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A Clockwise P-T Path from the Variscan Basement of the Tisza Unit, Pannonian Basin, Hungary

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Key words: Gneiss, Amphibolite, Geothermobarometry, Variscan regional metamorphism, Tisza Unit, Pannonian Basin, Hungary.

Abstract

The polymetamorphic basement of the Tisza Unit forms a detached fragment of the Variscan European foreland of the Neotethyan realm. A clockwise evolution path of a gneiss-amphibolite complex of the Tisza Unit was reconstructed, investigating the polymetamorphic rocks of the borehole Baksa-2, SE Transdanubia, Hungary. The results obtained by microstructural and mineral paragenetic observations, mineral chemical analyses, and thermobarometric calculations define a P-T loop which suggests a complex Variscan polyphase model rather than a pre-Variscan - Variscan polycyclic one. The early part of the prograde path with kyanite is characterized by T-P conditions of 480±50°C and 470±70 MPa, respectively. The metamorphism reached its peak at 660±25°C and 750±50 MPa, when both kyanite and staurolite were stable. This metamorphic climax was followed by a nearly isothermal decompression to 440±20 MPa at 650±40°C. This event is marked by the presence of sillimanite and a second generation of garnet, and is closely related to the collisional Variscan granitoid magmatism observed in considerable parts of the Tisza Unit. In amphibolites intercalated with gneisses, only this last event was preserved, providing T-P estimates of ca. 650-690°C / 400-500 MPa. The present paper provides the first demonstration of a continuous, clockwise P-T path from the metamorphic basement of the Hungarian part of the Tisza Unit.

1. INTRODUCTION

The Tisza Unit (Fig. 1), a prominent part of which forms the objective of the present study, originated from the northern, European margin of Tethys by mostly meso-Alpine horizontal block (microplate) displacements (GÉCZY, 1973; KOVÁCS, 1982, KÁZMÉR & KOVÁCS, 1985). The Tisza Unit in the sense of CSONTOS et al. (1992), which is equivalent to the Tisia megaunit of SZEDERKÉNYI (1996), was one of the most stable blocks of the Pannonian Basin during the Alpine tectonometamorphic cycle (ÁRKAI, 1991).

In general, the first metamorphic event recorded in the Tisza Unit is characterized by Barrow-type amphibolite facies regional metamorphism. This event was overprinted by a low-pressure Variscan event with grades varying from subgreenschist facies up to amphibolite facies with andalusite, closely related to granitoid magmatism (for reviews see LELKES-FELVÁRI & SASSI, 1981; ÁRKAI, 1984; SZEDERKÉNYI, 1984; ÁRKAI et al., 1985). Having applied various thermobarometric methods ÁRKAI (1984) and ÁRKAI et al. (1985) calculated for gneisses, micaschists and intercalated amphibolites, peak conditions of 500-600°C and 500-900 MPa for the first Barrow-type amphibolite facies event.

This event was supposed to be pre-Variscan (LELKES-FELVÁRI & SASSI, 1981). ÁRKAI et al. (1985) elaborated alternative pre-Variscan - Variscan polycyclic and Variscan polyphase models. For the time being no isotopic ages older than Variscan are available from the metamorphic basement of the Tisza Unit (LELKES-FELVÁRI et al., 1996), which can be, at least partly explained by the intense Variscan heating.

The aim of the present paper is to provide thermobarometric data on the metamorphic history of a gneiss-amphibolite complex on the basis of new microstructural, mineral paragenetic and mineral chemical data and thermobarometric calculations, paying special attention to the chemical zoning of garnet porphyroblasts and their coexisting mineral assemblages (mineral inclusions and adjoining matrix minerals, respectively).

2. GEOLOGIC OUTLINE AND PREVIOUS DATA

The Baksa-2 borehole, from which the investigated samples originated, is located at the SE part of the Tisza Unit in SE Transdanubia, Hungary (Fig. 2). Below a few tens of metres of Neogene sedimentary cover, the elevated metamorphic basement of the Görcsöny Ridge (referred to GR in this study) is exposed, for a total thickness of over 1000 m, with near 100% core recovery (Fig. 3). According to SZEDERKÉNYI (1976) the rocks of the GR suffered prograde "Barrovian" regional metamorphism changing from the chlorite zone to the sillimanite zone. KOVÁCH et al. (1985) described the metamorphic pile crosscut by the Baksa-2 borehole, as the following downward succession: "upper marble", chloritic two-mica gneiss, "lower marble" and garnetiferous two-mica gneiss and schist, intercalated with

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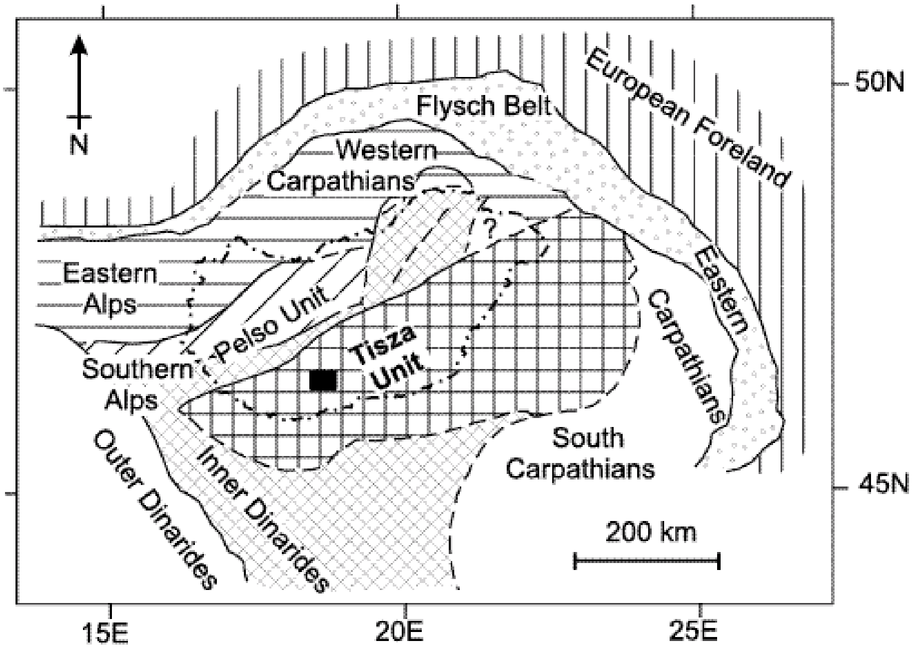

Fig. 1 Tectonic sketch map of the Pannonian Basin (box indicates the study area, enlarged in Figure 2). The –·–·– line shows the state boundary of Hungary.

amphibolites. According to KOVÁCH et al. (1985), the first metamorphic event that produced garnet, staurolite, kyanite and sillimanite in gneiss and micaschist, diopside in carbonate rocks and hornblende + andesine-labradorite in amphibolite occurred at 630-650 °C and 500-700 MPa. They obtained a whole rock Rb/Sr isochron age of 331 ± 13 Ma for these rocks that was interpreted as the age of this first metamorphic event. KOVÁCH et al. (1985) also defined a second phase of regional metamorphism that occurred at 400-410 °C and 300-400 MPa at ca. 315±4 Ma as deduced from a single Rb/Sr model age obtained on biotite. According

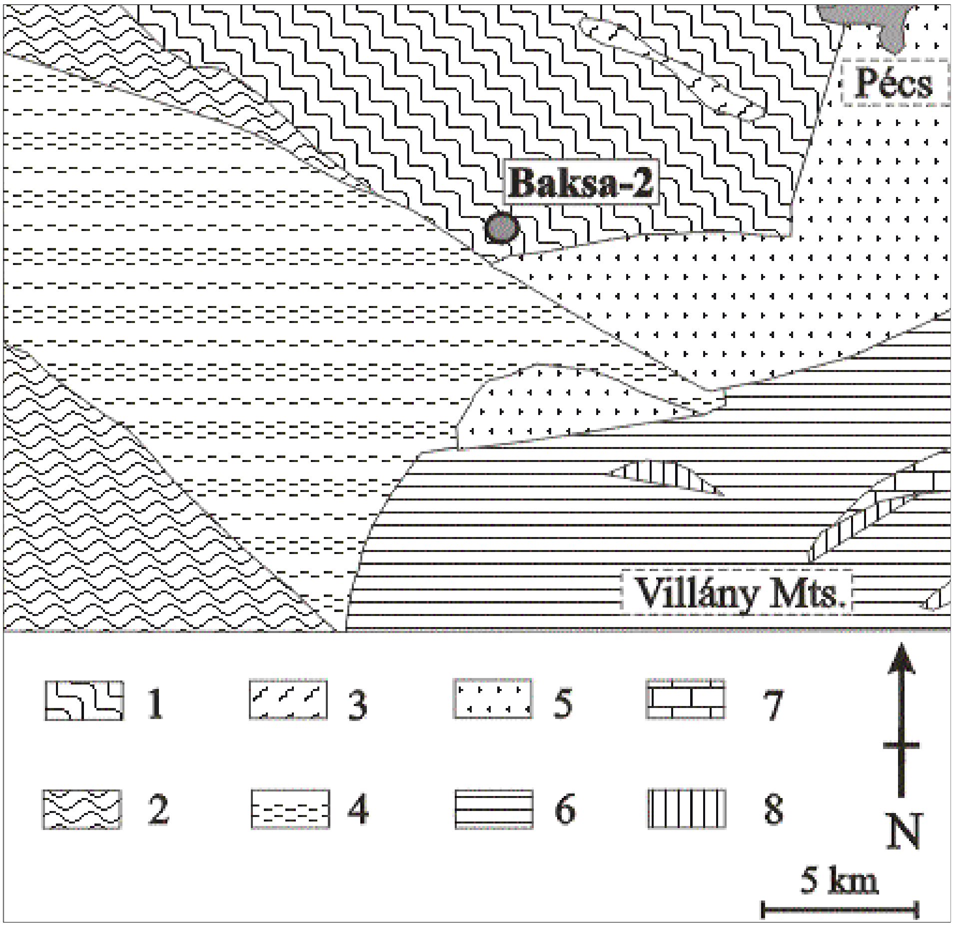

Fig. 2 A simplified pre-Tertiary geological map of the Görcsöny Ridge and surrounding area after FÜLÖP (1994), with the location of the Baksa-2 borehole. Legend: 1) metamorphic rocks of the Görcsöny Ridge; 2) metamorphic rocks of the Somogy-Dráva Basin; 3) Gyód Serpentinite; 4) Carboniferous molasse; 5) Permian molasse; 6-8) Villány-type Mesozoic; 6) Triassic rocks; 7) Jurassic rocks; 8) Cretaceous rocks.

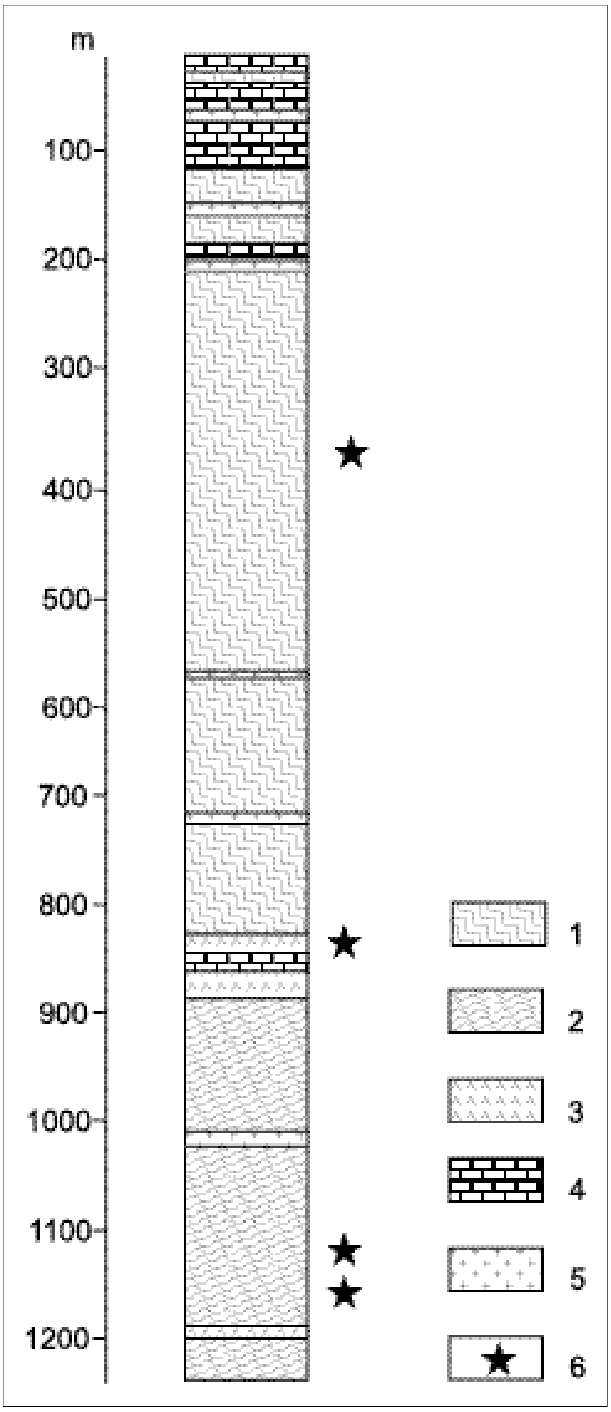

Fig. 3 Geologic profile of the Baksa-2 borehole (modified after KOVÁCH et al., 1985). Legend: 1) gneiss; 2) micaschist; 3) amphibolite; 4) marble; 5) aplite; 6) samples used for geothermobarometric calculations.

to KOVÁCH et al. (1985), this event is demonstrated by the formation of a new biotite generation and partly, by a second generation of garnet, and was followed by a contact metamorphism restricted to the carbonate intercalations (pyroxene hornfels, hornblende hornfels) caused by aplite intrusions connected to the S-type, collisional Variscan granitoid magmatism in the surrounding region (see also BUDA, 1981, 1985).

3. PETROGRAPHY

In the metamorphic section of the Baksa-2 borehole paragneisses and micaschists are predominant, intercalated with some amphibolites, minor calc-silicate rocks and marbles. For the present study characteristic paragneiss and amphibolite samples from various parts of the rock column were selected. The mineral abbrevations are after KRETZ (1983) except for amphibole (Amph).

The **paragneisses** consist of biotite + quartz + plagioclase + garnet + sillimanite ± muscovite ± staurolite ± kyanite ± K-feldspar and accessory apatite, zircon and tourmaline. Two types of gneisses can be distinguished in thin-sections. Type I gneisses contain large subhedral garnet porhpyroblasts with a few biotite and plagioclase inclusions. Biotite and plagioclase are also present near the garnet rims with staurolite and kyanite. Type II gneisses also have garnet, but these garnets are much smaller and contain abundant inclusions of biotite, plagioclase and quartz. The matrix consists of fibrolitic sillimanite, biotite, muscovite, plagioclase and quartz. Relic kyanite and staurolite can also be seen.

Biotite occurs in both types of gneiss, either as fine flakes in the matrix with fibrolitic *sillimanite* aggregates defining the foliation, or as relic crystals wrapped by and pre-dating the foliation. The latter types of biotite also occur as inclusions in the large garnet porphyroblasts and rim the garnet blasts. Fine-grained fibrolitic sillimanite is intergrown with biotite. *Muscovite* was found only in association with matrix biotite in Type II gneisses. Biotite, muscovite and sillimanite are often folded together. The presence of large (generally >1 cm diameter) *garnet* porphyroblasts is the most remarkable feature of Type I gneisses. These subhedral, garnet grains display smooth surfaces, contain inclusions of biotite and plagioclase, and are sometimes rimmed by biotites (Fig. 4a). The smaller garnets (max. 1-2 mm) found in Type II gneisses generally form poikiloblastic, irregularly shaped skeletal grains lacking any internal fabric. Instead, they contain numerous inclusions of biotite and *plagioclase* (Fig. 4b). Plagioclase is usually xenoblastic or subhedral, and untwinned. *Kyanite* and *staurolite* occur as relic porphyroblasts in biotite-sillimanite-muscovite and/or quartz-plagioclase matrix in both types of gneisses. Rarely, they reach the size of the garnet porphyroblasts in the Type I gneisses, where they exhibit a rounded shape and occur in larger quantities than in Type II gneisses. Sometimes small biotite inclusions are embedded in kyanite grains.

Amphibolites exhibit lineation and show equigranular microstructure. Their primary mineral assemblage contains amphibole + plagioclase + quartz and subordinate epidote. *Amphibole* is the dominant phase forming prismatic or subhedral grains of 2-5 mm in length that are aligned with the lineation. *Plagioclase* occurs as interstitial, xenoblastic grains, or forms veinlets with quartz. *Epidote* forms small grains generally associated

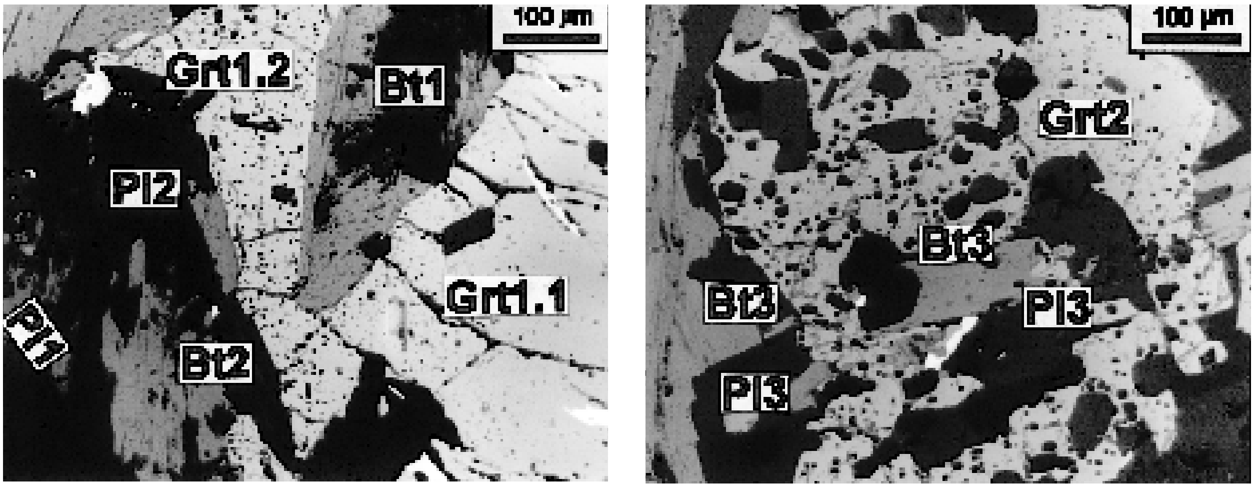

Fig. 4 a) BSE image of the large garnet (Grt1) porphyroblast with biotite and plagioclase as inclusions and near the garnet; b) BSE image of a Grt2 porphyroblast with biotite and plagioclase occuring as inclusions and rimming the garnet. Numbers refer to the mineral compositions given in Tables 1-4, $G_{1.1}$ = Grt1core, $G_{1.2}$ = Grt1rim.

with amphibole. The amphibolites contain some secondary K-feldspar and chlorite.

Location	Bt1 Grt1 core	Bt2 Grt1 rim	Bt3 Grt2 rim	Ms Grt2 rim
SiO_2	34.55	34.80	35.09	45.76
TiO_2	1.95	2.59	1.96	0.60
Al_2O_3	19.68	19.48	19.09	34.47
FeO*	19.09	19.16	20.01	0.93
MnO	0.10	0.10	0.13	0.04
MgO	8.87	8.85	8.53	0.59
CaO	-	-	0.02	0.01
Na_2O	0.15	0.36	0.09	1.06
K_2O	9.41	8.84	9.43	9.68
Total	93.80	94.18	94.35	93.14
cation numbers on the basis of 22 oxygens				
Si	5.344	5.346	5.415	6.204
Ti	0.227	0.299	0.227	0.061
Al	3.587	3.527	3.472	5.508
Fe^{2+}	2.469	2.461	2.582	0.105
Mn	0.013	0.013	0.017	0.004
Mg	2.045	2.026	1.962	0.119
Ca	-	-	0.003	0.001
Na	0.045	0.107	0.027	0.279
K	1.857	1.732	1.856	1.674
Total	15.586	15.511	15.562	13.956
mg#	0.45	0.45	0.43	0.53
Al^{IV}	2.656	2.654	2.585	1.796
Al^{VI}	0.931	0.872	0.887	3.712
T site	8.000	8.000	8.000	8.000
Y site	5.685	5.672	5.676	4.002
Z site	1.901	1.839	1.887	1.954

Table 1 Biotite and muscovite compositions used for P-T calculations. FeO* = Fe total.

4. MINERAL CHEMISTRY

Chemical analyses of minerals were carried out using a JEOL JXCA-733 electron microprobe equipped with 3 WDS, with a measuring programme of NAGY (1984) in the Laboratory for Geochemical Research, Hungarian Academy of Sciences. The measuring conditions were 15 kV, 30 nA, defocused electron beam with a diameter of 5-10 μm, measuring time 5x5 s. Matrix effects were corrected using the method of BENCE & ALBEE (1968). The following standards were used for quantitative analysis: orthoclase (K, Al, Si), synthetic glass (Fe, Mg, Ca), spessartine (Mn), rutile (Ti) and albite (Na). Statistical (absolute) errors expressed as 1 σ are as follows: SiO_2: ±0.3, TiO_2: ±0.05, Al_2O_3: ±0.05, FeO: ±0.2, MgO: ±0.1, MnO: ±0.05, CaO: ±0.1, Na_2O: ±0.03, and K_2O: ±0.02 %. Mineral compositions used in geothermobarometric calculations are given in Tables 1-4.

Representative analyses and the structural formulae of biotite and muscovite are given in Table 1. *Biotite* occurs in all the metapelites investigated. Its grains are unzoned, and their $Mg/(Mg+Fe^{2+})$ ratios range from 0.42 to 0.47. The Ti content is between 0.22-0.3. Biotites in the large garnet porphyroblasts of Type I gneisses have the highest MgO (Bt1). The highest Ti was observed in biotites near the rim of the large garnet porphyroblasts (Bt2). The composition of biotite in Type II gneisses is quite uniform regardless of whether the flakes are in the matrix or occur as inclusions in the garnets (Bt3). Inclusions of biotite in kyanite have the same composition as the biotites in the large garnet porphyroblasts. The composition of *muscovite* flakes is homogenous. It contains 6.15-6.2 Si atoms p.f.u. The *garnets* are Alm-rich in all rock types, independent of their textural position (Table 2). The large garnet porphyroblasts (Grt1) display composite zoning. The core is $Prp_7Alm_{76}Sps_3Grs_{14}$, while the rim is richer in Prp and

Location	Grt1 core	Grt1 rim	Grt2 rim
SiO_2	36.77	36.90	37.48
TiO_2	0.16	0.01	0.08
Al_2O_3	21.01	21.55	20.87
FeO*	34.18	33.36	33.69
MnO	1.12	2.37	2.89
MgO	1.59	3.31	2.98
CaO	5.50	2.37	1.66
Na_2O	0.06	0.03	0.01
K_2O	-	0.07	-
Total	100.39	99.97	99.64
cation numbers on the basis of 12 oxygens			
Si	2.966	2.964	3.023
Ti	0.010	0.010	0.004
Al	1.997	2.040	1.984
Fe^{2+}	2.306	2.241	2.272
Mn	0.076	0.161	0.197
Mg	0.191	0.396	0.358
Ca	0.475	0.204	0.143
Na	0.009	0.005	0.002
K	-	0.007	-
Total	8.030	8.020	7.982
Prp	6.37	13.20	12.11
Alm	77.14	74.64	76.97
Sps	2.55	5.37	6.67
Grs	13.99	6.79	4.20

Table 2 Garnet compositions used for P-T calculations. FeO* = Fe total.

poorer in Grs content ($Prp_{13}Alm_{74}Sps_6Grs_7$) with almost constant Alm and Sps. In comparison, the small garnet (Grt2) shows a homogeneous chemical composition, with $Prp_{12}Alm_{77}Sps_7Grs_4$. *Plagioclase* coexisting with a core of Grt1 is richer in An (An_{62}), than plagioclase in contact with the rim of Grt1 or with Grt2 which are An_{26} and An_{30}, respectively (Table 3). The composition of the plagioclase in amphibolites is rather homogeneous, showing an average An content of 33%. Amphibole compositions are given in Table 4. The calculations of cation numbers for *amphiboles* follow the scheme of ROBINSON et al. (1982). Using the classification of LEAKE et al. (1997) the analyzed amphiboles all belong to the calcic amphibole group, and within this fall into the tschermakite field (LEAKE et al., 1997).

5. GEOTHERMOBAROMETRY

Temperatures and pressures for the paragneisses were calculated by the TWEEQU programme (version 2.02) of BERMAN (1991) using the thermodynamic dataset of BERMAN (1988), and activity models for garnet (BERMAN, 1990), biotite (McMULLIN et al., 1991), muscovite (CHATTERJEE & FROESE, 1975) and plagioclase (FUHRMAN & LINDSLEY, 1988).

	Plagioclase			
Location	Grt1 core	Grt1 rim	Grt2 rim	Amphibolite
SiO_2	52.20	61.09	60.08	59.04
Al_2O_3	30.04	24.18	24.72	24.70
CaO	12.79	5.43	6.40	6.96
Na_2O	4.30	8.52	8.11	7.61
K_2O	0.06	0.10	0.15	0.15
Total	99.39	99.32	99.46	98.46
cation numbers on the basis of 8 oxygens				
Si	2.381	2.739	2.690	2.673
Al	1.615	1.273	1.304	1.318
Ca	0.625	0.260	0.307	0.338
Na	0.380	0.738	0.704	0.668
K	0.003	0.006	0.009	0.009
Total	5.004	5.006	5.014	5.006
An	61.96	25.90	30.11	33.28
Ab	37.70	73.54	69.05	65.87
Or	0.34	0.56	0.83	0.85

Table 3 Plagioclase compositions used for P-T calculations.

We also used the computer programme THERMOBAROMETRY of SPEAR (1993) with various calibrations of the garnet-biotite thermometer (FERRY & SPEAR, 1978; HODGES & SPEAR, 1982; KLEEMANN & REINHARDT, 1995), and the GASP barometer of NEWTON & HASELTON (1981) and HODGES & SPEAR (1982). In addition, the garnet-phengite thermometer of GREEN & HELLMAN (1982), the phengite barometry of MASSONNE & SCHREYER (1987) and the garnet-plagioclase-biotite-muscovite barometer of GHENT & STOUT (1981) and HODGES & CROWLEY (1985) were applied to the gneiss sample containing muscovite. For the zoned garnet porphyroblasts the GIBBS programme of SPEAR (1993) provided additional information on the P/T conditions for the garnet cores. For the amphibolites the thermobarometric methods of PLYUSNINA (1982), HOLLAND & BLUNDY (1994) and GERYA et al. (1997) were applied. Results obtained by various methods are listed in Table 5.

In **paragneisses** the composition of the core of the large garnet porphyroblasts (Grt1), together with the biotite and plagioclase inclusions were used to obtain P-T data for the early part of the garnet growth, and the garnet rim composition with adjacent biotite and plagioclase for the conditions of the crystallization of the rim. On the basis of mineral paragenetic microstructural observations, kyanite was the stable aluminosilicate in these assemblages. Garnet-biotite thermometry gave temperature estimates of 480±50 °C, and GASP (garnet-kyanite-quartz-plagioclase) barometry gave pressure estimates of 460±50 MPa for the core using the TWEEQU programme. Similar results were derived from the THERMOBAROMETRY programme (470-490 °C and 400-550 MPa). Using the GIBBS pro-

	Amphibole		
SiO_2	42.47	42.89	42.86
TiO_2	0.57	0.84	0.69
Al_2O_3	13.29	12.40	12.62
FeO^*	16.07	15.77	16.01
MnO	0.30	0.33	0.31
MgO	10.81	11.01	10.86
CaO	11.44	11.72	11.59
Na_2O	1.56	1.55	1.49
K_2O	0.71	0.55	0.76
Total	97.22	97.06	97.19
cation numbers on the basis of 23 oxygens			
Si	6.248	6.335	6.325
Al^{IV}	1.752	1.665	1.675
Al^{VI}	0.552	0.494	0.520
Ti	0.063	0.093	0.077
Fe^{3+}	0.889	0.727	0.767
Mg	2.370	2.424	2.389
Fe^{2+}	1.088	1.221	1.209
Mn	0.037	0.041	0.038
Ca	1.803	1.855	1.833
Na	0.445	0.444	0.426
Na	0.248	0.299	0.260
K	0.133	0.104	0.143
Total	15.684	15.649	15.663
Al total	2.304	2.159	2.195

Table 4 Amphibole compositions used for P-T calculations. FeO* = Fe total.

gramme of SPEAR (1993) we obtained 520°C and 400 MPa for the core. For the rim assemblage of Grt1 660±25°C and 750±50 MPa were obtained using TWEEQU, and 640-680°C and 700-800 MPa with THERMOBAROMETRY. The chemically homogeneous, small garnet (Grt2) with matrix and inclusion biotite and plagioclase, together with matrix muscovite and sillimanite, gave P-T estimates of 650±40°C and 440 ±20 MPa with TWEEQU. For the same assemblage 630-650°C and 400-500 MPa were estimated with THERMOBAROMETRY. Using the phengite barometry of MASSONE & SCHREYER (1987) with 6.2 Si atoms p.f.u, similar pressure-ranges were obtained. However the pressures obtained with phengite barometry can only be interpreted as minimum pressures, because no K-feldspar was found in this assemblage.

For **amphibolites** three thermobarometric calibrations were used to decipher the P and/or T conditions of their formation. The results obtained by the methods of HOLLAND & BLUNDY (1994) and GERYA et al. (1997) are close to each other (680-690°C at 450 MPa, 650-670°C at 400-500 MPa, respectively), while the earlier method of PLYUSNINA (1982) gave significantly lower T (550°C) but similar P (550 MPa) values.

6. DISCUSSION

Figure 5 displays a model for joint interpretation of the results outlined above. Microstructural and mineral paragenetic observations gave clear evidence for relative time-relations of the various mineral assemblages. These relations are indicated by the arrows in Fig. 5.

The detectable, first point in the prograde part of the P-T-relative time path was of medium-pressure type, with kyanite as index mineral. Its calculated physical conditions were 480±50°C and 470±70 MPa. Staurolite started to form in later stages of the prograde path. The metamorphism reached its peak conditions of 660±20°C, and 750±50 MPa, when both kyanite and staurolite were stable. This path, characterized by a simultaneous increase in temperature and pressure, was followed by a nearly isothermal decompression to 440±20 MPa at 650±40°C. This event is marked by the presence of sillimanite, a new generation of small garnets and the formation of the observed foliation in the gneisses. It is likely to be closely related to the collisional Variscan granitoid magmatism observed in the immediate vicinity of the studied occurrence and also in various parts of the Tisza Unit (BUDA, 1981, 1985). In amphibolites intercalated with gneisses, only this last event was preserved, providing less precise T-P esti-

Assemblage	Temperature (°C)					Pressure (MPa)				
Paragneiss	FS78	HS82	KR94	TWQ	GH82	NH81	HS82	TWQ	HC85	GS81
Grt1core+Bt1+Pl+Ky	440-460	450-490	520-530	430-530	-	400-550	400-500	410-510	-	-
Grt1rim+Bt2+Pl+Ky+St	630-670	640-670	600-630	635-685	-	700-820	660-770	700-800	-	-
Grt2+Bt3+Ms+Pl+Sil	610-650	620-650	590-620	610-690	620-650	480-600	460-530	420-460	580-700	400-430

	Temperature (°C)			Pressure (MPa)	
Amphibolite	P82	HB94	G97	P82	G97
Amph+Pl	550	680-690	650-670	550	400-500

Table 5 P-T calculations on samples from the Baksa-2 borehole. Legend: FS78) FERRY & SPEAR (1978); HS82) HODGES & SPEAR (1982); KR94) KLEEMANN & REINHARDT (1995); TWQ) TWEEQU; GH82) GREEN & HELLMAN (1982); NH81) NEWTON & HASELTON (1981); HC85) HODGES & CROWLEY (1985); GS81) GHENT & STOUT (1981); P82) PLYUSNINA (1982); HB94) HOLLAND & BLUNDY (1994); G97) GERYA et al. (1997).

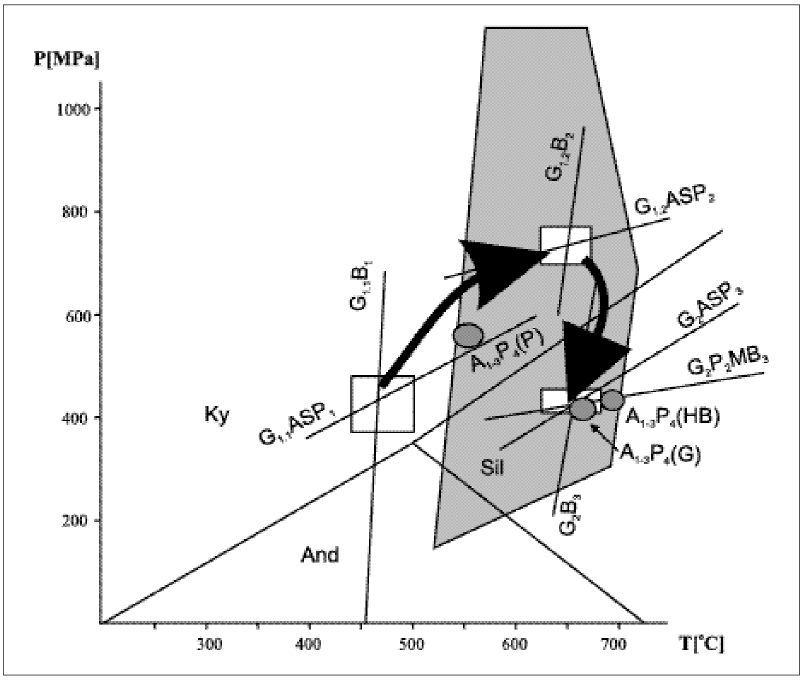

Fig. 5 Reconstructed pressure-temperature path of the gneiss-amphibolite complex from the Baksa-2 borehole. Boxes represent the estimated P-T conditions for the gneisses and circles for the amphibolites. Al_2SiO_5 triple point is after HOLDAWAY (1971), the stability field of staurolite (grey area) is from SPEAR (1993). Legend: GB) garnet-biotite thermometry; GASP) garnet-Al_2SiO_5-quartz-plagioclase barometry; GPMB) garnet-plagioclase-muscovite-biotite barometry; AP) amphibole-plagioclase thermobarometry; G) GERYA et al. (1997); HB) HOLLAND & BLUNDY (1994); P) PLYUSNINA (1982). Numbers in subscript refer to the mineral compositions given in Tables 1-4, $G_{1.1}$ = Grt1core, $G_{1.2}$ = Grt1rim.

mates (ca. 650-690°C/400-500 MPa) than the gneisses. As no prograde zonation was observed either in amphibole or in plagioclase of the amphibolites, one has to presume that the P-T results obtained from the amphibolites reflect the conditions of the last phase of metamorphism. The results obtained using the calibrations of HOLLAND & BLUNDY (1994) and GERYA et al. (1997) are in agreement with those obtained for the small garnet-bearing assemblage of the gneisses.

As to the opinion of the present authors, the only isotopic data on the gneisses published by KOVÁCH et al. (1985) do not provide a reliable time-scale for the detailed metamorphic history, especially if the errors of age determinations are also taken into consideration. In addition, these dates are also in contradiction with the age of the granitoid magmatism (320-350 Ma), that was summarised by BUDA (1985), who applied a wide series of isotopic methods to various minerals. Therefore, the present authors think that the results of KOVÁCH et al. (1985) prove only the Variscan age of the metamorphism in general, and demonstrate that no significant post-Variscan heating occurred in the rocks investigated. In order to determine the age-sequence of the metamorphic events depicted in the present study, further isotope geochronological investigation of garnets and other accessory minerals is needed.

Nevertheless, the continuous changes in mineral chemistry, and especially the lack of any signs of retrogression (considerable cooling) between the metamorphic events, suggest that at present the complex polyphase Variscan metamorphic model outlined by ÁRKAI (1984) and ÁRKAI et al. (1985) seems to be a more realistic working hypothesis than the polycyclic pre-Variscan - Variscan model.

7. CONCLUSIONS

On the basis of microstructural, mineral paragenetic, mineral chemical and geothermobarometric investigations of gneisses and amphibolites characteristic of the basement of the Tisza Unit in SE Transdanubia, Hungary, the metamorphic evolutionary path was reconstructed.

Using the chemical compositions of mineral inclusions and the core of large garnet porphyroblasts the P-T conditions of the early prograde path were constrained (480±50°C and 470±70 MPa). The metamorphic peak conditions (660±25°C, and 750±50 MPa) were similar or near to those calculated by ÁRKAI (1984) and ÁRKAI et al. (1985) for other parts of the basement of SE Transdanubia (Somogy-Dráva Basin). The metamorphic climax was followed by isothermal decompression to 440±20 MPa at 650±40°C, most probably related to the Variscan granitoid magmatism. Considering the available isotope geochronological data, the new results can be best explained by a complex polyphase Variscan metamorphic evolution model.

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8. REFERENCES

ÁRKAI, P. (1984): Polymetamorphism of the crystalline basement of the Somogy-Dráva Basin (Southwestern Transdanubia, Hungary).- Acta Miner. Petr. Szeged, 26, 129-153.

ÁRKAI, P. (1991): Alpine regional metamorphism of the different tectonic domains in the Hungarian part of the Pannonian Basin.- In: BAUD, A., THÉLIN, P. & STAMPFLI, G. (eds.): Paleozoic geodynamic domains and their alpidic evolution in the Tethys. IGCP Project No. 276, Newsletter No. 2, Mémoires de Géologie (Lausanne), 10, 5-13.

ÁRKAI, P., NAGY, G. & DOBOSI, G. (1985): Polymetamorphic evolution of the South Hungarian crystalline basement, Pannonian Basin: geothermometric and geobarometric data.- Acta Geol. Hung., 28, 165-190.

BENCE, A.E. & ALBEE, A. (1968): Empirical correction factors for electron microanalysis of silicates.- J. Geol., 76, 382-403.

BERMAN, R.G. (1988): Internally-consistent thermodynamic data for minerals in the system Na_2O-K_2O-CaO-MgO-FeO-Fe_2O_3-Al_2O_3-TiO_2-H_2O-CO_2.- J. Petrol., 29, 445-522.

BERMAN, R.G. (1990): Mixing properties of Ca-Mg-Fe-Mn garnets.- Am. Mineral., 75, 328-344.

BERMAN, R.G. (1991): Thermobarometry using multi-equilibrium calculations. A new technique, with petrologic applications.- Can. Mineral., 29, 835-855.

BUDA, Gy. (1981): Genesis of the Hungarian granitoid rocks.- Acta Geol. Acad. Sci. Hung., 24, 309-318.

BUDA, Gy. (1985): Genesis of collision type Variscan granitoides in Hungary, Western Carpathians and in the Bohemian Massif.- Unpublished PhD Thesis (in Hung.), University of Budapest, 148 p.

CHATTERJEE, N.D. & FROESE, F. (1975): A thermodynamic study of the pseudobinary join muscovite-paragonite in the system $KAlSi_3O_8$-$NaAlSi_3O_8$-Al_2O_3-SiO_2-H_2O.- Am. Mineral., 60, 985-993.

CSONTOS, L., NAGYMAROSY, A., HORVATH, F. & KOVAC, M. (1992): Tertiary evolution of the Intra-Carpathian area: a model.- Tectonophysics, 208, 221-241.

FERRY, J.M. & SPEAR, F.S. (1978): Experimental calibration of the partioning of Fe and Mg between biotite and garnet.- Contrib. Mineral. Petrol., 66, 113-117.

FUHRMAN, M.L. & LINDSLEY, D.H. (1988): Ternary-feldspar modeling and thermometry.- Am. Mineral., 73, 201-216.

FÜLÖP, J. (1994): The geology of Hungary, Paleozoic II.- Monograph, Akadémiai Kiadó, Budapest, 445 p.

GÉCZY, B. (1973): The origin of the Jurassic faunal provinces and the Mediterranean plate tectonics.- Ann. Univ. Sci. Budapest. R. Eötvös Nom. Sect. Geol., 16, 99-114.

GERYA, T.V., PERCHUK, L.L., TRIBOULET, C., AUDREN, C. & SEZ'KO, A.I. (1997): Petrology of the Tumanshet Zonal Metamorphic Complex, Eastern Sayan.- Petrology, 5, 503-533.

GHENT, E.D. & STOUT, M.Z. (1981): Geobarometry and geothermometry of plagioclase-biotite-garnet-muscovite assemblages.- Contrib. Mineral. Petrol., 76, 92-97.

GREEN, T.H. & HELLMAN, P.L. (1982): Fe-Mg partitioning between coexisting garnet and phengite at high pressure, and comments on a garnet-phengite geothermometer.- Lithos, 4, 253-266.

HODGES, K.V. & CROWLEY, P.D. (1985): Error estimation and empirical geothermobarometry for pelitic systems.- Am. Mineral., 70, 702-709.

HODGES, K.V. & SPEAR, F.S. (1982): Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire.- Am. Mineral., 67, 1118-1134.

HOLDAWAY, M.J. (1971): Stability of andalusite and the aluminium silicate phase diagram.- Amer. J. Sci., 271, 97-131.

HOLLAND, T.J.B. & BLUNDY, J. (1994): Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry.- Contrib. Mineral. Petrol., 16, 433-447.

KÁZMÉR, M. & KOVÁCS, S. (1985): Permian - Paleogene paleogeography along the Eastern part of the Insubric - Periadriatic lineament system: evidence for the continental escape of the Bakony - Drauzug Unit.- Acta. Geol. Hung., 28, 71-84.

KLEEMANN, U. & REINHARDT, J. (1995): Garnet-biotite thermometry revisited: The effect of Al VI and Ti in biotite.- Eur. J. Mineral., 6, 925-941.

KOVÁCH, Á., SVINGOR, É. & SZEDERKÉNYI, T. (1985): Rb-Sr dating of basement rocks from the southern foreland of the Mecsek Mountains, Southeastern Transdanubia, Hungary.- Acta Miner. Petr. Szeged, 27, 51-56.

KOVÁCS, S. (1982): Problems of the "Pannonian Median Massif" and the plate tectonic concept. Contributions based on the distribution of Late Paleozoic - Early Mesozoic isopic zones.- Geol. Rundschau, 71, 617-640.

KRETZ, R. (1983): Symbols for rock-forming minerals.- Am. Mineral., 68, 277-279.

LEAKE, B.E., WOOLLEY, A.R., ARPS, C.E.S., BIRCH, W.D., GILBERT, M.C., GRICE, J.D., HAWTHORNE, F.C., KATO, A., KISCH, H.J., KRIVOVICHEV, V.G., LINTHOUT, K., LAIRD, J., MANDARINO, J., MARESCH, W.V., NICKEL, E.H., ROCK, N.M.S., SCHUMACHER, J.C., SMITH D.C., STEPHENSON, N.C.N., UNGARETTI, L., WHITAKERR, E.J.W. & YOUZHII, G. (1997): Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names.- Mineral. Mag., 61, 295-321.

LELKES-FELVÁRI, Gy. & SASSI, F.P. (1981): Outlines of the pre-Alpine metamorphism in Hungary.- In: KARAMATA, S. & SASSI, F.P. (eds.): IGCP Project No. 5 Newsletter, 3, 89-99.

LELKES-FELVÁRI, Gy., ÁRKAI, P., SASSI, F.P. & BALOGH, K. (1996): Main features of the regional metamorphic events in Hungary. A review.- Geol. Carp., 47, 257-270.

MASSONNE, H.J. & SCHREYER, W. (1987): Phengite barometry based on the limiting assemblage with K-feldspar, phlogopite, and quartz.- Contrib. Mineral. Petrol., 96, 212-224.

McMULLIN, D.W., BERMAN, R.G. & GREENWOOD, H.J. (1991): Calibration of the SGAM thermometer for pelitic rocks using data from equilibrium experiments and natural assemblages.- Can. Mineral., 29, 889-908.

NAGY, G. (1984): Computer programs for quantitative electron microprobe analysis developed for geological applications.- Proc. 8th Eur. Congr. on Electron Microscopy, EUREM '84, Budapest, 1041-1042.

NEWTON, R.C. & HASELTON, H.T. (1981): Thermodynamics of the garnet-plagioclase-Al_2SiO_5-quartz geobarometer.- In: NEWTON, R.C. (ed.): Thermodynamics of Minerals and Melts. Springer Verlag, New York, 131-147.

PLYUSNINA, L.P. (1982): Geothermometry and geobarometry of plagioclase-hornblende bearing assemblages.- Contrib. Mineral. Petrol., 80, 140-146.

ROBINSON, P., SPEAR, F.S., SCHUMACHER, J.C., LAIRD, J., KLEIN, C., EVANS, B.W. & DOOLAN, B.L. (1982): Phase relations of metamorphic amphiboles: natural occurrence and theory.- In: VEBLEN, D.R. & RIBBE, P.H. (eds.): Amphiboles: Petrology and Experimental Phase relations. Reviews in Mineralogy, 9B, Mineralogical Society of America, 227 p.

SPEAR, F.S. (1993): Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths.- Monograph, Mineralogical Society of America, Washington D.C., 799 p.

SZEDERKÉNYI, T. (1976): Barrow-type metamorphism in the crystalline basement of Southeastern Transdanubia.- Acta Geol. Hung., 13, 27-34.

SZEDERKÉNYI, T. (1984): Az Alföld kristályos aljzata és földtani kapcsolatai (Crystalline basement of the Great Plain and its geological connections).- Unpublished PhD Thesis (in Hung.), University of Szeged, 184 p.

SZEDERKÉNYI, T. (1996): Metamorphic formations and their correlation in the Hungarian part of the Tisia megaunit (Tisia megaunit terrane).- Acta Miner. Petr. Szeged, 37, 143-160.

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