	120±11
Co	45±2	25±1	33±1	46±2	65±3
Ni	197±9	111±5	132±6	163±8	391±19
Cu	37±2	72±3	30±1	56±2	141±6
Pb	13±1	17±1	13±1	21±1	19±1
Zn	54±2	61±2	48±2	110±4	215±7
Rb	25±1	32±1	58±2	73±3	48±2
Sr	289±4	463±6	220±3	396±6	300±4
Y	20±2	22±2	18±2	23±2	16±1
Zr	89±2	134±4	86±2	103±3	86±2
Mo	<1	<1	<1	<1	<1
V	98±3	144±5	118±4	166±6	88±3
Cs	7±4	17±7	10±6	8±5	7±4
Ba	231±29	360±45	275±34	566±70	209±26
La	13±1	9±1	9±1	8±1	15±2
Ce	<9	<9	<9	<9	12±1
Pr	<6	<6	6±	<6	<6
Nd	<6	8±1	<6	12±2	<6
Nb	<1	<1<	<1	<1	<1
Th	7±1	10±2	6±1	8±1	8±1

Based on major element composition, Mg number (Mg#=100 MgO/(MgO+FeO); O'Neill and Wood, 1979) of the five borecores varies between 28 and 50. Mg# of the investigated core is ~40. According to the FeO^{tot}–MgO–Alk diagram of Irvine and Baragar (1971), the examined samples plot to the calc-alkaline field (Fig. 4a). Using only incompatible and essentially immobile trace elements for classification, both Ti–Zr–Sr and Ti–Zr–Y diagrams (Pearce and Cann, 1973) (Fig. 4b,c) suggest a calc-alkaline character of the basalts. Despite the evolved state of alteration, based on the concordant results of the above discrimination plots the protolith of the Jánoshalma eclogite is thought to be a sub-alkaline andesite–basalt.

5. Petrography and mineral chemistry

The investigated eclogite from the Jánoshalma area is yellow, with dark greenish parts of a few centimetres wide. The yellow parts seem to form the veins within the green segments (Fig. 5a). On the basis of microscopic observations, two varieties of eclogite — yellow and

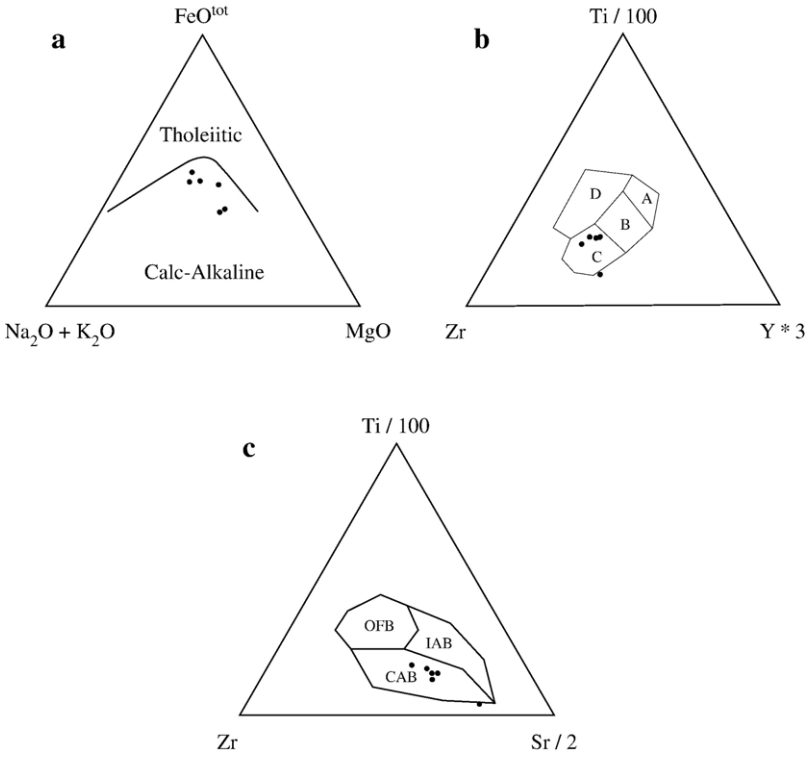


Fig. 4. Geochemical characteristics of the Jánoshalma eclogite. (a) FeO^{tot}–MgO–Alk (Irvine and Baragar, 1971) (b) Ti–Y–Zr (Pearce and Cann, 1973), B, C: calc-alkaline basalt. (c) Ti–Sr–Zr (Pearce and Cann, 1973), CAB: calc-alkaline basalt. For details see text.

green can be distinguished. Except bore core 1/3 (Table 1) that represents the green type all samples are cut by carbonate veins and the amphibole of the amphibole–plagioclase symplectite matrix of the rock is fully turned to carbonate.

Both types show a symplectitic texture of amphibole (amph1) and plagioclase, with amphibole porphyroblasts (amph2) set in this symplectitic matrix (Fig. 5b and e). The main difference between them is the presence of remarkable amount of garnet (Fig. 5b), kyanite (Fig. 5d) and zoizite, as well as occurrence of phengite and clinopyroxene (cpx1) in the yellow type (Fig. 5c). These phases are absent in the green type; only sporadic appearance of small, resorbed garnet is discernible (Fig. 5e). The green type contains a paragenesis of biotite+white mica+plagioclase+amphibole. Typical are a) rounded plagioclase aggregates with dark green amphibole (amph3) around them, rarely with garnet in the centre, and b) oval, fine-grained white mica aggregates with plagioclase corona around them set in the amphibole (amph1)+plagioclase symplectite (Fig. 5e). In the latter case, two zones of plagioclase — an inner, displaying higher refractive index, and an outer with lower refractive index are observable. Tiny kyanite grains in the middle of the corona structure can be observed. Rounded, fine-grained biotite aggregates are present in the matrix symplectite, as well. Idiomorphic amphibole porphyroblasts (amph2) (Fig. 5e) are the only coarse grained minerals in the assemblage.

Summarizing the above-mentioned observations one can recognize that the green type eclogite represents the fully hydrated retrogressed version of the HP metabasalt while in the yellow type pervasive carbonatization preserved the HP mineral assemblage. We have no information about the origin of the carbonate. Since it altered the amphibole–plagioclase symplectite matrix of the rock and carbonate veins cut garnet grains we suppose that carbonate was not part of the eclogite facies mineral assemblage rather it was introduced during the retrograde path.

In this study we focus on the yellow type because this contains a well-preserved eclogite facies mineral assemblage.

5.1. Garnet

Garnet is the most abundant phase, with hypidiomorphic grains of 300 to 2400 μm in diameter and pale

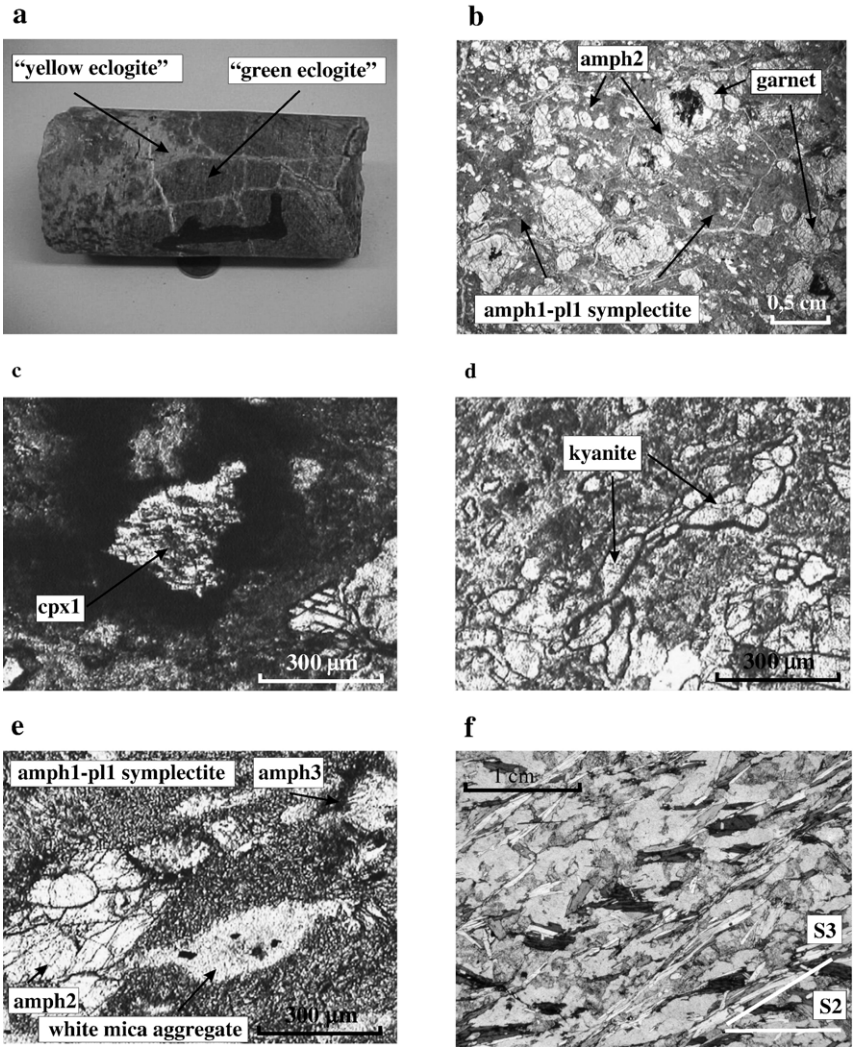


Fig. 5. Macro- and microphotographs of the Jánoshalma eclogite. (a) Relationship between green and yellow types of eclogite. Note that the yellow type is present along the carbonatic veins in the green type. (b) Symplectitic texture of the yellow type eclogite. Plane polarised light, also in (c)–(f). (c) Resorbed matrix clinopyroxene surrounded by a symplectitic corona. (d) Matrix kyanite surrounded by fine-grained white mica. (e) Symplectitic texture of the green type eclogite with amphibole2; egg shaped coronitic pseudomorph after kyanite; rounded aggregate of plagioclase and amphibole3. (f) Foliation planes S2 and S3 in the Jánoshalma gneiss.

greyish-pink colour (Fig. 5b). The garnet composition is $Xpy_{0.35–0.40}Xgrs_{0.17–0.24}Xalm_{0.39–0.42}Xsps_{0.01}Xadr_{0–0.01}$ (Table 3). Larger grains have generally more inclusions in the core than in the rims, and the outermost parts of the garnet are free of inclusions (Fig. 6a). The inclusions in the core are kyanite, rutile, quartz and K-feldspar whereas zoisite, clinopyroxene, K-feldspar and phengite occur in the rims. Based on previously obtained electron microprobe analyses (Zachar and M. Tóth, 2004), the core displays composition that significantly differs from the outer parts. The difference is well-expressed in a drop of pyrope content down to $Xpy_{0.32}Xgrs_{0.22}Xalm_{0.43}Xsps_{0.01}$ (Zachar and M. Tóth, 2004). The outer, inclusion-free zone of the big grains is commonly resorbed (Fig. 6a,c) Usually the biggest grains have several rounded, inclusion-rich parts suggesting that these grains are aggregates of several smaller garnets. The smaller grains lack any inclusion-rich core and they are homogeneous, though a very slight increase of Mg associated with decrease of Fe from core to rim is typical. The difference is of 0.1 Mg or Fe pfu. Ca varies generally in the same way as Fe. Concerning the larger grains, their composition in the outer part is similar to that of the smaller, homogeneous grains.

Table 3
Representative garnet compositions from Jánoshalma eclogite

	Core	Core	Rim	Rim	Next to phg incl.*	Next to omph incl.**	Next to omph incl.**
SiO_2	39.786	39.599	39.684	39.467	39.388	39.855	39.424
TiO_2	0.075	0.056	0.009	0.013	0.199	0.011	0.114
Al_2O_3	22.051	22.098	22.132	22.186	21.786	22.397	21.807
Cr_2O_3	0.016	0.000	0.000	0.028	0.000	0.000	0.038
MgO	10.088	10.085	10.081	9.905	9.483	9.661	9.537
CaO	8.019	7.910	7.867	8.136	8.878	8.916	8.754
MnO	0.408	0.371	0.425	0.430	0.385	0.424	0.405
FeO	18.917	18.818	19.119	19.260	18.579	18.984	18.584
Fe_2O_3	0.654	0.412	0.540	0.392	0.631	0.367	0.684
Na_2O	0.033	0.015	0.000	0.000	0.000	0.000	0.047
Total	100.047	99.364	99.857	99.817	99.329	100.614	99.394
Basis 24ox							
Si	5.996	6.000	5.993	5.972	5.990	5.981	5.992
Ti	0.009	0.006	0.001	0.002	0.023	0.001	0.013
Al	3.917	3.946	3.939	3.957	3.905	3.961	3.906
Cr	0.002	0.000	0.000	0.003	0.000	0.000	0.005
Mg	2.266	2.278	2.270	2.234	2.150	2.161	2.161
Ca	1.295	1.284	1.273	1.319	1.447	1.434	1.426
Mn	0.052	0.048	0.054	0.055	0.050	0.054	0.052
Fe^{2+}	2.384	2.385	2.415	2.437	2.363	2.383	2.362
Fe^{3+}	0.074	0.047	0.061	0.045	0.072	0.041	0.078
Na	0.009	0.005	0.000	0.000	0.000	0.000	0.014
Cat	16.004	15.999	16.006	16.024	16.000	16.016	16.009
Fe/(Fe+Mg)	0.513	0.511	0.515	0.521	0.523	0.524	0.522
Al	39.75	39.78	39.76	40.02	38.86	39.23	38.86
Py	37.79	38.00	37.37	36.69	35.35	35.59	35.55
Sps	0.87	0.79	0.90	0.90	0.81	0.89	0.86
Grs	21.59	21.42	20.96	21.66	23.79	23.61	23.45
Adr	1.24	0.78	1.01	0.73	1.19	0.68	1.29

*Next to phg incl.: garnet next to phengite inclusion.
**Next to omph incl.: garnet next to omphacite inclusion.

5.2. Clinopyroxene

Clinopyroxene occurs as inclusion in garnet (Fig. 6c) and kyanite (Fig. 6d), and as a matrix mineral (Figs. 5c and 6b). Inclusions of clinopyroxene have a grain size from about 5 to a few tens of microns. The composition of primary clinopyroxene (cpx1) – omphacite – is $Xjd_{0.32-0.41}Xdi_{0.47-0.62}Xhd_{0.05-0.13}Xaug_{0.01-0.04}$ (Table 4). Clinopyroxene inclusions in kyanite have the highest Xjd and the lowest Xhd ($Xjd_{0.35-0.41}$ $Xdi_{0.52-0.56}Xhd_{0.04-0.05}Xaug_{0.01-0.04}$). In the matrix, clinopyroxene occurs as pale green xenomorphic grains with a slight pleochroism, the grain size is up to 0.5 cm. Most of the matrix grains have a composition similar to that of clinopyroxene inclusions in kyanite (Table 4). Clinopyroxene inclusions in garnet have similar Xjd to those in kyanite but they differ in the Fe/Mg ratio (Table 4). This is due to Fe–Mg exchange between garnet and clinopyroxene. Secondary clinopyroxene (cpx2) is present at the rim of primary clinopyroxene (cpx1), where it forms symplectic intergrowths with plagioclase and amphibole (Fig. 6b). Cpx2 has diopsidic composition: $Xdio_{0.76-}$ $Xhd_{0.09}Xjd_{0.05}XCa\text{-}tsch_{0.11}$. Alteration of cpx2 to amphibole (amph1 of the matrix symplectite) is shown on the BSE images (Fig. 6b).

5.3. Phengite

Phengite occurs mainly as inclusions in garnet (Fig. 6a and f) and very rarely in the matrix (Fig. 6e). Its composition is $Xcel_{0.22-0.39}Xmu_{0.61-0.78}$, and shows a range of $XMg_{0.57-0.62}$ (Table 5). In the matrix it is coarse grained (up to 300 μm), pale green or colourless, surrounded by a corona of biotite and plagioclase symplectite (Fig. 6e). In most cases only elongated, rod-like biotite+plagioclase pseudomorphs are present. Inclusions in garnet are of ~20 μm size (Fig. 6a,f). These

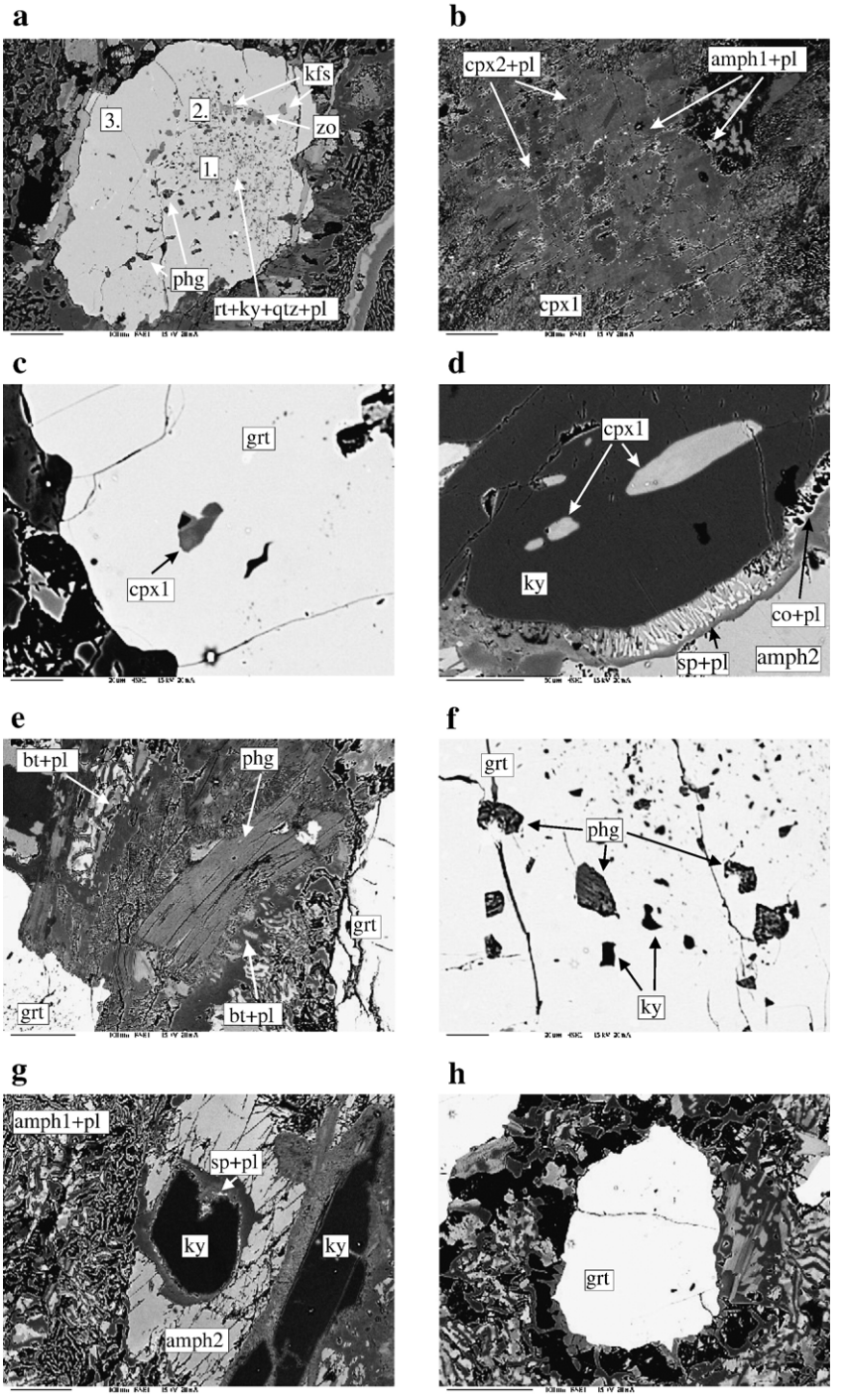


Fig. 6. Back scattered electron (BSE) images depicting eclogite facies phases in the retrogressed Jánoshalma eclogite. (a) Inclusion zonation in garnet; 1) garnet core containing kyanite, rutile, K-feldspar and quartz inclusions; 2) inclusion-poor zone of garnet with K-feldspar, phengite, zoizite, clinopyroxene1 (omphacite) inclusions; 3) the outer inclusion-free portion of garnet. (b) Matrix clinopyroxene1; clinopyroxene2 (diopside)–plagioclase and amphibole–plagioclase symplectite on the grain boundaries of matrix clinopyroxene. (c) Clinopyroxene1 (omphacite) inclusion in the inclusion-poor part of the garnet (d) corundum–plagioclase and spinel–plagioclase symplectite on the edge of matrix kyanite grain. The rounded inclusion in the kyanite is omphacite. (e) Phengite and rutile inclusions in garnet, marking the border between the inclusion-rich core and the inclusion-poor outer part. (f) Matrix phengite. (g) Amphibole porphyroblast (amph2) with inclusion of kyanite set in the amphibole (amph1)–plagioclase symplectite. (h) Small, inclusion-poor garnet grain. Mineral abbreviations are after Kretz (1983) excepting phengite (phg) and amphibole (amph) throughout this paper.

Table 4
Representative clinopyroxene compositions from Jánoshalma eclogite

	Ky incl.*	Ky incl.*	Ky incl.*	Ky incl.*	Ky incl.*	Ky incl.*	Matrix**	Matrix**	Gar incl.***
SiO_2	56.675	55.641	56.395	55.878	55.925	55.808	56.281	55.237	55.475
TiO_2	0.039	0.051	0.047	0.037	0.052	0.057	0.045	0.099	0.072
Al_2O_3	10.344	10.478	10.115	9.690	10.764	9.697	10.500	8.916	10.781
Cr_2O_3	0.163	0.201	0.063	0.022	0.019	0.013	0.260	1.109	0.000
MgO	10.569	10.133	10.449	10.951	10.155	10.627	10.176	10.899	10.146
CaO	15.321	15.067	15.467	16.154	15.032	15.997	15.264	16.540	14.852
MnO	0.000	0.020	0.028	0.011	0.011	0.004	0.020	0.020	0.039
FeO	1.607	1.642	1.652	1.721	1.713	1.793	1.763	1.939	2.846
NiO	0.005	0.000	0.014	0.035	0.049	0.000	0.000	0.000	0.000
Na_2O	5.849	5.870	5.721	5.017	5.486	5.581	5.986	5.229	5.857
K_2O	0.018	0.002	0.005	0.017	0.002	0.005	0.002	0.000	0.011
F	0.207	0.024	0.000	0.000	0.000	0.295	0.051	0.252	0.651
Cl	0.003	0.000	0.000	0.000	0.000	0.000	0.009	0.004	0.010
Total	100.800	99.129	99.956	99.516	99.208	99.877	100.357	100.244	100.740
Basis 6ox									
Si	1.984	1.981	1.991	1.984	1.985	1.979	1.982	1.964	1.955
Ti	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.003	0.002
Al IV	0.016	0.019	0.009	0.015	0.013	0.020	0.018	0.036	0.045
Al VI	0.410	0.421	0.412	0.391	0.437	0.385	0.417	0.337	0.402
Cr	0.005	0.006	0.002	0.001	0.001	0.000	0.007	0.031	0.000
Mg	0.552	0.538	0.550	0.580	0.537	0.562	0.534	0.578	0.533
Ca	0.575	0.575	0.585	0.615	0.572	0.608	0.576	0.630	0.561
Mn	0.000	0.016	0.001	0.000	0.000	0.000	0.001	0.001	0.001
Fe	0.047	0.049	0.049	0.051	0.051	0.053	0.052	0.058	0.084
Ni	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000
Na	0.397	0.405	0.392	0.345	0.378	0.384	0.409	0.360	0.400
K	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001
Cat	3.988	4.011	3.992	3.985	3.976	3.993	3.997	3.998	3.984
Jd	39.69	40.53	39.17	34.54	52.08	38.37	40.87	36.04	40.01
Di	52.76	52.60	53.63	56.36	5.09	55.45	52.39	57.24	47.68
Hd	4.70	4.89	4.88	5.11	5.07	5.32	5.19	5.76	8.39
Aug	2.85	1.98	2.32	3.99	37.76	0.86	1.55	0.96	3.92

*Ky incl.: clinopyroxene inclusion in kyanite.
**Matrix: clinopyroxene porphyroblast in the matrix.
**Gar incl.: clinopyroxene inclusion in garnet.

phengite inclusions have composition $Xcel_{0.22}Xmu_{0.78}$, with $XMg_{0.62}$. We suppose that Fe–Mg exchange between phengite and biotite or enclosing garnet may have affected the XMg (Table 5).

5.4. Kyanite

Kyanite in the matrix has an average size of about 400 μm and commonly contains inclusions of omphacitic clinopyroxene (Fig. 6d). Inclusions of kyanite in the garnet core are tiny, randomly oriented laths. Matrix kyanite is strongly corroded, rimmed by a symplectite of spinel+plagioclase and corundum+plagioclase (Fig. 6d). The composition of spinel and plagioclase is $Xspl_{0.71}Xhc_{0.29}$ and $Xan_{0.94}Xab_{0.06}$ respectively.

5.5. Clinozoizite

Fresh, hypidiomorphic laths of pure end-member clinozoizite occur frequently in close association with kyanite. They form elongated narrow stripes between the matrix porphyroblasts, garnet and clinopyroxene.

5.6. Rutile

Rutile is quite abundant both in the matrix and as inclusion in the garnet (Fig. 5b).

5.7. Plagioclase

Plagioclase is present as primary phase in the core of the garnet. As a secondary mineral plagioclase forms

Table 5
Representative white mica compositions from Jánoshalma eclogite

	Gar incl.*	Gar incl.*	Next to ky**
SiO_2	51.378	51.082	45.570
TiO_2	0.143	0.004	0.000
Al_2O_3	27.788	28.071	34.983
Cr_2O_3	0.017	0.026	0.031
MgO	3.369	3.169	0.644
CaO	0.280	0.239	0.202
MnO	0.002	0.011	0.068
FeO	2.035	2.230	0.893
NiO	0.048	0.000	0.000
Na_2O	0.182	0.106	0.151
K_2O	9.804	9.606	10.933
F	0.000	0.493	0.526
Cl	0.002	0.002	0.010
Total	95.048	95.039	94.011
Basis 22ox			
Si	6.825	6.783	6.152
Ti	0.014	0.000	0.000
Al IV	1.175	1.218	1.848
Al VI	3.176	3.175	3.718
Cr	0.002	0.003	0.003
Fe^{2+}	0.226	0.248	0.101
Mn	0.000	0.001	0.008
Mg	0.667	0.627	0.130
Ca	0.040	0.034	0.029
Na	0.047	0.027	0.039
K	1.661	1.627	1.883
Ni	0.005	0.000	0.000
At	13.838	13.743	13.911
Mu	78.05	78.40	94.16
Cel	21.95	21.60	5.84

*Gar incl.: white mica inclusion in garnet.
**Next to ky: white mica next to kyanite.

symplectite with cpx2 and amph1 after omphacite ($Xab_{0.74–0.81}Xan_{0.19–0.26}$), with biotite after phengite, and spinel + corundum after kyanite ($Xab_{0.06}Xan_{0.94}$). It also constitutes corona with amph3 around garnet ($Xab_{0.56}Xan_{0.44}$) (Zachar and M. Tóth, 2004).

5.8. K-feldspar

K-feldspar is regarded to be a primary phase, present as inclusions in the core and middle parts of the garnet (Fig. 6a), and in the matrix. Its composition is end-member orthoclase ($Xor_{0.97–0.98}Xab_{0.01–0.02}Xan_{0.00}$).

5.9. Amphibole

Amphibole is present as a secondary phase in three textural types. Fine-grained amphibole1 (amph1) is grass green; it forms symplectite with plagioclase in the matrix (Fig. 5b and e). According to Leake (1997), it is of tremolitic composition (Table 6). Presumably, amph1 has been developed by the decomposition of clinopyroxene (cpx1). In the yellow eclogite type amph1 is pervasively replaced by yellow carbonate that determines the overall colour of the rock (Fig. 5b). Amphibole2 (amph2) is the matrix amphibole (Fig. 5b and e). It is euhedral and shows slight zoning; the core is colourless, whereas the rim is pale green. It also contains inclusions of garnet and kyanite. The matrix amphibole is characterised texturally by preferred alignment, undulate extinction, presence of deformation lamellae and carbonate along cleavage planes and grain boundaries is actinolite in composition (Leake, 1997) (Table 6). Fine-grained amphibole (amph3) forms corona with plagioclase around garnet (Fig. 5e); it has a dark green colour with notable pleochroism. Its composition is actinolite with a slightly higher Fe-content than of the matrix amphibole (amph2).

6. Thermobarometry

6.1. Methods

Thermobarometric estimations were carried out on experimentally calibrated geothermometers and geobarometers employing exchange and net-transfer reactions.

Application of garnet–clinopyroxene Fe–Mg exchange thermometers of different calibrations is always a crucial point in temperature estimations. The most generally accepted approaches applied for eclogites are those by Ellis and Green (1979), Powell (1985), Krogh (1988), Ai (1994) and Krogh Ravna and Terry (2004). Carswell et al. (1997) tested the applicability of different geothermometers with garnet compositions of Xgrs between 0.26–0.53. They found that for eclogites where garnet with composition of Xgrs > 0.35 is present, the method of Krogh (1988) gives the best results, whereas for garnet compositions having Xgrs < 0.35, Powell's (1985) calibration provides the best estimations compared with the temperature values obtained from garnet–phengite thermometers from the same sample. Because of this we present the results obtained from all the methods applied but based on the Xgrs content of garnet in the Jánoshalma eclogite (0.20–0.22), we take the temperature value suggested by the method of Powell (1985) into consideration in estimating the peak temperature conditions.

Peak metamorphic conditions can be better calculated from a combination of the net-transfer reactions equilibria:

$$3\ \text{diopside} + 2\ \text{kyanite} = \text{grossular} + \text{pyrope} + 2\ \text{quartz} \quad (1)$$

6 diopside + 3 muscovite
= 3 celadonite + 2 grossular + pyrope (2)

calibrated as geothermobarometers by Krogh Ravna and Terry (2004).

These geothermobarometric methods are less affected by later re-equilibration than common cation exchange thermometers, and the methods also diminish the problems related to estimation of Fe^{3+} in omphacite (Krogh Ravna and Terry, 2004).

6.2. Results

For the above-mentioned exchange and net-transfer reactions, equilibria between garnet cores, omphacite and phengite inclusions have been assumed to determine the maximum *P–T* conditions. Omphacite grains with the highest jadeite content, garnet with maximum pyrope and grossular contents and phengite with the highest Si content have been chosen to calculate peak pressure conditions. Inclusions of omphacite and enclosing garnet compositions provided temperatures higher than 700 °C in every case (725±20 °C; 765±20 °C) with the highest value of 867±10 °C (Table 7). The wide spread of temperature values implied by the different omphacite inclusions and adjacent garnet compositions suggests that these inclusions re-equilibrated following the metamorphic peak, in this way they are not relevant in determining peak temperature conditions. In general, the method of Krogh (1988) yielded temperatures 20–35 °C lower, while that of Ellis and Green (1979) 10–20 °C higher than Powell's (1985) thermometer. Estimations with the methods of Krogh Ravna (2000) and Ai (1994) yielded 85–90 °C lower temperatures than the one of Powell (1985). The garnet–phengite Fe–Mg exchange thermometer of Green and Hellman (1982) provided a peak temperature of 815±25 °C for the Jánoshalma eclogite, but it is important to

Table 6
Representative amphibole compositions from Jánoshalma eclogite

	Matrix (rim)	Matrix (core)	Matrix (core)	Omph incl.*	Symplectite**	Gar incl.***
SiO_2	52.976	52.873	54.319	54.908	55.841	45.917
TiO_2	0.109	0.079	0.066	0.194	0.085	0.816
Al_2O_3	7.104	6.350	5.995	4.542	3.030	14.874
Cr_2O_3	0.015	0.015	0.037	0.419	0.083	0.000
MgO	19.596	20.303	19.934	21.361	21.472	16.423
CaO	10.110	9.998	10.378	10.829	12.276	11.044
MnO	0.046	0.020	0.009	0.000	0.086	0.029
FeO	4.791	4.729	4.591	3.245	3.708	5.742
NiO	0.051	0.051	0.030	0.165	0.000	0.067
Na_2O	2.253	1.945	1.994	1.450	0.744	2.819
K_2O	0.238	0.217	0.208	0.015	0.107	0.609
F	0.012	0.000	0.000	0.000	0.089	0.194
Cl	0.020	0.000	0.013	0.000	0.023	0.077
Total	97.321	96.580	97.574	97.128	97.544	98.611
Basis 23ox						
Si	7.379	7.551	7.753	7.599	7.719	6.454
Ti	0.011	0.000	0.000	0.020	0.009	0.086
Al IV	0.610	0.449	0.247	0.381	0.272	1.460
Al VI	0.557	0.578	0.599	0.360	0.222	1.005
Cr	0.002	0.000	0.000	0.046	0.009	0.000
Fe^{2+}	0.558	0.486	0.480	0.376	0.429	0.675
Mn	0.005	0.000	0.001	0.000	0.010	0.003
Mg	4.068	4.330	4.067	4.406	4.424	3.441
Ca	1.509	1.400	1.538	1.606	1.818	1.663
Na	0.609	0.282	0.278	0.389	0.199	0.768
K	0.042	0.000	0.000	0.003	0.019	0.109
Ni	0.000	0.000	0.000	0.000	0.000	0.000
Cat	15.350	15.076	14.963	15.186	15.130	15.666
Classification (Leake et al., 1997)	Magnesio-hornblende	Actinolite	Actinolite	Tremolite	Tremolite	Alumino-pargasite

*Omph incl.: amphibole alteration of omphacite porphyroblasts.
**Symplectite: amphibole of the matrix amphibole+plagioclase symplectite.
***Gar incl.: amphibole inclusion in garnet.

Table 7
Pressure and temperature estimations of the HP metamorphic stage of the Jánoshalma eclogite

Mineral pair compositions (applied for Fe–Mg exchange thermometry) or equilibrium or net-transfer reactions used for thermometric calculations	Temperature (°C)	Barometer	Pressure (GPa)	Calibration
Omphacite inclusion in garnet–enclosing garnet	703–856±20			Krogh (1988)
	741–879±20			Ellis and Green (1979)
	725–867±20			Powell (1985)
	658–817±20			Krogh Ravna (2000)
Omphacite inclusion in kyanite–garnet core	575±20			Krogh (1988)
	605±20			Powell (1985)
Matrix omphacite–garnet core	605±15			Krogh (1988)
	633±15			Powell (1985)
	657±15			Ellis and Green (1979)
Phengite inclusion in garnet–enclosing garnet	815±25			Green and Hellman (1982)
Jadeite (in clinopyroxene)+ quartz=albite (in plagioclase)		Jadeite content of clinopyroxene	1.42	Holland (1980)
		Si content in phengite	1.44	Massone and Schreyer (1987)
		Si content in phengite	2.00–2.90	Massone and Schreyer (1989)
Pyrope+2 grossular=6 diopside+3 $Al_2Mg_{-1}Si_{-1}$			1.60–2.73	Waters and Martin (1996)
(1) 3 diopside+2 kyanite=grossular+ pyrope+2 quartz	710±10		2.60–2.70	Krogh Ravna and Terry (2004)
(2) 6 diopside+3 muscovite=3 celadonite+ 2 grossular+pyrope				

mention that this method is only appropriate to basaltic systems with $XMg_{\sim 0.67}$. In the case of Jánoshalma eclogite XMg is less (~0.40), so the estimated temperature can be regarded as a maximum temperature. Rough estimation of pressure considering the jadeite content of clinopyroxene (Holland, 1980) resulted in $P \sim 1.42$ GPa; though this value can be regarded only as minimum pressure because of the presence of plagioclase inclusions in the garnet core. Evaluation of pressure, based on the Si content of phengite co-existing with K-feldspar, phlogopite and quartz conforming to the method of Massone and Schreyer (1987) implies a pressure of 1.44±0.05 GPa. In the absence of phlogopite, this is also assumed to be a minimum pressure. The calculations with another calibration of Massone and Schreyer (1989) resulted in 2.0–2.9 GPa. Pressure estimations applying the garnet–clinopyroxene–phengite geobarometer calibration of Waters and Martin (1996) suggest a pressure of 1.6–2.73 GPa for the Jánoshalma eclogite (Table 7).

In the course of the calculations we take into account the intersections of equilibria (1) and (2) in case of six different omphacite ('clinopyroxene inclusion in kyanite' compositions in Table 4), four garnet ('core' compositions in Table 3) and two phengite ('white mica inclusion in garnet' compositions in Table 5) compositions. These define maximum temperature and pressure of 680–738 °C and 2.47–2.76 GPa, with an average of 710±13 °C and 2.6±0.75 GPa. We suggest that these values best record the peak metamorphic conditions of Jánoshalma eclogite.

7. Discussion

7.1. Evolution of Jánoshalma eclogite

K-feldspar, plagioclase and quartz inclusions in the garnet core are the first observable paragenesis which was inherited from the pre-eclogitic stage. Owing to the disappearance/destabilization of amphibole and plagioclase with increasing pressure, these minerals may have provided material (Mg, Fe, Ca, K) for growing garnet, omphacite, phengite, kyanite and zoizite. Following the metamorphic peak, during exhumation the breakdown of omphacite led to the development of symplectites of diopsidic clinopyroxene and plagioclase. The matrix, however, consists mainly of amphibole+plagioclase symplectite (Fig. 6b). Zachar and M. Tóth (2003) estimated the temperature of 490–500±25 °C for this symplectitic stage, from amphibole+plagioclase pair using the method of Spear (1980) and Blundy and Holland (1990). The increasing Al^{IV} content of the matrix idiomorphic amphibole porphyroblasts from core to rim is attributed to re-heating (Zachar and M. Tóth, 2003).

Corundum+plagioclase and spinel+plagioclase symplectites around kyanite (Fig. 6d) suggest a medium-temperature conditions during decompression (M. Tóth

et al., 2000), no sapphirine typical for high-temperature condition decompression has been observed.

7.2. Regional correlations and implications for high-pressure metamorphism

Eclogites with similar type and evolution to those in the present study can be traced to the east–northeast from the Jánoshalma high in the Tisza Megaunit (Fig. 1). The metamorphic evolution of their host rocks is considered to be the same (M. Tóth and Zachar, 2003; Zachar and M. Tóth, 2003). Szepesházy (1962) assumed the existence of a SW-NE extended orthogneiss zone in southern Hungary (see orthogneiss occurrences in Fig. 1). He proposed that its westernmost part is the orthogneiss block of the Jánoshalma high. The assumption of the orthogneiss zone is supported by the presence of similar textural features of the orthogneisses from the different localities (Zachar and M. Tóth, 2001). The most typical textural feature is the presence of amphibole and feldspar xenocrysts and xenoliths of different rock types and metamorphic evolution in the orthogneiss (M. Tóth and Zachar, 2003). In most of these localities late low-temperature mylonitic deformation is also typical (Schubert and M. Tóth, 2002).

Eclogite occurrences west-southwest from Jánoshalma high (Görcsöny area) contain kyanite (Ravasz-Baranyai, 1969), their correlation awaits the test from future work, involving a detailed mineralogical, petrological and geochemical study.

Lelkes-Felvári et al. (2000) found an exposure of ultramylonite with a protolith that has been specified as orthogneiss in borehole Mőcsény-1, while M. Tóth et al. (2005) found the exposure of the same mylonitic orthogneiss in the Ófalu region. The same association of eclogite and orthogneiss (as in the eastern part of Tisza Megaunit) has not been identified to the west of the Jánoshalma high. According to the above-mentioned evidences, correlation of the Jánoshalma high is more consistent with the eastern parts of the Tisza Megaunit.

The main question remains whether the eclogites and their host orthogneisses underwent a common or different metamorphic evolution. Zachar and M. Tóth (2003) determined a peraluminous character and syn-collision origin for the granodioritic protolith of the orthogneiss. Zachar and M. Tóth (2004) suggested that such granodiorite intrusions had sampled the eclogite xenoliths from the subduction melange in an ancient subduction-accretionary complex. The occurrence of resorbed, unoriented "floating" amphibole and feldspar xenocrysts in the orthogneiss, and presence of other xenoliths than eclogite, i.e. amphibolite, felsic granulite, pyroxenite and serpentinite suggest that even medium and low-pressure rocks have been incorporated into the orthogneiss (Zachar and M. Tóth, 2003). If the whole orthogneiss body was subducted, all of these xenoliths should be affected by high-pressure metamorphism, and this is not observed.

Investigations of inclusions in common accessory phases (mainly zircon) however provide a possibility to discover the traces of former high-pressure metamorphism even in strongly re-equilibrated rocks (e.g. Tabata et al., 1998; Liu et al., 2002; Massone and Nasdala, 2003). Evidence for high-pressure event in the orthogneisses hosting eclogites comes from several areas of the world (e.g. Dabie-Sulu orogenic belt, China; Dora Maira Massif, Switzerland; Western Gneiss Region, Norway) (e.g. Liou et al., 1998; Carswell and Compagnoni 2003; Chopin et al., 1991; Krogh, 1977; Griffin and Carswell, 1985). The presence of minor jadeite and coesite inclusions in zircons extracted from the orthogneiss suggests that large portions of the felsic rocks may underwent high-pressure metamorphism (e.g. Ye et al., 2000). Further investigations including the country rocks of eclogites are therefore needed to clarify the extent of high-pressure metamorphism in the Tisza Megaunit.

8. Conclusions

Jánoshalma eclogite provides important information about the crystalline basement of the Tisza Megaunit in southern Hungary. It experienced metamorphism under amphibolite facies and reached the metamorphic peak at 710±10 °C and 2.6–2.7 GPa, well within the eclogite facies stability field. Subsequent decompression and after that some re-heating at amphibolite facies conditions occurred during exhumation. Jánoshalma eclogite can be classified as medium-temperature/high-pressure type (B-type eclogite sensu Coleman et al., 1965). The timing of metamorphism is not very well-known, Variscan age is presumed. Further attention should be paid to the study of other potential high-pressure relics in the crystalline basement of the Tisza Megaunit. This may elucidate regional extent of high-pressure metamorphism and correlation with adjacent units of the Central Europe.

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