

## GEOCHEMISTRY OF VARISCAN AMPHIBOLITES FROM THE METAMORPHIC BASEMENT OF THE KÖRÖS COMPLEX (TISZA BLOCK, HUNGARY)

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**Abstract:** Variscan metamorphic complexes of the Apuseni Mountains in Romania continue westward in the pre-Neogene basement of the Pannonian Basin. To better understand the spatial relationship between the two neighbouring areas and to have a chance to sketch their common metamorphic evolution, geochemical and petrologic features of specific rock types must be focused on. The most promising lithologies for this reason are diverse metabasic rocks, first of all, amphibolites. Previous work on determination of the protolith of metabasic rocks from the Körös Complex, a large subarea of the eastern end of the Tisza microplate in Hungary, gave contradictory results. To solve this problem, major and trace element data of 60 amphibolite samples were treated by traditional geochemical methods as well as by a multivariate geo-mathematical approach. For the mathematical study a combination of correlation, principal component, cluster and discriminant function analyses were used in order to recognize presence of different igneous series in the area. The results of the geo-mathematical treatment were also tested and confirmed by the evaluation of trace element and REE data of representative unaltered samples. Based on this examination three geochemically distinct groups of amphibolites can be defined. Each of them can be related to structural units of different metamorphic evolution. The lowermost tectonic realm is dominated by orthogneiss containing metabasic xenoliths of MORB character. This unit is covered by a sillimanite-biotite paragneiss zone in which garnetiferous amphibolite intercalations occur exhibiting highly differentiated OIB basalt protolith. The topmost unit consists essentially of amphibolites and biotite gneisses representing a pre-metamorphic volcanoclastic series. Here, the amphibolite members are of T-MORB character tholeiites that possibly developed in a back-arc basin.

**Keywords:** amphibolite, geochemistry, Variscan orogeny, Tisza block, geomathematics

### 1. INTRODUCTION

The present structure of the basement of the Pannonian Basin is a result of horizontal microplate movements due to the Alpine tectogenesis. According to the available reconstructions (Haas et al., 1995) diverse fragments of the basement were situated in different parts of the northwestern Tethyan realm during the Palaeozoic and Mesozoic times. The large blocks (Tisza and the Alcázar units) came into adjacent position during the Paleogene-Miocene period and at present are separated by the Mid-Hungarian lineament and other strike slip faults (Fig. 1, Csontos & Nagymarosi, 1998). During the early period of the extension of the Pannonian Basin following the Middle Miocene, numerous parts of the of the metamorphic basement exhumed forming a series of metamorphic core complexes, while deep

sub-basins were formed among them (Tari et al., 1992; Posgay et al., 1996; Horváth et al., 2006). Due to the overall subsidence of the basin afterwards, at present the metamorphic basement is covered by a significant amount of young sediments.

In order to reveal the metamorphic and pre-metamorphic evolution of the Tisza microplate many efforts have been made in the last decades. A special interest was shown in its NE segment (Körös Complex, Fig. 2), because in this relatively big area several hundreds of wells penetrated the crystalline basement, and a large amount of petrological data exists. Many previous works dealt with the determination of the protoliths of the most frequent rock types, gneiss, mica schist and, first of all, amphibolite (e.g. Szederkényi, 1983; Szili-Gyémánt, 1986; Bedini et al., 1998; Tóth, 1992, 1994). Based on these geochemical investigations, the protolith of gneiss and mica schist

became relatively well known. Most of them were first found to be of sedimentary origin by Szepesházy (1966, 1971). Based on discrimination methods of Bhatia (1983) both gneiss and mica schist represent active continental margin sediments (Tóth et al., 2000). Szepesházy (1973) also found orthogneiss an important constituent of the basement in the study area. This idea was later confirmed by Zachar & Tóth (2001) pointing to the importance of relic igneous myrmekite grains in the gneiss texture. Zachar & Tóth (2003) as well as Tóth & Zachar (2003, 2006) inferred common presence of mafic and ultramafic xenoliths in this orthogneiss body.

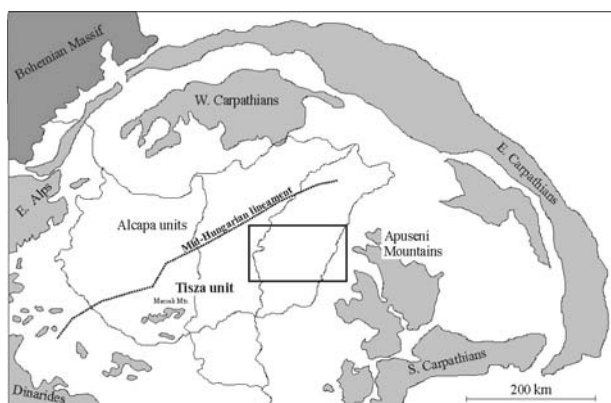


Figure 1. The present location of the Tisza unit within the frame of the Alp-Carpathian system. Position of the Körös Complex is shown by the rectangle.

Although dozens of amphibolite samples were also examined geochemically, the results are still contradictory. Applying different sets of elements to determine the protolith, a wide spectrum of possible rock types occurs. Based on previous work, both andesite (Szederkényi, 1996) and basalt (Tóth, 1994) seem possible; their chemical character may be tholeiitic (Tóth, 1994), calc-alkaline (Szederkényi, 1996) or even alkaline (Bedini et al., 1998). Accordingly, there are many suggestions about the paleotectonic setting, in which the protoliths of the amphibolites may have formed. An assumption of an island-arc volcanism could correspond to the above-mentioned greywacke type pelitic sediments (Szederkényi, 1996), examination of immobile trace elements, however, implies that amphibolite may rather be MORB-character tholeiitic basalt than a low-K andesite (Tóth, 1994).

Recent seismic studies suggest a complex internal structure of the uplifted metamorphic domes formed essentially due to post-metamorphic tectonic movements (Tóth et al., 2008). On these seismic profiles an older set of overthrust structures is complicated by younger normal faults developed during basin formation. Detailed petrographic

descriptions and thermobarometry calculations of numerous borecore samples suggest co-existence of three different realms in the study area with significantly different metamorphic evolutions (Tóth & Zachar, 2006). Although they all must be present, the real spatial extension of the three units is highly questionable as most core samples are not available for thermobarometry calculations either because of lacking appropriate mineral assemblages or due to significant retrograde overprint.

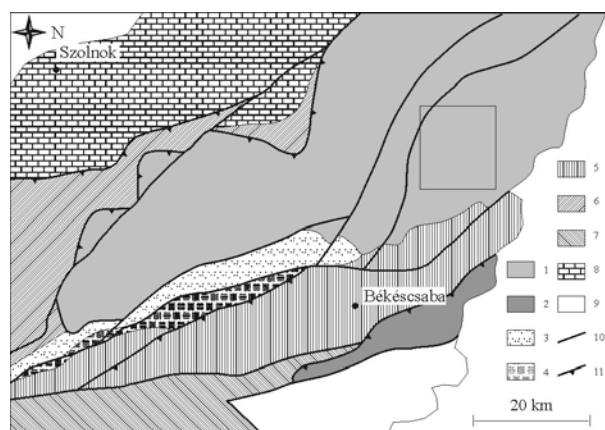


Figure 2. Pre-Neogene geological sketch map of the Körös Complex and the surrounding areas (modified after Haas et al., 2010). Legend: 1: metamorphic rocks of the Körös Complex, 2: S-Hungarian metamorphic units, 3: Triassic sequences, 4: Jurassic sequences, 5: Cretaceous sequences, 6: Cretaceous volcanites, 7: Undefined Mesozoic sequences, 8: Paleogene flysch type sediments, 9: Unknown basement, 10: First-order tectonic line, 11: Mesozoic nappe and overthrust. Rectangle points to the position of a more detailed geological map on figure 3b.

Because metabasic rocks are common lithologies throughout the basement, spatial extension of these tectonic zones may be sketched using diverse geochemical properties of the amphibolites. To do so, first all samples are handled together using traditional geochemical and mathematical methods. In the second step a more detailed evaluation of selected, unaltered samples follow.

## 2. GEOLOGICAL SETTING

Crystalline rocks of the Tisza block are well known in the Apuseni Mountains in Western Romania (Balintoni et al., 2009), while these rocks are exposed only in a small area in the in the Hungarian part of the microplate (Mecsek Mts, SW-Hungary, Fig. 1). In Eastern and Central Hungary the basement is covered by 2000-7000 m thick Miocene to Pleistocene sediments making the

examination possible only on borecores close to the topmost areas of the elevated metamorphic domes.

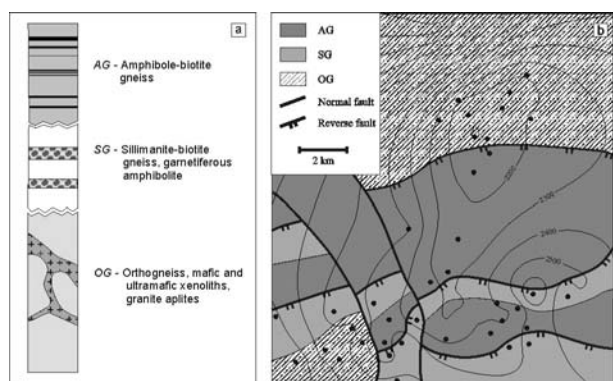


Figure 3. a) Ideal rock column of the metamorphic basement of the Körös Complex. The main structural units OG (orthogneiss), SG (sillimanite-biotite paragneiss) and AG (amphibole-biotite gneiss) are separated by post-metamorphic tectonic zones. b) Detailed geological map of a selected basement high (Mezősas-Furta area, after Tóth & Zachar, 2006) Numbers denote depth below the present surface; dots represent boreholes penetrated the basement.

The Körös Complex (KC), a relatively big subarea examined in this paper, is located in the eastern end of the Hungarian part of Tisza block (Fig. 1). In the south it is separated from the S-Hungarian metamorphic and sedimentary units by the assumed front of the Cretaceous Codru nappe system (Fig. 2) Current geological and structural maps of the pre-Neogene basement in this area are rather deficient due to little information. Although, several boreholes penetrated diverse Mesozoic formations, the basement essentially consists of metamorphic rocks (Fig. 2). According to present interpretations, three realms of petrologically different evolutions can be distinguished in the region. According to the ideal rock section (Fig. 3a, Tóth & Zachar, 2006), a medium grade orthogneiss complex (OG) is overlain by high grade sillimanite-biotite paragneiss (SG) and amphibole-biotite gneiss (AG) sequence. The three realms got juxtaposed due to post-metamorphic tectonic movements (Tóth et al., 2008) and during the Neogene the amalgamated basement uplifted (Tóth et al., 2000, Schubert et al., 2007). A detailed geological map of the best known segment of the basement (Mezősas-Furta area) is shown on figure 3b (following Tóth & Zachar, 2006). At present, these crystalline domes form the most important fractured basement hydrocarbon reservoir of Hungary (P'an, 1982; Nelson, 2001).

Petrography and detailed thermobarometry calculations for the main lithologies have been presented previously; here only a brief summary follows. The main rock type of the lowermost unit

(OG) is orthogneiss consisting essentially of two feldspars, quartz and biotite; in some samples also muscovite occurs. The common accessory phases, zircon and apatite show euhedral shape (Tóth et al., 2000). Although, based on its obvious gneissic structure this rock type is clearly metamorphic in origin, the common relic polygonal texture of feldspar grains; at places even quartz-feldspar aggregates within the common granoblastic texture, remind an intrusive igneous protolith (Vernon & Collins, 1988). K-feldspar often exhibits perthitic appearance, while plagioclase is at places myrmekitic (Zachar & Tóth, 2001). Orthogneiss contains a wide scale of xenocrysts (Zachar & Tóth, 2003); the most common among which is garnet of diverse grain sizes usually being partially replaced by chlorite and carbonate minerals. Single, oriented amphibole grains usually have resorbed rim. At places amphibole xenocrysts coexist with clinopyroxene and/or garnet grains (Fig. 4a).

Orthogneiss contains not only diverse xenocrysts but also a rather wide spectrum of xenoliths (Fig. 4 b, c) of mafic and rarely ultramafic composition. The most common among these lithologies is garnetiferous amphibolite (Fig. 4d), which itself can be subdivided into several subtypes. The compact amphibolite consists essentially of amphibole with no or little plagioclase content. Garnet either occurs as a matrix constituent or forms inclusions in large amphibole grains (Fig. 4d). Another common inclusion phase in amphibole grains is clinopyroxene, which systematically coexists with garnet (Fig. 4a). Rutile is a frequent inclusion mineral both in amphibole and in garnet. A few xenoliths exhibit a clear eclogitic texture and mineralogy, some of which are available for detailed thermobarometry calculations (Tóth, 1997; Zachar et al., 2007). A few xenoliths of actinolite schist, antophyllite schist and serpentinite mineralogy suggest ultramafic compositions. There exists a gradual transition between massive mafic and ultramafic lenses and the orthogneiss containing the xenocrysts. Towards the orthogneiss the amount of the large amphibole grains decreases, developing a resorbed, wiggly grain boundary (Fig. 4 b, c).

Thermobarometry calculations in diverse xenocrysts and xenoliths give a wide range in formation *P-T* conditions, especially pressures. The low jadeite component as well as the negligible Cr-content in single clinopyroxene xenocrysts infers low-pressure (Tóth & Zachar, 2006). Using the single pyroxene enstatite-in-Cpx thermometer (Nimis & Taylor, 2000), a coherent temperature of 810-830°C can be got presuming 2-4 kbar. Single amphibole crystal cores vary in composition

resulting in pressures of 3.0-4.5 kbar at 660-680°C using the estimation of Gerya et al., (1997). Based on the complex mineralogy of the garnet amphibolite xenoliths remarkable *P-T* data can be got (~8 kbar, 620°C), while the two eclogite xenoliths suggest a peak pressure at around 15 kbar (800-820 °C).

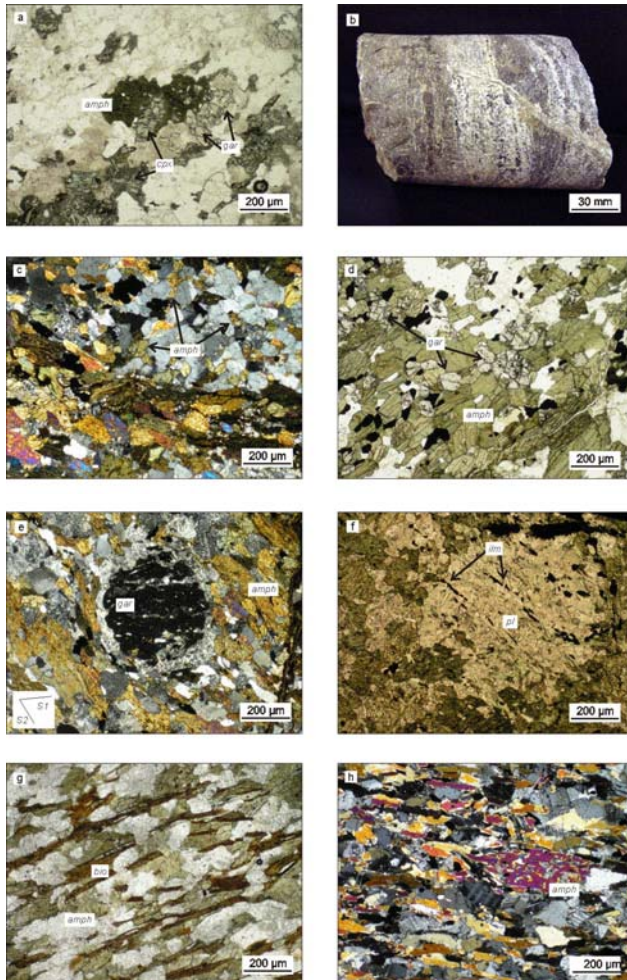


Figure 4. Typical structures and microtextures of the amphibolite types of the Körös Complex. a) amphibole, clinopyroxene and garnet xenocrysts coexist in orthogneiss, b) gradual transition between massive mafic lenses and the orthogneiss is obvious at hand specimen (bocere) scale, c) and at microscopic scale, too, d) the most characteristic xenolith type of the OG unit is garnetiferous amphibolite, e) in the SG unit a polymetamorphic garnetiferous amphibolite occur with relic garnet grains, f) plagioclase replaces relic garnet in the same rock type, g) alternating amphibole and biotite rich zones suggest a volcanosedimentary origin, h) normal amphibolites consist essentially of amphibole and plagioclase.

The sillimanite-biotite gneiss consists essentially of quartz, two feldspars and biotite, while most samples also contain bunches of thin sillimanite needles. Muscovite is totally missing.

Most samples include resorbed relic garnet grains with kyanite inclusions, suggesting a pre-kinematic event also confirmed by preserved schistosity of biotite. Sillimanite-biotite gneiss contains a few intercalations of garnetiferous amphibolite. In addition to dark green amphibole and plagioclase, this massive, coarse-grained amphibolite variety also contains large, resorbed garnet grains, which at places are entirely replaced by a fine-grained aggregate of plagioclase crystals. Based on the orientation of the rutile and ilmenite inclusion trails (S1) significantly different from that shown by matrix amphiboles (S2), garnet is pre-kinematic (Fig. 4e, f.). In the sillimanite-biotite gneiss unit two subsequent stages of the metamorphic evolution can be evaluated (Tóth & Zachar, 2006). Biotite inclusions together with garnet core suggest a temperature of 730-750°C (Bhattacharya et al., 1992), while using the GASP paragenesis and the  $\text{Grs} + 2\text{Ky} + \text{Qtz} = 3\text{An}$  reaction, pressure is around 7.5-7.8 kbar. Using the same equilibria for matrix assemblages, temperature is 630-650°C, while pressure varies around 4-5 kbar. In garnetiferous amphibolite, pressure estimation using inclusion compositions in the garnet and based on the approach of Bohlen & Liotta (1986) results in a rather coherent  $K_D$  value in case of the calibrated reaction  $\text{Grs} + 2\text{Alm} + \text{Rt} = 2\text{Ilm} + \text{An} + \text{Qtz}$ . There are, however only limited possibilities for temperature estimation. The fact that garnet is unzoned clearly suggests a high temperature diffusive homogenization, so pressure is calculated assuming a *T* between 600-800°C and yields ~9.5 kbar. For single matrix amphiboles a temperature range of 640-680°C and a pressure of 4 kbar can be calculated by Gerya et al. (1997). For matrix amphibole-plagioclase pairs *T* ~ 670°C is got at 5 kbar using the method of Holland & Blundy (1994).

Three main lithologies are classified as amphibole-biotite gneiss unit (AG); in the whole rock sequence several centimetres thick layers of biotite gneiss, amphibolite and amphibole-biotite gneiss are interlocking suggesting a volcano-sedimentary series (Fig. 4 g, h, Tóth, 1994). In amphibolite, the common phases are the small-grained, at places even zoned green hornblende and plagioclase. Accessory phases are epidote, ilmenite and in some cases also small, idiomorphic garnet occurs. In the gneiss sections quartz, K-feldspar and plagioclase dominate; the relevant mica is biotite, which is interlayered by white chlorite flakes. Some samples also contain small, syn-kinematic garnet grains. Amphibole-biotite gneiss always forms the transition from the massive amphibolite towards biotite gneiss. For amphibole-plagioclase pairs

similar  $P$ - $T$  results can be calculated by diverse approaches. The method of Holland & Blundy (1994) gives 550-570°C, Gerya et al., (1997) yields 560°C at 3-4 kbar, while Plyusnina (1982) results in 530°C at 4 kbar. Similar  $P$ - $T$  conditions can be calculated using garnet-biotite equilibria for the biotite gneiss members.

Although, several amphibolite core samples are rather characteristic concerning their mineralogical and textural features making the above classification possible, most pieces cannot be grouped based only on petrographic reasons. That is why for sample identification and classification geochemical features must be used.

### 3. ANALYTICAL METHODS

At the Johannes Gutenberg University in Mainz, Germany, the compositions of 60 amphibolite samples were measured on a Philips PW1453 XRF machine using a Sc-Mo tube. In addition to the major elements the following set of trace elements was determined: V, Cr, Co, Ni, Zn, Cu, Ga, Rb, Sr, Zr, Y, Nb, Ba, Th, U, Pb with an accuracy better than 2% for each element. For calibration natural standards were used.

After the geochemical and geo-mathematical investigation of major and trace element data, 12 amphibolite samples were selected for determining their rare earth and additional trace element concentrations in order to test and further specify the previous results. The measurement was made by using  $\gamma$ -spectroscopy at the neutron activating laboratory of the Technical University of Budapest. The following elements were detected: La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Ta, Sc, Hf. The geochemical database is available from the author.

### 4. GEOCHEMICAL OUTLINE

Using elements generally assumed to be immobile, most amphibolite samples plot into the fields of subalkaline basalt and basaltic andesite (Fig. 5, Winchester & Floyd, 1977, Floyd & Winchester, 1978). The number of samples in the alkaline basalt field is subordinate. The Cr-Ti diagram (Pearce, 1975), among others, suggests an ocean floor origin, however, most of the other traditional diagrams (e.g. Zr-Nb-Y, Meschede, 1986, Zr-Ti, Zr-Ti-Y, Zr-Ti-Sr, Pearce & Cann, 1973, not presented here) give contradictory results or significant overlap.

In order to reach the full potential of the geochemical data set and to determine the geochemical characteristics of distinct amphibolite

groups, multivariate mathematical methods were applied first (for application these approaches in igneous geochemistry see Owen, 1989; Ragland et al.; 1997, Hannigan et al., 2001 among many others). In the complex geo-mathematical system a series of conventional methods (correlation analysis, principal component analysis, cluster analysis, discriminant function analysis and multidimensional scaling) has been applied using the Statistical Package for the Social Sciences (SPSS Statistics 17.0). The detailed description of the mathematical background of these methods is concluded in numerous handbooks and papers (e.g., Miller & Kahn, 1967; LeMaitre, 1982; Swan & Sandilands, 1995).

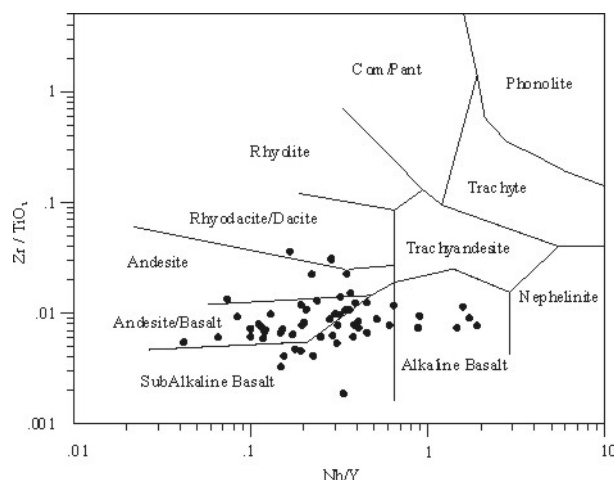


Figure 5. On the Nb/Y vs. Zr/TiO<sub>2</sub> diagram (Winchester, Floyd, 1977) most samples plot into the subalkaline basalt field.

Prior to applying the multivariate methods, univariate tests were made element by element in order to filter extreme values and outliers ( $2\sigma$  method) as well as to normalize the distributions if necessary. Each element examined shows unimodal normal (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, CaO, Na<sub>2</sub>O, K<sub>2</sub>O, Co, Ga, Y, Zr, Rb, Sr, Pb) or lognormal (TiO<sub>2</sub>, MnO, MgO, P<sub>2</sub>O<sub>5</sub>, V, Cr, Ni, Nb, Ba, Th, U) distributions, outliers were found only in cases of K<sub>2</sub>O and Rb. Lognormal distributions were transformed to normal, because most of the methods listed above presume variables of normal distribution. In the geo-mathematical system applied here first a simultaneous application of principal component and correlation analysis is performed. As a result, these methods can produce groups of the original variables, which may represent independent geological processes. The purpose of the next step (cluster analysis) is the classification of the samples in the multidimensional space of principal components (processes). Result of sample clustering can be tested and evaluated by simultaneous application of multidimensional scaling,



discriminant function analysis and the calculation of differentiation components. This latter one is a repeated application of principal component analysis for variables, which play an important role in igneous differentiation (Owen, 1989).

## 5. RESULTS AND DISCUSSION

### 5.1. Results of the geo-mathematical treatment

Linear correlation between variables is figured in a correlation profile instead of in a table form. In this graph those variables are connected which are in significant connection to each other. Evaluation of this profile (significance level is 0.99) confirms the igneous origin of the rocks (Fig. 6) through the variable group represented by MgO, Ni, Cr, Co, SiO<sub>2</sub> and Na<sub>2</sub>O. During tholeiitic differentiation Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> must increase together with incompatible elements (Pearce & Cann, 1973; Beccaluva et al., 1977), consequently, the close connection between the groups represented by Fe<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, MnO, V, and that of Zr, Nb, Y and P<sub>2</sub>O<sub>5</sub>, respectively, may refer to the tholeiitic character of differentiation. Because the geochemical nature of K<sub>2</sub>O and Rb are very similar, the tight correlation between these elements may be explained in many different ways.

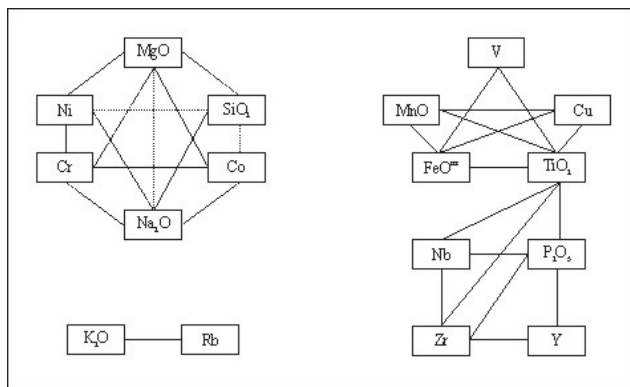


Figure 6. On the correlation profile (significance level of 0.99) of the Körös Complex amphibolites four main element groups can be identified.

The result of the principal component analysis confirms and completes these conclusions giving clearly distinguishable groups of elements each reflective of an independent process. The first three principal components (PCs) collect the variables of the most compatible, the most incompatible elements and those, which are responsible for the tholeiitic character of the differentiation (Table 1). Because the K<sub>2</sub>O-Rb pair (PC4) commonly moves together during diverse geological processes, e.g.

low-temperature hydrothermal metamorphism, it does not represent any specific process unequivocally. On the other hand, the conspicuous independence of K<sub>2</sub>O and Rb from the igneous PCs (PC1, 2, 3) suggests that alkaline basalt was probably not the protolith of the amphibolites.

Table 1. Results of the principal component analysis

	Elements involved	Eigenvalue	%
PC1	-Si, Mg, -Na, Cr, Co, Ni	5.36	28.2
PC2	Ti, P, Ga, Y, Zr, Nb	4.51	23.7
PC3	Ti, Fe, V	2.18	11.5
PC4	K, Rb	1.76	9.3

For a more detailed investigation of the amphibolite samples a hierarchical cluster analysis is applied first. It operates with the petrologically meaningful processes (PC1, 2, 3), with a complete linkage method and the Euclidean measure. Because of the usage of only the igneous processes, the exclusive goal of this approach is the specification of the role of igneous differentiation in the protolith. A simplified version of the hierarchical structure of three major groups A, B and C revealed by cluster analysis is shown in figure 7. After several loops of cluster analysis, the calculation of differentiation components, multidimensional scaling and discriminant function analysis also the two subgroups of B (B<sub>1</sub>, B<sub>2</sub>) proved to be petrologically interpretable.

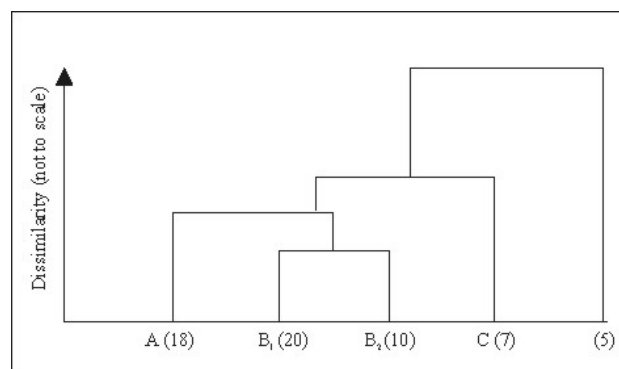


Figure 7. Simplified structure of the dendrogram produced by the cluster analysis using complete linkage method and Euclidean measure. Numbers in the brackets mark the number of samples in each group.

PC1 and PC3 were applied for calculating differentiation components in order to decide whether the given groups represent different states of igneous differentiation or not. While, in case of PC1 the result could not be interpreted clearly, in case of tholeiitic differentiation (PC3) the calculated distribution curves belonging to groups A, B<sub>1</sub>, B<sub>2</sub> and C form very sharp peaks (Fig. 8) on the diagram. The same order (A→B<sub>1</sub>→B<sub>2</sub>→C) may be

seen on figure 9, which shows the result of the multidimensional scaling calculations. To determine the differences among the four groups more exactly, a discriminant function analysis was applied (Table 2). One can see that every pair of groups (but B<sub>2</sub> and C) may be distinguished based mainly on PC3 that is on tholeiitic differentiation. As group C differs notably from the others also in the PC2 (incompatible elements, Table 1), this group contains the most differentiated samples.

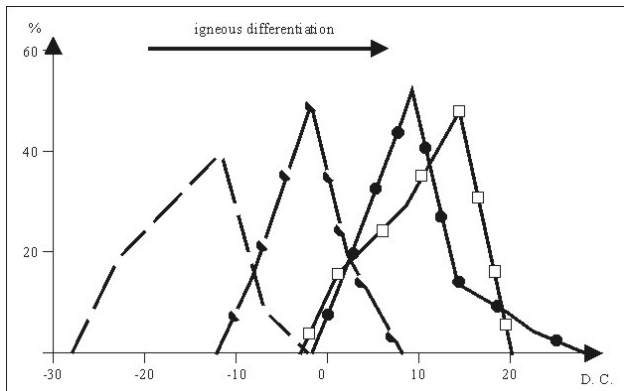


Figure 8. Distributions of the differentiation component (D.C.) values in the four distinct amphibolite groups A (open circles), B<sub>1</sub> (half circles), B<sub>2</sub> (closed circles) and C (squares) form sharp peaks.

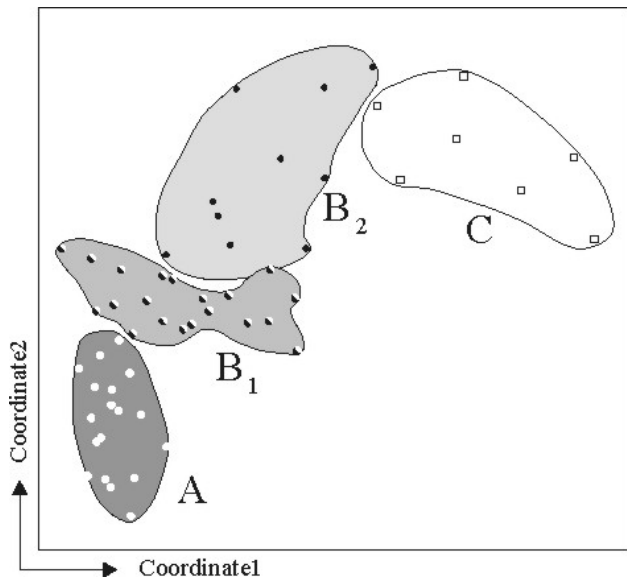


Figure 9. Relative position of the samples in the multidimensional geochemical space can be visualized on 2D using the multidimensional scaling procedure. The result confirms the existence of the separate amphibolite groups.

Comparison of results of the geochemical classification with the petrographic characteristics of the typical samples suggests that most mafic xenoliths of the OG unit plot into group A, while group B represents amphibolites of the AG unit. All

but a few garnetiferous amphibolite samples of the SG and some amphibolites of the AG unit fall into group C.

Table 2. Coefficients of the bivariate discriminant functions. Note the large values of PC3 in most cases (highlighted).

Pairs of groups	PC1	PC2	PC3
A, B <sub>1</sub>	2.24	1.09	<b>-2.75</b>
A, B <sub>2</sub>	0.00	0.00	<b>1.80</b>
B <sub>1</sub> , B <sub>2</sub>	0.78	0.54	<b>2.19</b>
B <sub>1</sub> , C	0.00	<b>1.47</b>	0.00
B <sub>2</sub> , C	0.65	<b>1.65</b>	<b>-2.34</b>
A, C	0.00	-1.13	<b>1.81</b>

## 5.2. Geochemical behaviour of the amphibolites

In order to further characterize the above groups of amphibolites, the trace element and REE-contents of three unaltered samples from each group were measured.

If a highly incompatible LIL element (e.g. Ta or Th) is plotted against other trace elements on a logarithmic scale, the course of differentiation may be modelled in relation with element loss or gain during the process. Allègre et al., (1977) suggest applying Ta vs. other possible incompatible elements (e.g. Th, Ce, La) for this purpose, because Ta has the lowest distribution coefficients for the mineral phases, which are likely to appear during crystallization of basalt magmas. In case of the last three amphibolite groups, negative slopes defined by the most compatible elements (Ni, Cr, Fig. 10) suggest that group B and C amphibolites define a normal differentiation trend with the most differentiated samples in group C. The highly incompatible trace elements (Eu, Ga, Zr, La, Fig. 10 as well as Rb, Sr, Hf, Nb, Y, Th, Sm, Ce, Nd, not shown) exhibit a linear increase with Ta with different slopes. Also Fe, Ti and V exhibit an incompatible character in group B and so confirm the tholeiitic type of the fractionation, while for group C samples Fe, Ti and especially V decreases abruptly. Bulk distribution coefficients calculated for group B and C samples show no highly incompatible behaviour for any element (Zr: 0.36, Y: 0.72, Nb: 0.2, Rb: 0.67, Hf: 0.31, Sr: 0.72, Ga: 0.87, La: 0.45, Ce: 0.42, Nd: 0.4, Eu: 0.74). The relatively high value for Y indicates a significant role of clinopyroxene (Villemant et al., 1981), while those for Sr, Ga and Eu refer to the moderate plagioclase crystallization. When clinopyroxene dominates the fractional crystallization, also the partition coefficient values for LREE may be as high as in our case. The low values for the compatible trace elements (Ni: 1.76→1.28, Cr: 1.75, Sc: 1.1) also suggest that the igneous

differentiation of the metabasic rocks in question was governed by clinopyroxene and moderate plagioclase crystallization.

Behaviour of the xenolith samples significantly differs from the above tendencies. Here, concentrations of all compatible elements remain well below the trends defined by the other sample groups, while incompatible element contents exceed them significantly. On the other hand, there is no relative gain in case of the most incompatible La, Ce and Th suggesting post-magmatic depletion in Ta (La, Ce, Th) for the xenoliths instead of a primitive basalt protolith.

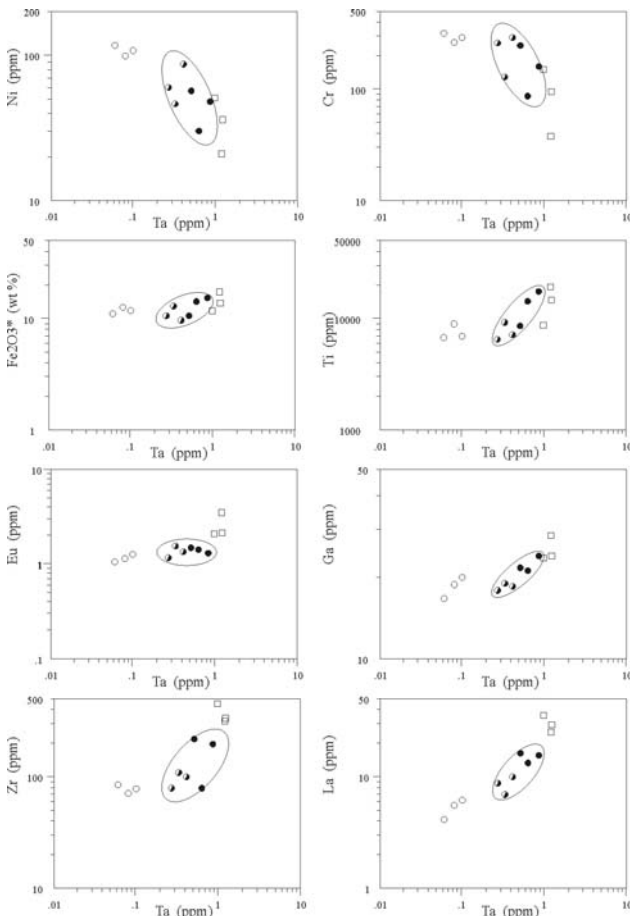


Figure 10. Selected Harker diagrams for three selected samples representing each amphibolite group (symbols like in figure 8). For details see text.

The average chondrite normalized spectra (using data from Evensen et al., 1978) show a significant increase in LREE in the above order of the sample groups (Fig. 11a). Similarly to the previous results, the xenoliths (group A) represent the most primitive composition, while garnetiferous amphibolites (group C) are the most enriched both in LREE and HREE. Although the same trend exists, there is no substantial difference in the HREE content of the first three groups, all exhibit the same low

degree of enrichment over chondrite. In fact, the  $(Yb)_N$  and  $(Lu)_N$  values are even lower for group B<sub>2</sub> than for group A samples suggesting depletion of xenoliths rather than enrichment of group B amphibolites in LREE. Europium shows a progressive decrease towards the most differentiated group of samples starting with a slightly positive anomaly in group A up to a slight negative anomaly in the most evolved samples. The extended N-MORB normalized (Sun & McDonough, 1989) spectra confirm the existence of the four distinct groups (Fig. 11b). The first three of them have similar composition to N-MORB for the heaviest elements and show only a slight increase for the light ones. Similarly to Eu, also Sr shows a decreasing anomaly trend with increasing differentiation.

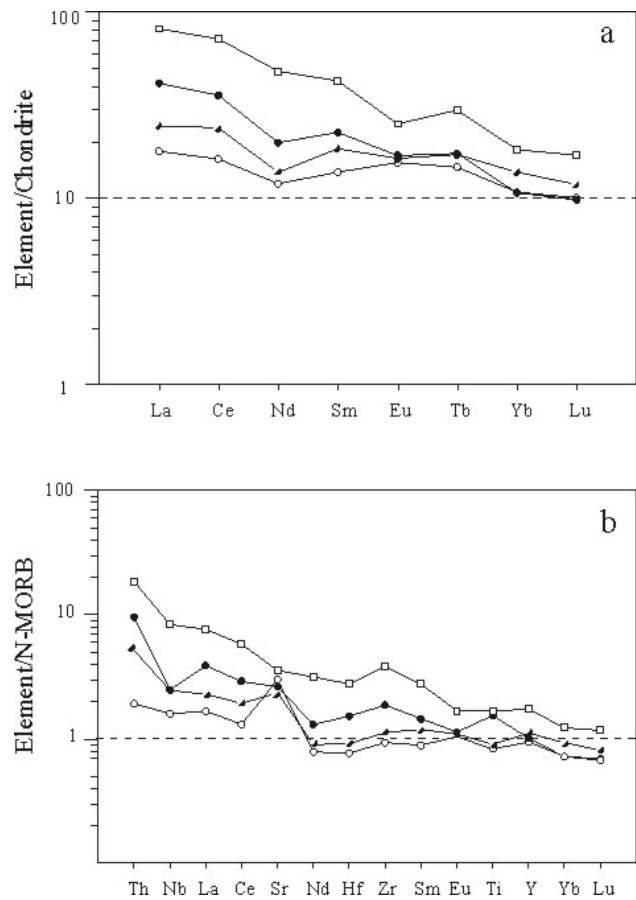


Figure 11. Average multielement spectra of the four amphibolite groups. a) Chondrite normalized REE spectra (chondrite data after Evensen et al., 1978), b) N-MORB normalized extended element spectra (N-MORB data after Sun, McDonough, 1989). Symbols like in figure 8.

In good agreement with the behaviour of both elements on the Harker diagrams, Sr and Eu behave incompatibly indicating slight plagioclase fractionation for group B and C samples. The rather typical positive Eu and Sr anomalies in the xenolith samples, on the other hand, suggest presence of



plagioclase cumulates in the igneous protoliths of the amphibolites at present contain a minor (<10%) proportion of feldspar. High pressure experiments of natural olivine gabbros (Yaxley & Sobolev, 2007) suggest that Sr and Eu anomalies in clinopyroxene that substitute plagioclase are similar to that indicative in feldspar. Positive Eu and Sr anomaly in rocks with little feldspar was found by Sobolev et al., (2000), Pietruszka et al. (2002) as well as Cesare et al., (2002) too. Presence of such a “ghost” plagioclase in the geochemical signal is interpreted so that metabasic rocks may preserve some of their original geochemical signatures even at HP overprint. Such a model can be applied also for the xenoliths of the orthogneiss (group A amphibolites) in question. Although, there is no general textural proof for HP metamorphism in these samples, presence of eclogite xenoliths and the common appearance of the relic cpx + gar + rt assemblage in amphibolite xenoliths makes an early HP event for several samples possible.

### 5.3. Geochemical character of the amphibolites

The geochemical composition of an igneous rock may significantly be modified by mixing with crustal material. One of the best indicators of crustal contamination is Th (Wood, 1980). By normalizing it with Yb, the disturbing effect of fractionation can also be eliminated (Pearce, 1982). Figure 12 shows that probably no significant amount of crustal material has contaminated for any of the four sample groups. Ce/Zr ratio for each but one sample is as low as <0.25 suggesting a subordinate role of contamination by pelagic sediments. In good agreement with the previous statements,  $c_1$  vs.  $c_1/c_2$  type plots ( $c_2$  being the less incompatible element than  $c_1$ , e.g. Th vs. Th/Hf, Fig. 13) (Minster & Allégre, 1978) show that the last three sample groups can basically be distinguished by their different amount of fractional crystallization. The subhorizontal distribution of the sample points indicates evolution from a melt of similar degree of partial melting. In harmony with the previous suggestions, group A samples do not seem to evolve from the same kind of parent melt. The mafic xenoliths instead must represent the most primitive samples being close to the ideal melting line suggesting various degree of re-melting resulting in depletion of highly incompatible elements. On this basis, xenoliths are similar to common nebulites, geochemically (e.g. Jung et al., 1999).

Traditional geochemical discrimination diagrams yielded a cumulative result when all of the

KC amphibolite samples were plotted. That is why only the less altered three samples from each of the four distinct groups are used to define the paleotectonic environment, in which the protoliths of the amphibolites formed. Taking subalkaline basalt into account, most of the discriminating methods, like Zr-Ti (Pearce & Cann, 1973), Cr-Ti (Pearce, 1975), Ti-V (Shervais, 1982) prefer MORB basalts to low-K tholeiite. The common positive Zr-anomaly over N-MORB, like high values of Ti/V (>30) among other often used indicators also speak against island arc basalts (Pearce, 1975; Emmet, 1987; Saunders et al., 1988). On the other hand, parameters like the slight negative Nb-anomaly, as well as  $La/Nb > 1$  recall subduction-related settings. The Th/La ratio varying in the range of 0.05-0.15 shows a significant overlap between arc-related (>0.1) and N-MORB-type (0.07) series (Sun, 1980; Saunders & Tarney, 1984).

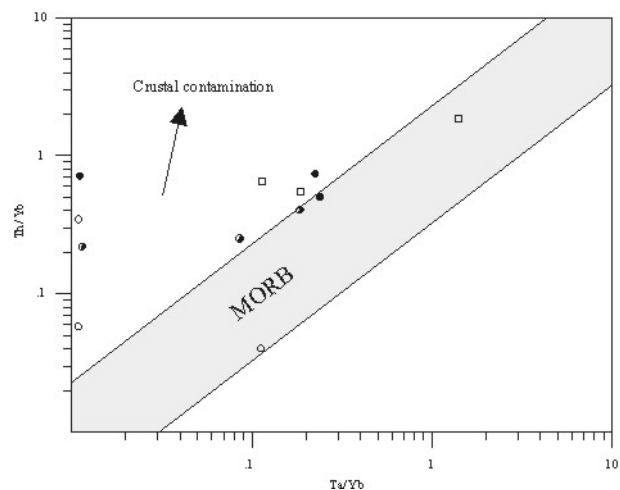


Figure 12. The Ta/Yb vs. Th/Yb plot suggests no significant amount of crustal contamination during the igneous evolution for any amphibolite group (symbols like in figure 8).

Diagrams by Shervais (1982, Ti-V), Pearce & Norry (1979, Zr-Zr/Y), Pearce & Cann (1973, Zr-Y-Ti), Vermeesh (2006, Sm-V-Ti) or Meschede (1986, Zr-Y-Nb) suggest that group A and B amphibolites are of MORB character, while the most evolved group C samples represent a trend towards OIB basalts (Fig. 14). Discrimination methods of Gill (1981, Th-La, Nb-La) as well as those by Wood (1980, Th-Hf-Ta, Th-Hf-Nb, Th-Zr-Nb) and Fodor & Vetter (1984, Zr/Nb-Zr/Y-Y/Nb) all suggest that the geochemical character of group A samples is close to N-MORB, while group B samples are between N-, and E-MORB within the ridge basalt field. The samples show a transitional T-MORB character on the Nb-normalized spidergram (Myers & Breitkopf 1989), too.

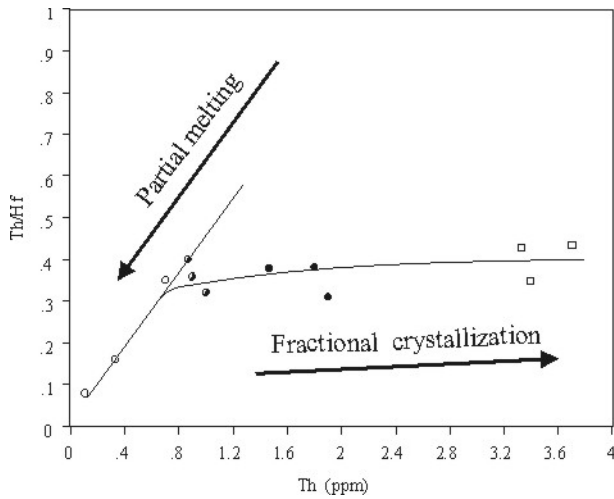


Figure 13. The Th vs. Th/Hf plot shows that the groups B<sub>1</sub>, B<sub>2</sub> and C represent samples of similar partial melting ratio, but different amount of fractional crystallization. Group A owns a significantly independent origin. Symbols like in figure 8.

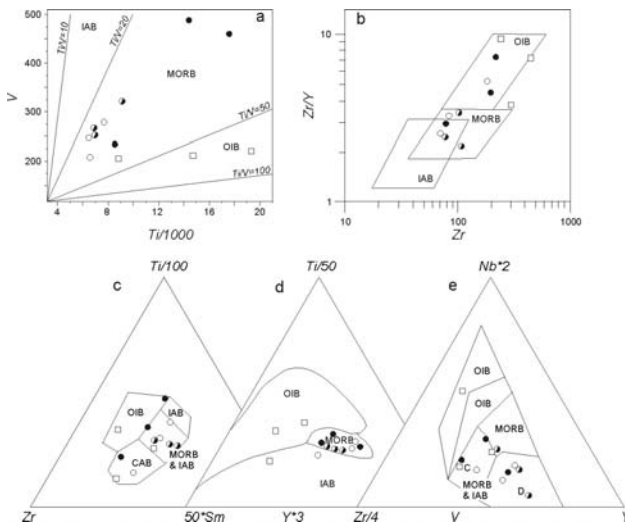


Figure 14. Selected geochemical discrimination diagrams for KC amphibolites. a) Ti-V (Shervais, 1982), b) Zr-Zr/Y (Pearce & Norry, 1979), c) Zr-Y-Ti (Pearce & Cann, 1973), d) Sm-V-Ti (Vermeesh, 2006), e) Zr-Y-Nb (Meschede, 1986). Symbols like in figure 8.

Although, each diagram mentioned suggests a MORB character for the most frequent group B amphibolites, there are some arguments that seem to reject the assumption of a one-time mid-ocean ridge setting. There is no petrological reason, which could suggest the existence of a previous ophiolite association. The majority of metamorphic rocks (mica-schist, paragneiss) in the AG unit imply a greywacke type composition of the original sediments, strange in a mid-ocean ridge setting. The elucidation of this contradiction is possible by assuming the opening of a back-arc basin characterized by T-MORB tholeiites. The mixing of some geochemical characteristics of MORB and

subduction-related basalts listed above is typical for back-arc basins (Saunders & Tarney, 1984). The initial opening of a marginal basin is confirmed by the positive Zr-anomaly (Weaver et al., 1979) too.

The normative compositions of all group B samples contain quartz as a significant constituent (2-6%). Quartz tholeiite may derive during melting under water saturated conditions, typical in marginal basins (Saunders & Tarney, 1979). Experiments of Yoder & Tilley (1962) showed that the presence of water during magma generation suppresses plagioclase crystallization. In the case of the group B amphibolites the slight positive Eu and Sr anomalies as well as the incompatible behaviour of these elements during the entire tholeiitic differentiation process points to the restricted role of plagioclase crystallization. Saunders & Tarney (1979) found the same for recent back-arc basin basalts. Both chondrite and N-MORB normalized REE spectra (Fig. 11) for group B amphibolites are similar to that of typical T-MORB (Saunders, 1984). Although REE spectra of marginal basin and island arc basalt overlap significantly (Cullers & Graf, 1984), the latter possibility has already been excluded earlier.

Each parameter studied shows that the amphibolite xenoliths of the orthogneiss are the most similar to N-MORB in composition, while for group C samples an enriched OIB-type plume source cannot be excluded either.

## 6. CONCLUSIONS

Metabasic rocks from a subarea (Körös Complex) of the Variscan basement of the Tisza block have been studied. The application of multivariate geo-mathematical methods proved to be remarkably suitable for discriminating and determining the distinct protolith series of the amphibolite assembly. Further geochemical characterization of each amphibolite group was possible by detailed examination of selected samples. Unlike the earlier assumptions about the geochemically very complex and contradictory igneous evolution, the present investigation implies a simpler model. Metabasic rocks are of diverse geochemical character in the three tectonic units that exhibit different metamorphic evolution.

Examining the spatial occurrence of the three main amphibolite types one can state that samples of the groups B and C tend to appear in the central regions of the crystalline highs, with group B amphibolites at the highest structural positions. Group A amphibolite samples, on the other hand occur separately; they are exclusively found in boreholes on the S and N flanks of the exhumed

basement domes (cf. Fig. 3b). Such a spatial distribution confirms the previous model about the structural relationship of the main tectonic units that form the basement in the study area.

Amphibolites in the lowermost OG unit represent xenoliths of the previous granitoid protolith of the orthogneiss. Geochemically, these rock samples are MORB basalts significantly depleted in LREE and other incompatible elements due to partial melting probably after being picked up by the granitoid melt. The rather wide spectrum of xenocrysts and xenoliths makes a migmatitic origin (Balázs et al., 1986) of this mixed rock type rather unlikely. Nevertheless, based on the peraluminous character of the granitoid host rock and the various metamorphic origin of the mafic and ultramafic xenoliths Tóth & Zachar (2006) and Zachar et al., (2007) suggested that the OG unit represents an intrusion formed in a subduction-accretion type orogeny belt (following the models of Kearey & Vine, 1996; Zurrbruggen et al., 1997).

The OG unit is covered by the SG unit along a post-metamorphic shear zone. Here, the main lithology is biotite-sillimanite gneiss, while a little amount of garnetiferous amphibolite samples represent metabasic rocks. The protolith is enriched plume-related OIB basalt representing the most differentiated samples in the whole study area.

The topmost structural unit (AG) is dominated by amphibolite and amphibole biotite gneiss suggesting a volcanoclastic protolith. It is different from the two other units both concerning petrographic appearance and metamorphic evolution. Amphibolite member of the succession defines a slightly enriched series of T-MORB tholeiitic basalts developed probably in a back-arc basin. These samples are significantly different from the metabasic xenoliths of the orthogneiss, while the most differentiated AG amphibolites overlap geochemically with the typical garnetiferous amphibolites of the SG unit.

Formation of the protolith of the KC amphibolites in a marginal basin is consistent with recent palaeogeographic reconstructions (Szederkényi, 1996; R. Varga et al., 2003; Krobicki & Zatoń, 2008) suggesting that the Variscan basement of the Tisza block represents portion of the European Variscan belt. These studies suggest that the protoliths of the amphibolites generally are MORB basalts characterized by variably enriched compositions (from T to E-MORB). They probably formed in back-arc (Pin, 1990) or in ensialic basins (Floyd et al., 1996) due to the fragmentation of the Gondwana by the development of intracontinental rifts. Floyd et al (2000) emphasize how important

role plumes and plume related OIB basalts may have played during this rifting event.

Relationship between origin, as well as metamorphic and structural evolutions between the basement of the Great Hungarian Plain and the Apuseni Mountains was suggested by numerous authors previously (Szepesházy, 1979; Balázs et al., 1986; Lelkes-Felvári et al., 2003; Balintoni et al., 2009). Most of these papers found that both taking petrological and age constraints the study area is most similar to Someş sequence of the Bihar Autochthonous Unit of the Apuseni Mountains. Essential geochemical, petrological and geochronological details, however, are still obscure and need cleaning.

In order to be able to state further relationships between the Tisza block and diverse subareas of the Apuseni Mountains, the geochemical characteristics together with metamorphic *P-T-t* evolution trends should be compared.

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