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REVIEW

MAIN FEATURES OF THE REGIONAL METAMORPHIC EVENTS IN HUNGARY: A REVIEW

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Abstract: The present paper reviews data concerning the crystalline basement of all tectonic units in Hungary. Their lithologic content, biostratigraphic data, metamorphic features and radiometric age data are presented and critically discussed. The effects of at least two regional metamorphic cycles have been definitely recognized, Alpine and Variscan, and some polymetamorphic situations suggest the possible existence of a third, older event. The following main events are distinguished: the Alpine, the Variscan and an early Variscan or pre-Variscan stage or event.

Alpine metamorphism turns out to be more widespread than previously reported. The Alpine metamorphic grade ranges from subgreenschist to greenschist facies conditions, locally reaching the lower amphibolite facies. Low to medium pressure conditions have been generally ascertained for it, with local exceptions of high and transitional medium to high pressure conditions.

The Variscan metamorphism has been detected in the majority of the pre-Permian rock sequences in Hungary. Its metamorphic grade covers the whole temperature field of metamorphism, up to anatectic conditions. The pressure conditions in the monometamorphi. Variscan low grade metapelites turn out to be low, related to a thermal gradient close to 40 °C/km.

A pre-Alpine polymetamorphic character is displayed by some Variscan amphibolite facies metapelites. The youngest mineral assemblages in them are characterized by the occurrence of andalusite in the rocks of suitable bulk composition, displaying a low-pressure character of the Variscan event, consistently with the above reported pressure estimate inferred from the greenschist facies monometamorphic metapelites. The oldest mineral assemblage is characterized by the occurrence of kyanite in rocks of suitable bulk composition, which may be either referred to an early Variscan stage or to a pre-Variscan event.

Key words: Hungary, Paleozoic Basement, pre-Alpine evolution, Variscan metamorphism, Alpine metamorphism, metamorphic features.

Introduction

The main features of the Alpine and pre-Alpine metamorphisms occurring in Hungary are outlined here to contribute to the interregional correlations within the ambit of IGCP Project No. 276. However, the basement rocks from the central-eastern part of the Tisza Superunit and the South Hungarian Nappe Zone (Great Plain) are not considered here; readers are referred for them to Szederkényi et al. (in prep).

The bases of the present paper are: i) the outlines of the pre-Alpine metamorphisms by Lelkes-Felvári & Sassi (1981), updated with a number of new stratigraphic, petrologic and radiometric data produced meanwhile; and ii) the outlines of the Alpine metamorphism by Árkai (1991). In fact, considerable progress has been done in recognizing new Alpine metamorphic areas in the basement covered by young sediments, and in better defining the distribution and T-P features of the Alpine metamorphism in other areas.

The main limits of this paper are related to the poor quality and quantity of the exposures of the basement rocks, and the relative scarcity of radiometric geochronologic data (about 380, including the previously published ones and those only presented in Internal Reports). The latter drawback is obviously related to the former one, which prevents the development of a systematic geochronological work on rock samples of suitable size and quality.

The metamorphic features will be described below in a number of Sections, each corresponding to an area characterized by some kind of uniformity from the geo-petrological point of view. The location of all these areas is shown in Fig. 1, with reference to the main structural units making up the territory of Hungary.

In the present paper, the term "basement" will be used both for old, amphibolite facies polymetamorphic rock sequences making

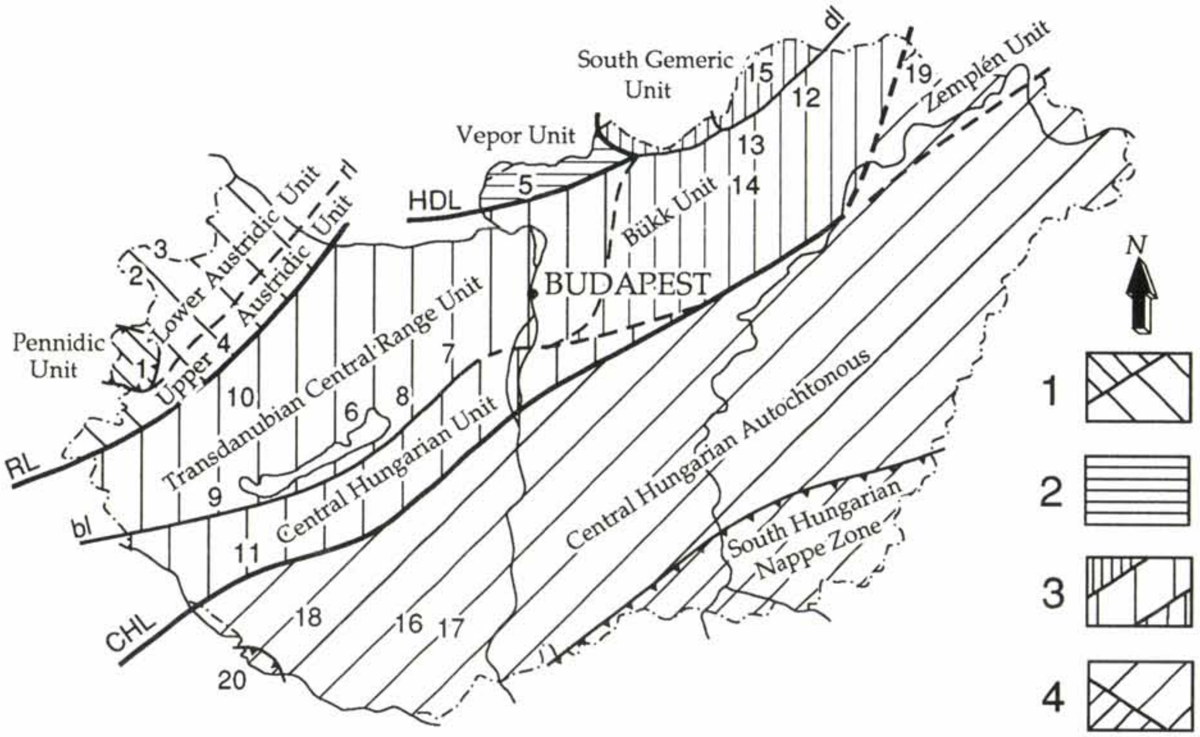

Fig. 1. Structural sketch of Hungary, based on Fülöp (1989). Numbers 1 to 20 in the sketch show the location of the twenty sites described in the text. **Legend:** 1 — East Alpine Superunit; 2 — West Carpathian Superunit; 3 — Pelso Superunit; 4 — Tisza Superunit. Abbreviations: **CHL** — Central Hungarian Lineament (also called Zagreb-Hernád Lineament); **HDL** — Hurbanovo-Diósjenő Lineament; **RL** — Rába Lineament; **bl** — Balaton Line; **dl** — Darnó Line; **rl** — Répce Line.

up the deepest structural element, and for metamorphic to anchimetamorphic Paleozoic sequences covered by a younger, commonly Paleo-Mesozoic, not metamorphic rock cover.

Structural frame

According to the structural model summarized by Fülöp (1989), the Hungarian territory consists of four superunits (Fig. 1), each bearing metamorphic rocks.

I. the **East Alpine Superunit**, to the NW of the Rába-Lineament;

II. the **West Carpathian Superunit**, north to the Hurbanovo-Diósjenő Line;

III. the **Pelso Superunit**, tectonically bounded by the Rába Lineament to the NW and the Central Hungarian (Zagreb-Hernád) Lineament to the SE;

IV. the **Tisza Superunit** to the south, which includes the South Hungarian Nappe Zone.

I. The **East Alpine Superunit** consists of: a) The Pennidic Unit, b) The Lower Austroalpine Unit, c) The Upper Austroalpine Unit.

a) The *Pennidic Unit* is represented by a Mesozoic sequence of calcschists and associated metapelites, metabasites and serpentinites, affected by a greenschist facies Alpine metamorphism which did not obliterate completely a low temperature, high pressure Early Alpine metamorphism. The Pennidic Unit occurs as a group of five small tectonic windows, globally called Rechnitz Window group, which mainly outcrops in the neighbouring Austria.

b) The *Lower Austroalpine Unit*, outcropping in the Fertőrákos and Sopron areas, comprises:

i) a polymetamorphic amphibolite facies basement in which Variscan metamorphism prevails and an Alpine, mainly greenschist facies overprint occurs;

ii) a greenschist facies, probably Paleozoic sequence, mainly consisting of metapelites and metavolcanoclastics.

c) The *Upper Austroalpine Unit* comprises the basement of the Little Hungarian Plain between the Répce Line and the Rába Lineament. Paleozoic sequences are encountered here by boreholes, with Variscan very-low to low-grade metamorphism overprinted by Alpine metamorphic effects.

II. The **West Carpathian Superunit**. Polymetamorphic rocks are found in boreholes south to the river Ipoly and north to the Hurbanovo-Diósjenő Line, which is the tectonic contact between the Veporic Unit of the Western Carpathians to the north and the Pelso Superunit to the south.

III. The **Pelso Superunit** consists of terraines with Southalpine and Dinaric affinities, arranged in four structural units: a) the Transdanubian Central Range Unit, b) the Central Hungarian Unit, c) the Bükk Unit, d) the South Gemeric Unit.

a) The *Transdanubian Central Range Unit (Bakony-Drauzug Unit)*. In the southern flank of this mountain range, basement rocks outcrop along the northern coasts of lakes Balaton and Velence, at the NE end of the lake Balaton and are also known from boreholes along the SW coast of this lake. On the northern flank of the mountain range, similar rock sequences are known only from boreholes in the Little Hungarian Plain, bounded to the north by the Rába Lineament. Their sedimentation age is Paleozoic. The Variscan metamorphic grade ranges from very low to low, but amphibolite facies rocks were also encountered locally. The name Bakony-Drauzug is also used in the literature for this unit, because of the paleogeographical affinity between its Mesozoic cover and that of Drauzug in the Eastern Alps.

b) The *Central Hungarian Unit* is located between the Balaton Lineament, which is the southern border of the Transdanubian Central Range Unit, and the Central Hungarian Lineament. This lineament is a complicated tectonic zone, along which the Bükk and the South Gemeric units moved horizontally to their present positions (Kovács 1982). This unit is made up of Permian to Triassic sequences affected by Alpine diagenetic and metamorphic alterations. The metamorphic grade mainly corresponds to subgreenschist and subordinate greenschist facies (chlorite zone) conditions.

c) The *Bükk Unit* comprises the Bükk, Uppony and Szendrő Mts., with thick, Paleozoic, subgreenschist to greenschist facies sequences and Mesozoic, diagenetic to anchizonal rock sequences.

d) The *South Gemeric Unit*, also called Aggtelek-Rudabánya Unit, is made up of Permian to Jurassic sequences with Eo-Alpine metamorphic alterations ranging from diagenesis up to the chlorite zone of the greenschist facies. Glaucophanitic greenschist facies rocks also occur.

IV. The **Tisza Superunit** (Tisia "microplate") is interpreted as a part of the northern (European) border of the Tethyan realm. It is bounded to the north by the Central Hungarian (Zagreb-Hernád) Lineament. It contains the following units: a) the *Central Hungarian Autochthonous* and b) the *South Hungarian Nappe Zone.*

Description of the considered areas

I. The East Alpine Superunit

Ia) Pennidic Unit

Kőszeg Mts. and Vas Hill (locality 1 in Fig. 1)

General features. In western Hungary, along the boundary with Austria, Pennidic rocks occur in two areas: the Kőszeg Mts. to the north *(a)* and the Vas Hill to the south *(b)*. Beside the outcropping rocks, Pennidic sequences are known from boreholes and from a talc mine in the area *(b)*. This basement is covered by Tertiary sediments.

Lithology. Area *(a)*: this basement is made up of calcschists and associated metapelites. Some lenses of the so-called "Cák Conglomerate" are interlayered: they are up to a few metres thick and consist of various types of recrystallized dolomites and dolomitic limestones. Metabasites are known only from boreholes in this area.

Area *(b)*: metabasites, serpentinites and talcschists prevail over the metapelites; metagabbroid rocks were only found as boulders.

Chronological data. The only biostratigraphic data available from this basement have been published by Mostler & Pahr (1981). They are Triassic forams found in carbonate pebbles from the above mentioned conglomerate. These fossil data indicate a post-Triassic sedimentation age for the protoliths of the calcschists.

As concerns radiometric geochronology, some K/Ar muscovite data from phyllitic rocks are available (Balogh, unpublished internal report, 1983). They fall in the range of 28-31 Ma.

Metamorphic petrological features. The mineral assemblages both in metapelites (quartz + albite + muscovite + chlorite + paragonite) and metabasites (albite + epidote + chlorite + actinolite + sphene) record thermal conditions of the lower part of the greenschist facies. Biotite occurs only locally. Moreover, ferroglaucophane has been reported in the metagabbro boulders (Lelkes-Felvári 1982), as relics at the core of pargasite nematoblasts. This relic mineral phase indicates an early Alpine metamorphic stage characterized by high pressure conditions. As regards the main metamorphic stage, an intermediate pressure character was estimated from metapelites. Therefore, the rocks from locality 1 record a two stage Alpine history, with evolution from high to medium pressure, and low temperature conditions.

Problems. The age of the early Alpine, high pressure metamorphic stage is completely unknown. Its determination in this area should be very useful, as well as the chronological correlation between the Alpine metamorphic evolution in the Kőszeg Mts. and that in the Tauern Window.

Ib) Lower Austridic Unit

Sopron Mountains (locality 2 in Fig. 1)

General features. In the northwestern part of Hungary, close to the boundary with Austria, basement rocks outcrop over 25 km^2 in continuity with those occurring in Austria, and make up the Sopron Mountains. They are surrounded by Miocene sediments.

Lithology. The protolith rock sequence mainly consists of pelitic to semipelitic rocks, in which coarse-grained granitoids were injected (Kisházi 1977). Several types of intercalations (amphibolites, quartzites etc.) occur in the pelitic to semipelitic sequence. Among them, the presence of Mg + Al-rich quartzites and Mg-rich semipelites is worth emphasizing. A particular type of white clinochlore (leuchtenbergite) appears in these rock levels, which were described as "leukophyllites" (Starkl 1883) and represent hydrothermally altered volcanic rocks (Lelkes-Felvári et al. 1983). REE-bearing minerals have been found in some Mg-rich semipelites (Fazekas et al. 1975).

As regards the stratigraphic sequence within the abovementioned rocks, nothing can be said. However, an important difference exists between some metapelites in which a complex polymetamorphic development is detectable, and some phyllites in which only the effects of a low-grade metamorphism are recorded. The difference between the two rock groups is not only in metamorphic grade but in complexity (and length?) of metamorphic evolution. The polymetamorphic sequence could represent an old basement and the phyllites its cover.

Chronological data. The pre-Alpine age of the granitoids is unquestionable: they have been found as pebbles in the lower Permian conglomerates of the neighbouring Wechsel area (Austria).

As regards the age of metamorphism, only a few Rb-Sr radiometric data are available (Kovách & Svingor 1981; unpubl. int. report 1988). They are: (i) partially rejuvenated Variscan age values of muscovite, in the range 281-90 Ma; and (ii) largely rejuvenated Variscan age values of biotite, in the range 55-41 Ma. K/Ar ages are also available (Balogh & Dunkl 1994): they fall in the range 160-84 Ma for muscovites, and in the range 101-78 Ma for biotites. A polymetamorphic micaschist supplied Variscan K/Ar cooling ages of two concentrates of biotites (272 and 281 Ma, same source).

From these radiometric data, the conclusion can be drawn that certainly an Alpine overprint affected these rocks under temperature values higher than 300 °C (as suggested by the extensive rejuvenation of biotite), and close to 500 °C (as suggested by the fact that the Variscan cooling age of muscovite is partially rejuvenated).

Metamorphic petrological features. As mentioned above, some rock sequences display a complex polymetamorphic history, which has been unravelled by Lelkes-Felvári et al. (1984). Others show a simple, low-grade feature (chlorite zone). Some thin leucosomes have been reported locally. Moreover, a retrograde metamorphic overprint is recorded in all sequences.

Disregarding this late overprint, the polymetamorphic metapelites bear mineral assemblages of amphibolite facies, in which contrasting elements occur: specifically, from the baric viewpoint kyanite contrasts with the overprinted andalusite, showing a two-stage amphibolite facies evolution, from medium to high thermal gradients. Kyanite + staurolite + sillimanite have been referred to the older stage, andalusite + sillimanite to the younger amphibolite facies stage. The retrograde overprint in these amphibolite facies rocks is characterized by the crystallization of new kyanite after andalusite and the following mineral alterations: staurolite → chloritoid, staurolite → sericite, plagioclase → clinozoisite, garnet → chlorite, biotite → chlorite. The crystallization of polycrystalline chloritoid aggregates pseudomorphosing euhedral staurolite porphyroblasts is very impressive, as well as kyanite pseudomorphs after andalusite porphyroblasts.

The set of chronological and petrological data indicate, as a whole, a three stage development of the metamorphic history of the Sopron area (Lelkes-Felvári et al. 1984):

— a Barrovian-type Alpine overprint related to temperatures higher than 300 °C but lower than 500 °C;

— a Variscan metamorphism, responsible for the crystallization of andalusite porphyroblasts in the basement and the main metamorphism in the phyllitic sequence; it was related to a thermal gradient higher than (or perhaps close) to 40 °C/km; migmatites were probably generated during this thermal climax;

— a pre-Variscan (or early Variscan) metamorphism related to a thermal gradient lower than 40 °C/km.

Problems. The situations occurring in the Sopron area are rather complex, and numerous aspects need to be clarified. Among them, the following are the most important as regards attempts at interregional correlations: the age of the oldest metamorphism in the amphibolite facies basement, the meaning of the phyllitic sequence, the age of the granitoid magmatism.

Fertőrákos (locality 3 in Fig. 1)

General features. Along the boundary between Hungary and Austria, near to Neusiedler See (Lake Fertő), basement rocks occur over an area of approx. 1 km^2. These rocks are unconformably covered by Miocene sediments. Numerous drillings (the deepest of which reaches 1100 m), allowed this sequence to be explored for a total thickness of 2000 m, giving a more complete picture of these rocks than that drawn from the poor outcrops. Therefore the following data refer mainly to the drilling core samples (Kósa & Fazekas 1981).

Lithology. Of the 2000 m drilled, the deepest thousand are made up of amphibolites and gneisses, the overlying 500 consists mainly of gneisses, while different rock types occur in the uppermost 500 making up the upper sequence. Pegmatoids are common in the amphibolitic and gneissic sequences. Different rock types are interlayered in different levels. Among these:

— phyllonitic micaschists occur in the higher sequence;

— biotite schists occur within the amphibolitic sequence;

— actinolitic schists form thin levels (1 to 10 cm thick), mostly occurring in the amphibolitic sequence;

— marble layers occur both in the gneissic and in the upper sequence;

— some apatite-rich levels (P_2O_5 > 20 %), often having high REE contents, have been found in the gneissic sequence;

— a sheet-like gneissic body of granitoid composition occurs within the upper sequence, forming two horizons separated by some metres of marble;

— leuchtenbergite-bearing metapelites have been found in the gneissic and in the upper sequence, systematically occurring at the boundary of the above mentioned, two sheet-like gneissic horizons. A MgO content as high as 15 % has been recorded in them (Lelkes-Felvári et al. 1983).

Chronological data. The main metamorphism of these rocks is believed to be Variscan, but textural evidence suggests that an Alpine metamorphic overprint occurs too. Radiometric data confirm such an interpretation: muscovite age values indicate undisturbed Variscan ages (Rb/Sr close to 350 Ma: Kovách & Svingor 1981), while the biotite ages are significantly lower, displaying a partial rejuvenation (Rb/Sr in the range 121-90 Ma, same source). Consequently the temperature of the Alpine overprint was lower than 500 °C and higher than 300 °C.

Metamorphic petrological features. Mineral assemblages correspond to the greenschist facies throughout the whole rock sequence. However, textural evidence indicates that two metamorphic assemblages overlap in these rocks.

The older metamorphic event produced amphibolite facies mineral assemblages: plagioclase + hornblende + biotite + almandine within the amphibolites, plagioclase + biotite + muscovite + almandine within the metapelites.

The younger metamorphic event produced greenschist facies mineral assemblages, and specifically the following mineral alterations: hornblende → actinolite, garnet → chlorite, biotite → chlorite, plagioclase → albite + clinozoisite.

The thermal gradients for both metamorphic events are unknown: however, extremely high thermal gradients are excluded by the common occurrence of almandine.

Problems. The genesis of the gneisses of granitoid composition should be studied, in order to ascertain the nature (sedimentary, volcanic or plutonic) of their protolith.

The pressure character of metamorphism in the Fertőrákos phyllites is still unknown. Moreover, it should be checked whether and in what extent the correlation reported in the literature between the Wechsel and Fertőrákos basement is valid.

Ic) Upper Austridic Unit

Basement of the Little Hungarian Plain to the NW of the Rába Lineament (locality 4 in Fig. 1)

General features. In the NW part of the Little Hungarian Plain, between the Rába Lineament (to the SE) and Répce Line (to the NW), basement rocks were encountered by numerous boreholes under a thick cover of Neogene sediments. This unit is generally correlated with the Paleozoic of Graz (Balázs 1971).

Lithology. This basement is made up of metapelites and carbonate schists, with subordinate metapsammites and pure marbles. Intermediate and basic metavolcanoclastics are also described from a few boreholes (Balázs 1971; Árkai et al. 1987).

Chronological data. Data concerning the sedimentation age are completely lacking in this area. As concerns the age of metamorphism, K/Ar radiometric data on < 2 μm grain-size fraction of white mica concentrates are available from slates, carbonate phyllites, phyllites and intermediate metavolcanoclastics (Árkai & Balogh 1989). They fall in the range 106–203 Ma. Similar age values have been reported from the upper tectonic unit of the Paleozoic of Graz (Flügel et al. 1980; Fritz 1988). These age values have been interpreted by Árkai & Balogh (1989) as Variscan ages partially rejuvenated by Alpine metamorphic effects.

Metamorphic petrological features. The metamorphic grade of the major part of this basement is to be assigned to the Variscan greenschist facies, mainly to the low pressure chlorite and locally biotite zone (Árkai et al. 1987).

Problems. A priority should be given in this area to paleontological research, because the sedimentation age of the whole rock sequence is completely unknown. The Calpionella remnants found by Juhász & Kőháti (1966) certainly do not clarify the chronological picture of this area, because conflict with the above reported radiometric metamorphic ages. If this finding will be confirmed, it could refer to a Mesozoic cover lying over the above described Variscan metamorphics. However it must be taken into consideration the possible occurrence of a Pennidic Unit in this area, as hypothetized by Balla (1994).

II. The West Carpathian Superunit

Ipoly Complex (locality 5 in Fig. 1)

General features. North to the Hurbanovo-Diósjenő Line, south to the river Ipoly, numerous boreholes crosscut metamorphic rocks covered by Cenozoic sediments (Ravaszné-Baranyai & Viczián 1976).

Lithology. Metapelites (partly graphitic), metapsammites and quartzites are interlayered with basic metavolcanics. Dioritic gneisses were also reported.

Chronological data. Sedimentation age is completely unknown for these sequences. More to the north, in Slovak territory, similar rocks outcrop and were also found in boreholes and correlated to the lowest tectonic unit of Veporides (Bezák et al. 1993), in which Paleozoic sedimentation ages were reported (Klinec et al. 1975).

For the age of metamorphism, K/Ar ages of mineral separates are available (Balogh 1984). Biotites coming from a paragneiss gave an age of 96 ± 7 Ma, and muscovites from a micaschist supplied 108 ± 5 Ma and 116 ± 6 Ma. These age data may either be interpreted as Variscan ages largely rejuvenated by later thermal events, probably the widespread Cenozoic magmatic activity (see also Hraško et al. 1995), or may represent cooling ages of the Alpine (Cretaceous) metamorphism, which is widespread in the Inner Western Carpathians.

Metamorphic petrological features. Mineral assemblages indicate thermal conditions of the upper part of the greenschist facies. They are: quartz + albite + muscovite + biotite + chlorite + paragonite + garnet + epidote + graphite in metapelites, quartz + albite + microcline + muscovite + biotite + chlorite + garnet in metapsammites, and quartz + albite + epidote + actinolite + hornblende + garnet + muscovite + chlorite in metabasites.

Problems. Also recalling the possible existence of a high grade pre-Variscan basement in Slovak territory (Bezák et al. 1993, p. 355–356), the paragenetic interpretation of the above mentioned mineral associations needs a revision, as they could represent the result of a younger, greenschist facies assemblage overprinted on older, relic amphibolite facies minerals. Therefore, the age and pressure conditions of metamorphism(s) should be estimated. However, a detailed lithostratigraphic and petrographic correlation with the Veporic crystalline sequences is the most important goal in this area.

III. The Pelso Superunit

IIIa) Transdanubian Central Range

a) Southern flank

Balaton Highland (locality 6 in Fig. 1)

General features. Two main exposures of these rocks crop out along the northern coast of lake Balaton, over an area of about 8 km^2. Similar rocks have also been found in numerous drillings in the surrounding areas, and outcrop more to the northeast of lake Velence, where they are the country rock of a Variscan, post-tectonic granitic body (loc. 7).

Lithology. The basement rocks consist mainly of metapelitic to metapsammitic sequences, in which acidic metavolcanics and metavolcanoclastics are frequently interlayered, with minor marble and metalydite intercalations. Intermediate metavolcanics also occur in one borehole, drilled in the most westerly outcrop. The occurrence of basic materials, reported as "metadiabases", is also known. The acidic metavolcanics and metavolcanoclastics are similar to the so-called "porphyroids" in the Eastern Alps. A Mediterranean affinity has been recognized for the whole rock sequence (Tongiorgi pers. comm. 1990).

Integrating the data from the many studied boreholes with those from the outcrops, the following interpretative lithostratigraphic sequence has been reconstructed (Lelkes et al. 1994):

i) *a lower pelitic to semipelitic metamorphic complex*, with sandstone and thin carbonate intercalations; it is Early Ordovician in age, as shown by Lower Arenigian acritarch levels (Albani et al. 1985);

ii) *a volcano-sedimentary metamorphic complex* including acidic, intermediate and basic suites; it is considered to be Late Ordovician and Silurian in age, on the basis of some Early Silurian fossils (Oravecz 1964; Góczán 1971; Kozur 1984) and lithostratigraphic correlation with the Eastern Alps;

iii) *a metamorphic carbonate complex*, which consists of pelagic carbonates with marly, lyditic and pelitic metamorphic intercalations bearing fossils belonging to various levels of Devonian (Lelkes-Felvári et al. 1986; Horváth & Kovács in prep.; Horváth & Kozur in prep.);

iv) *a bituminous carbonate* sequence rich in lower Carboniferous (Visean) fossils, with pelitic, psammitic and lydite metamorphic intercalations (Földvári 1952).

Chronological data. These basement rocks are unconformably covered by unmetamorphosed upper Permian conglomerates, in which they occur as pebbles. Furthermore, fragments of these basement rocks occur as pebbles also in the unmetamorphosed upper Carboniferous conglomerate at Füle. Therefore, a pre-upper Carboniferous age of their metamorphism must be admitted.

Paleontological findings indicate sedimentation ages from Early Ordovician (Arenigian) to Early Carboniferous (Visean), through Silurian and Devonian.

Metamorphism is Variscan, as shown by the radiometric data below:

—a Rb/Sr whole rock-white mica isochron from acidic metavolcanics gives an age value of 316 ± 22 Ma, which is to be referred to the time of metamorphism (Kovách & Svingor 1990);

—a consistent K/Ar age value of metamorphism has been obtained from sericite concentrates from three slates and from five acidic metavolcanic samples (Balogh et al. 1987, 1990).

Metamorphic petrological features. The degree of recrystallization of all these rocks is rather low, as the abundance of pre-metamorphic structural features and the occurrence of microfossils demonstrate. Illite crystallinity data indicate a rather low metamorphic grade, covering the uppermost part of the anchizone. Low pressure and a metamorphic thermal gradient of about 40 °C/km have been estimated. Two deformational stages have been recognized by means of microstructural analyses (Dudko 1986): however, the metamorphic crystallization is mainly related to the older, foliation-producing deformational stage.

Hydrothermal alteration is very common both in the outcropping rocks and in those encountered in the boreholes.

Problems. The general picture arising from the basement rocks of the Balaton Highland is relatively clear, although some important problems are still to be solved. Among them, the age and geochemical affinity of the metavolcanics are worthy to be investigated, because these features may be used as tools for interregional correlations and geodynamic interpretations.

Another problem is the relation between the above described basement rocks, the "metadiabases" occurring as scarce pebbles in the Upper Permian conglomerate and the "metadiabases" encountered in some boreholes. It is not yet known to what igneous event the protoliths of these rocks are related, and whether the two types of "metadiabase" occurrences refer to a single magmatic cycle.

Velence Hill (locality 7 in Fig. 1)

The situation in this locality is the same as that described above. The only peculiarity is the widespread contact metamorphism produced by late Variscan granitoids on these foliated rocks (Jantsky 1957). The K/Ar radiometric age values of biotites from these granitoids (Balogh et al. 1983) mostly fall in the range 250-290 Ma, with some lower values up to 137 Ma. They reveal a widespread rejuvenation due to heating probably related to the later igneous activities.

Balatonfokajár Hill (locality 8 in Fig. 1)

General features. This is a very small outcrop at the NE end of lake Balaton. Similar rocks have been found in the surrounding boreholes and to the south of the lake (Lelkes-Felvári 1978).

Lithology. These basement rocks consist mainly of quartz phyllites associated with carbonate-bearing quartz phyllites, quartzitic schists, acidic metavolcanics, graphitic schists and a few chlorite schists. The occurrence of acidic metavolcanoclastics is worthy of mention; they are similar to those commonly found in the Balaton Highland within the very low-grade complex described under locality 6.

Chronological data. The Eocene rocks which lie over this basement are not metamorphic: therefore metamorphism in the basement is pre-Eocene. The age of protoliths is unknown. However, the occurrence of acidic metavolcanoclastics suggest that this basement sequence is, at least in part, the same (Ordovician-Silurian in age) which occurs along the northern side of lake Balaton, displaying very low grade.

Metamorphism is Variscan. In fact, the few K/Ar radiometric data available for these phyllites, obtained from muscovite concentrates, fall in the range 320-343 Ma (Balogh, pers. comm., 1993).

Metamorphic petrological features. Metamorphic grade corresponds to the lowest part of the greenschist facies. Biotite only locally occurs, within the pressure shadows around the premetamorphic large crystals. The main schistosity (S2) in these rocks is a crenulation cleavage after an earlier foliation. A postkinematic stage is only weakly recorded, represented by new crystallization of muscovite, quartz and albite.

Structural analyses by Dudko (1986) demonstrated that these low-grade rocks underwent metamorphism in the same stress field which affected the very low-grade sequence described under locality 6.

Low pressure and a metamorphic thermal gradient around 40 °C/km have been estimated (Lelkes-Felvári et al. 1982; 1994).

Problems. Further radiometric research concerning the age of metamorphism (e.g. Rb/Sr analyses on white micas) and the age of the pre-metamorphic magmatic event (e.g. U/Pb datations on zircon separates coming from the acidic metavolcanics) are of crucial importance.

Balatonhidvég-Garabonc (locality 9 in Fig. 1)

General features. Metamorphic rocks have been found by boreholes in this area, which is located to the SW of the lake Balaton, very close along the Balaton Lineament. They cover a wide metamorphic range and consist of different rock sequences, whose interrelationships are unknown and very probably are in large extent tectonic.

Lithology. Metapelites, metapsammites and metamorphic carbonate rocks make up this basement (Árkai 1987).

Chronological data. Because biostratigraphic data are lacking, the sedimentation age of this rock sequence is unknown. However, some geological situations provide a set of chronological constraints: (i) these rocks are locally covered by an unmetamorphic Mesozoic sequence; (ii) in some places they were intruded by Variscan granitoids when they were already schistose; (iii) their metamorphic history is identical to that recognized in many pre-Alpine polymetamorphic areas.

Metamorphic petrological features. These rock sequences cover a wide range of metamorphic conditions, from very low grade to amphibolite facies. Polymetamorphic rocks also occur.

The very low-grade metapelites and metapsammites are composed of quartz + albite + muscovite + chlorite + carbonate, and are to be referred to low pressure conditions. In some boreholes, these very low-grade rocks show a contact metamorphic overprint, with crystallization of biotite in some places, andalusite + corundum + biotite + plagioclase in others. Marbles contain small amounts of quartz, plagioclase, muscovite, chlorite, andalusite.

The low-grade metapelites consist of quartz + albite + muscovite + biotite + garnet, while quartz + plagioclase + muscovite + biotite + garnet + staurolite make up the medium grade metapsammites (Árkai 1987).

The polymetamorphic metapelites bear two, overprinted amphibolite facies mineral assemblages: an older one consists of quartz + oligoclase + muscovite + biotite + garnet + kyanite + staurolite, and is overprinted by a younger, muscovite + biotite + plagioclase + andalusite assemblage. The older event is characterized by T = 500-550 °C, P = 800-900 MPa, the younger event by T = 560-585 °C, P = 200-300 MPa. A later contact metamorphism was also reported for these rocks (Török 1992).

Problems. New paleontological and isotope geochronological data are needed to clear the sedimentation ages and metamorphic histories of the different parts of this complicated, fragmented tectonic zone.

b) Northern flank

Basement of the Little Hungarian Plain, to the SE of Rába Lineament (locality 10 in Fig. 1)

General features. On the northern flank of the Transdanubian Central Range, between the Rába Lineament and the Bakony Mts., numerous boreholes crosscut basement rocks buried under a thick sedimentary cover of mainly Neogene age. In a few boreholes the basement rocks are disconformably overlain by Permian and Mesozoic sediments.

Lithology. According to Balázs (1971) and Árkai et al. (1987), this basement is made up of metapelites and metapsammites, with marbles, acidic and minor basic metavolcanoclastic intercalations.

Chronological data. Considering that the Permian sediments are not metamorphic, a Paleozoic sedimentation age and a Variscan age of metamorphism may be assumed, at least where Permian occurs. Lithostratigraphic similarities with the southern flank of the Bakony Mts. support this assumption. As concerns the age of metamorphism, K/Ar white mica (< 2 μm fraction) data obtained from slates are available (Árkai & Balogh 1989; Balogh et al. 1990) and fall in the range 310-350 Ma (i.e. Variscan).

Metamorphic petrological features. The mineralogical composition of metapelites is quartz + albite + muscovite + chlorite. The metamorphic grade is very low, as deduced from illite crystallinity measurements in all investigated boreholes. Pressure estimates indicata low values (Árkai et al. 1987; Árkai & Lelkes-Felvári 1993).

Problems. The main goal suggested for future research in this area is to establish a reliable chronological frame for the sedimentation age.

IIIb) Central Hungarian Unit (locality 11 in Fig. 1)

General features. From this tectonic unit, which is located between the Balaton Lineament and the Central Hungarian Lineament, metamorphic rocks are known only from boreholes.

Lithology. The lithological composition is rather various: in fact, beside metapelites and metapsammites, metamorphic limestones, marls and metavolcanoclastics also occur, metaradiolarites and serpentinites being present locally. Among the metavolcanoclastics, acidic to basic compositions have been reported (Árkai et al. 1991).

Chronological data. The sedimentation ages are well established in some drilling core samples of this unit, by means of Early to Late Permian, Triassic and Jurassic microfossils (Bérczi-Makk 1981; Haas et al. 1988). The sedimentary cover is Miocene or younger in age. Therefore, the metamorphism is Alpine. In fact, K/Ar determinations on < 2 μm white mica separates supplied age values of 96.7 ± 12.3 Ma from a slate, and in the range 93-97 Ma from acidic metavolcanoclastics (Árkai et al. 1991). These data can be interpreted as the age of metamorphism, considering the low grade of these rocks.

Metamorphic petrological features. These rocks belong mainly to the anchizone, partly to the epizone and locally to the diagenetic zone. They are also affected by various types of overprint: contact metamorphism, cataclastic and hydrothermal retrograde alterations. White mica $d_{33\bar{1},060}$ values point to intermediate to high thermal metamorphic gradients (Árkai et al. 1991).

Problems. Among the problems which need to be clarified, is that of understanding in what extent the above mentioned low pressure character detected in the area, is really related to the Alpine regional metamorphism, or is a result of later changes related to the widespread hydrothermal alterations.

IIIc) Bükkium (localities 12, 13, 14 in Fig. 1)

General features. The Bükkium and the Aggtelek-Rudabánya (South Gemer) Unit make up the so-called Borsod Unit, which is separated from the Gemeric Unit of the Inner West Carpathians by the Rožňava Line. The Bükkium, i. e. the southern part of the Borsod Unit, is bordered by the Hernád Line in the east, by the Central Hungarian Lineament in the south, and by the Darnó Line in the northwest i.e. towards the Aggtelek-Rudabánya Unit. The Paleozoic and Mesozoic formations of the Bükkium and Aggtelek-Rudabánya Unit show clear lithological, paleontological and paleogeographic affinities with the northwestern part of the Inner Dinarides. The Bükkium consists of three main units: the **Szendrő**, **Uppony** and **Bükk Mountains** (localities 12, 13, 14 in Fig. 1). The former two consist of Paleozoic rocks, the latter of Paleo-Mesozoic formations with variegated lithologies.

Lithology; chronology of sedimentation.

These paragraphs are based on the results obtained by Kovács & Péró (1983) and Kovács (1989) as summarized by Fülöp (1994).

i) **Szendrő Mts.** The sedimentary sequence ranges from the Lower Devonian (Emsian) up to the Middle Carboniferous (Bashkirian), and consists of metapelites and metapsammites, in which different types of carbonate metamorphic intercalations occur according to a well known stratigraphic succession. Effects of increasing mobility and deepening of the sedimentary basin are recorded in its upper part. The Breton and Sudetian phases of the Variscan orogenic cycle influenced only the character of Paleozoic sedimentation, but did not cause folding and regional metamorphism in it (Árkai 1983).

ii) **Uppony Mts.** The rock sequence ranges from the Upper Ordovician to the Middle Carboniferous. It consists of metapsammites, metapelites and carbonate metasediments of various types, subordinate metacherts, metatuffs and basic metavolcanics. The stratigraphy is well documented, and displays deepening of the sedimentary basin.

iii) **Bükk Mts.** According to Csontos (1988), the Bükk Mts.

are built up of the Fennsík Parautochthon, the Szarvaskő-Mónosbél Nappe and the Kisfennsík (Little Plateau) Nappe.

The Fennsík Parautochthon consists of a rock sequence ranging from Middle Carboniferous to Upper Jurassic, the stratigraphy of which is well documented. The sequence includes metapelites, metapsammites, metacarbonates of various composition and structure, evaporites, and two Triassic volcanic horizons: a Ladinian metandesite complex and a Carnian bimodal suite. Near to the Triassic/Jurassic boundary the deepening of the basin is indicated by cherty limestones, radiolarites, dark slates and turbiditic metasandstones.

The Szarvaskő-Mónosbél Nappe consists of a Lower-Middle Jurassic, ophiolite-like, MORB-type magmatic complex, covered by slates and sandstones. An Upper Jurassic olistostromal sequence (limestone olistoliths with pelitic-silty matrix) makes up the upper part of the nappe.

The Kisfennsík Nappe contains upper Triassic limestones and intermediate metavolcanics.

Metamorphic petrological features.

The characterization of metamorphism in the Bükkium is based on the results by Árkai (1977, 1979, 1983) and Árkai et al. (1981).

i) **Szendrő Mts.** Based on the illite crystallinity distribution and average values, the regional metamorphism of the Szendrő Paleozoic sequence corresponds to the low temperature part of the greenschist facies (chlorite zone). The main metamorphic minerals are quartz, albite, sericite, chlorite, calcite. Epidote and biotite were found in the metatuffitic, cipollino-like marble, indicating that the biotite isograd was reached locally. The ordering of the fine-dispersed organic matter refers also to the greenschist facies. The average $d_{33\bar{1},060}$ value of the fine-grained metasedimentary detritic rocks indicate a transitional pressure between low and intermediate values. No significant difference exists between the southern and northern tectonic units of the mountains.

ii) **Uppony Mts.** Illite crystallinity distributions indicate transitional anchi- to epizonal regional metamorphism, with average values corresponding to the boundary between the anchi- and epizone. Metamorphic minerals are similar to those occurring in the Szendrő Paleozoic sequence, except epidote and biotite. Intergranular chloritoid of metamorphic origin has also been identified in the Rágyincsvölgy metasandstone. The spine-like overgrowth structures around detrital quartz grains and the values of illite crystallinity indicate that chloritoid crystallized in anchizonal conditions.

In the metabasalt and metatuff intercalations, glauconite-celadonite formed due to postmagmatic or weathering processes, and stilpnomelane crystallized during regional metamorphism. The coexistence of glauconite-celadonite and stilpnomelane suggests, if equilibrium is assumed, minimal P-T conditions of 160 MPa - 260 °C. Coexisting graphite-d2, anthracite and metabituminite with mosaic reflexion were detected in the clayey meta-cherts. The sericite $d_{33\bar{1},060}$ average values in metapelitic rocks suggest low pressure conditions. Compared to the Szendrő Paleozoic sequence, both temperature and pressure might have been lower in the Uppony Mts.

iii) **Bükk Mts.** The Late Paleozoic and Mesozoic formations of the Bükk Mts. were affected by a predominantly anchizonal regional metamorphism. The strong scattering of the illite crystallinity data both in the whole rock and clay fraction samples has been related to a metamorphic zoneography. In general, metamorphic grade decreases from north to south, from older to younger formations, from the epizone to the lower part of the anchizone and to the zone of medium-late diagenesis. However, depending on the tectonic position, considerable differences in grade can be observed.

The metamorphic minerals occurring in the Paleozoic and Mesozoic metasediments (quartz, albite, sericite, chlorite, carbonate, pyrite, hematite) and in the Middle Triassic metavolcanics (quartz, albite, sericite, chlorite, epidote, hematite, calcite, dolomite) are not suitable for the rigorous determination of metamorphic conditions. The microstructural features are mostly characteristic of the anchizone.

The minerals occurring in the upper Triassic metabasalt (quartz, albite, sericite, chlorite, pumpellyite, epidote, actinolite, hematite, talc, calcite) correspond to the pumpellyite-actinolite-chlorite zone, showing transition towards the greenschist facies. Fluid pressure did not exceed the approximate value of 300 MPa, as inferred from the lack of lawsonite, and temperature was around 350 °C.

If the metamorphic grade of the surrounding metasediments is considered, the crystallization of pumpellyite, prehnite, actinolite, pyrophyllite and talc in the Jurassic metabasites of the Western Bükk, can be referred to a regional metamorphism.

The white mica $d_{33\bar{1},060}$ distribution in the rocks of the Bükk Paleozoic is composite: i) the Bükkszentlélek zone of the Fennsík Parautochthon displays medium pressure conditions; ii) the Bükk Mesozoic displays low pressure conditions; iii) all other rock sequences excluding the Bükk Mesozoic are to be referred to the boundary between the low and intermediate pressure range.

Chronology of metamorphism and cooling.

Earlier tectonic, stratigraphic and metamorphic petrological evidence summarized by Árkai (1983) refers to only one, Alpine, Cretaceous, pre-Senonian, regional metamorphic event, which affected both the Paleozoic and Mesozoic formations of the Bükkium. A recent systematic K/Ar investigation on < 2 µm illite-muscovite separates gives a more detailed insight into the timing of regional metamorphism and cooling (Árkai et al. 1995).

The K/Ar system of the illite-muscovite approached equilibrium only in epizonal and high T anchizonal conditions. The orogenic metamorphism culminated between the Eo-Hellenic phase (ca. 160–120 Ma) connected with the beginning of the subduction in the Dinarides, and the Austrian phase (ca. 100–95 Ma) characterized by the compressional crustal thickening. No isotope evidence was found proving any Variscan thermal event.

Problems.

Considering the MORB-like composition of the basic-ultrabasic sequences of the Western Bükk Mts., the hypothesis of overprinted regional metamorphic effects over ocean floor metamorphic effects seems to be reasonable. In the case of the Darnó Hill pumpellyite, prehnite, albite, quartz, chlorite, celadonite and calcite occurring in the metabasalts have been related to the ocean-floor metamorphism, while the sedimentary sequences do not display any metamorphic alteration. On the other hand, the illite crystallinity, vitrinite reflectance and microstructural data from the metasediments of the Szarvaskő area indicate late-diagenetic to low-T anchizonal conditions, which are consistent with the prehnite-pumpellyite-quartz facies of the metabasic rocks (Árkai 1983). However, a detailed study of the metamorphic mineral assemblages of the dismembered ophiolite-like suite (ranging from pillow lava through a sheeted diabase complex down to a differentiated gabbro-ultrabasite) is needed, in order to prove or preclude the existence of an ocean-floor metamorphism with steep geothermal gradient preceding the regional metamorphism.

A further problem to be studied is the correlation of the rock sequences occurring in the Szendrő Mts. with those in the adjacent Slovak territory, which are capped by a Permian conglomerate including metamorphic pebbles (Vozárová 1995, pers. comm.).

IIId) Aggtelek-Rudabánya (South Gemeric Unit)
(locality 15 in Fig. 1)

General features. This unit is separated by the Rožňava Line from the mostly lower Paleozoic Gemeric Unit in the north, and by the Tertiary Darnó Line (transform fault) from the Bükkium in the south. It is built up by various nappes with southern vergency. Their Dinaric-South Alpine affinities are similar to those of the Bükkium. According to Grill et al. (1984) and Réti (1985), from which most of the structural information given in this section are taken, the Aggtelek-Rudabánya Unit is built up by the following nappes (from the shallower to the deeper): Silicic, Bódva Nappe, Komjáti Nappe, Meliatic and Tornaic.

Lithology; chronology of sedimentation. The oldest known rocks are represented by Upper Permian evaporitic formations (gypsum, anhydrite-bearing shales, sandstones, carbonates). The Lower Triassic consists of sandstones, marls and limestones. At the beginning of the Middle Triassic a uniform carbonate platform was built up, which differentiated during the Middle and Upper Triassic to different paleotectonic units (nappes) in various ways. Besides the various carbonate and silicic Triassic sediments occurring in different nappes, the Meliatic Unit (Meliata Ocean) is worthy of a special mention. It is characterized by basic magmatic rocks and deep-water sediments (radiolarites, cherts, marly slates). Jurassic rocks are known only locally, and include shales, radiolarian shales, marls and rhyolites. For a more detailed description see Kovács (1989).

Metamorphic petrological features. As it was stated by Árkai & Kovács (1986), the grade of regional metamorphism in the Mesozoic sequences within the different tectonic units of the Aggtelek-Rudabánya Mts. changes from the diagenetic zone through the anchizone up to the epizone (greenschist facies: chlorite zone). The uppermost tectonic units predominantly display diagenetic effects. Anchizonal metamorphism could be detected only in peculiar tectonic zones. The low temperature part of the anchizone is recorded in the type locality of Meliatic Unit (Meliata). The lowermost tectonic unit, the Tornaic, was metamorphosed under partly anchizonal, partly epizonal conditions.

In general, the anchi- and epizonal metamorphism of the Mesozoicum in the Aggtelek-Rudabánya Mts. proved to be of medium pressure type. With increasing metamorphic grade, i.e. with decreasing IC values, the pressure (as monitored by $d_{33\bar{1},060}$ values) also increases. This fact is the most reasonable explanation of the relatively high scattering of these values. The distribution of these values suggests transitional low to medium pressure in the Szendrő and Bükk Paleozoic, and low pressure in the Uppony Paleozoic and Bükk Mesozoic. The Tornaicum, which is the deepest tectonic unit, indicates medium/high pressures, very similar to the pressure range found in the glaucophane schists of the Rožňava Zone, Slovak Karst (Rozložník 1978). In the latter case, P_{H_2O} = 700 MPa and T = 400 °C may be assumed based on amphibole geobarometry and mineral paragenetic data. Using these approximate values, assuming an average crustal density of 2.8 g/cm^3 and a linear depth-temperature relation, a relatively low (16 °C/km) metamorphic thermal gradient can be estimated.

Chronology of metamorphism. Field data indicate that the regional metamorphism is older than the youngest nappe movement. Based on the geodynamic model by Horváth et al. (1977), its age may be put in the interval between the Late Jurassic "Eohellenic" phase (Jacobshagen 1976) and the Cretaceous Austrian phase. For further details and references see Árkai & Kovács (1986).

Problems. Detailed petrological studies (including IC, R, $d_{33\bar{1},060}$ data) of the Late Paleozoic and Mesozoic formations in the Slovak part of the South Gemeric Unit is strongly needed, in order to reconstruct the metamorphic evolution of the unit as a whole. Furthermore, isotope geochronological characterization of the Alpine metamorphism would give a valuable contribution to the comparison of the metamorphic age relations of the Bükkium and the Aggtelek-Rudabánya units.

IV. The Tisza Superunit

IV a) Central Hungarian Autochthonous

Szalatnak (locality 16 in Fig. 1)

General features. North to the eastern Mecsek Mountains, a very-low grade rock sequence was found in some boreholes, covered by Triassic sediments.

Lithology. This is a volcano-sedimentary sequence. Metagreywackes intercalated with silty metaslates prevail both in the upper and in the lower parts, separated by a horizon of a metavolcanic agglomerate bearing a large variety of rock types. A few metalydite intercalations occur both in the upper and lower parts. A porphyric syenite body was encountered at the bottom of one borehole.

Chronological data. The occurrence of Silurian beds is indicated by paleontological findings in some metalydites (Góczán 1971; Kozur 1984). Therefore, the age of metamorphism, which is certainly pre-Alpine because the Triassic cover is not metamorphic, can only be Variscan. As regards the syenite, it is not affected by the Variscan metamorphism, so that it may be considered younger. K/Ar data concerning this syenite (Balogh, unpublished internal report) are consistent with the above inference: impure, mica rich, < 2 µm grain size concentrates gave values in the range 220–270 Ma; and a sericitized K-feldspar from the syenite gave 180 Ma.

Metamorphic petrological features. Chlorite crystallinity, chlorite geothermometric data and coal rank data indicate transitional anchi/epizonal (ca. 350 °C) conditions (Árkai et al. 1995). Muscovite $d_{33\bar{1},060}$ data indicate low pressure metamorphic conditions. However, these rocks underwent contact metamorphic effects by a syenite intrusion. They consist of a widespread, post-foliation crystallization of biotite and the local occurrence in some levels of spotted schists and biotite-plagioclase hornfelses at the contact with the syenite.

Problems. The detailed petrological characterization of the pre-metamorphic volcanic event is the most important goal in this area.

Mórágy Mts. (locality 17 in Fig. 1)

General features. Basement rocks outcrop in the Mórágy Mts. along streams, within an area of approx. 200 km^2. The surrounding rocks are represented by unmetamorphic Mesozoic and Miocene sediments.

Lithology. Two different complexes, separated by faults, can be distinguished in this area.

The more widespread complex is made up of S-type K-rich ilmenite-bearing calcalkaline granitoids (Buda 1981), which in some areas contain enclaves of various size and rock type. The enclaves are reported to be partly migmatized.

The other complex consists of a volcano-sedimentary sequence; metagreywackes prevail in it, with intercalations of basic and intermediate metavolcanics and metavolcanoclastics. Acidic metavolcanics, metapelites, siliceous slates and impure marbles are subordinate. Amphibolites and serpentinites have also been reported (Ghanem & Ravasz-Baranyai 1969; Ghoneim & Szederkényi 1977, 1979; Szederkényi 1983).

Chronological data. From the geological point of view, metamorphism is pre-Permian. A Lower Paleozoic sedimentation age for the greenschist facies complex is suggested by some broken conodonts (Kovács, pers. comm.).

As regards the granitic-migmatitic complex, granitic rocks supplied the following radiometric age values:

— zircon and sphene separates gave an U/Pb intercept age of 365±8 Ma, which is interpreted as the oldest age of anatectic granitoids (Kouvo, in Balogh et al. 1983);

— whole rock gave a Rb/Sr age value of 320 ± 59 Ma from a granite, and 309 ± 60 and 317 ± 31 Ma from aplites (Svingor & Kovách 1981);

— biotite concentrates from granites supplied Rb-Sr age values of 325 ± 38, 352 ± 25 and 365 ± 41 Ma (same authors);

— biotite K/Ar ages from granites fall in the range 323-352 Ma, while biotites from microgranites supplied K/Ar ages of 318 ± 16 and 343 ± 19 Ma (Balogh et al. 1983; Balogh 1984; unpubl. int. report 1991).

As regards the greenschist facies complex, two K/Ar data from amphibole separates are only available: 333 ± 11 and 350 ± 20 Ma (Balogh et al. 1983).

Metamorphic petrological features. The petrological situations are very different in the two complexes. The occurrence of sillimanite plus cordierite, reported within the granitoid-migmatitic complex, indicates amphibolite facies conditions related to a high thermal gradient metamorphism. On the other side, the mineral assemblages occurring within the volcano-sedimentary complex indicate upper greenschist to lower amphibolite facies conditions related to an undetermined thermal gradient.

Problems. The main problem in this area is the better definition of the migmatitic rocks. In fact, recent investigations still under way show that, in most cases, the so-called "migmatitic" rocks are indeed various types of mylonites, and that the intimate association of various rocks of different metamorphic grade is due to intensive shearing and retrograde effects. This situation is further complicated by contact effects of intruding Mesozoic alkaline dyke swarms.

The age of mylonitic deformation could be determined by the radiometric datation of biotite separates from biotite-grade mylonites.

Somogy-Dráva Basin (locality 18 in Fig. 1)

General features. Numerous boreholes crosscut metamorphic rocks in southern Transdanubia over a large area. In some drillings, a not metamorphic upper Carboniferous sequence has been found, but its relationship with the basement rocks is completely unknown. However, this Carboniferous clastic sequence may represent the original cover of the basement, on the basis of the occurrence of metamorphic rocks as pebbles in it. The Permian cover is also not metamorphic.

Lithology. The basement rocks represent mainly a pelitic to semipelitic sequence, with some intercalations of pure and impure carbonate levels and basic rocks. Metaultrabasic rocks occur locally (Szederkényi 1983).

Chronological data. It is commonly assumed that the metamorphic development in these rocks is, at least partly, pre-Variscan. However, the radiometric data till now available only indicate a Variscan thermal event. In fact:

— Rb/Sr age determinations gave a biotite + whole rock isochron age of 328 ± 5 Ma from a kyanite-bearing micaschist affected by a retrograde alteration (Ferrara in Kovách et al. 1985);

— a 10 point Rb/Sr whole rock isochron of 331 ± 13 Ma was obtained from these micaschists, and their biotite ages scatter in the range 311-327 Ma (Kovách et al. 1985);

— K/Ar mica ages from the same rocks fall in the range 307-356 Ma for muscovites and in the range 275-293 Ma for biotites (Balogh et al. 1983);

— a Variscan K/Ar cooling age of muscovite (317 ± 12 Ma) was measured (Balogh, pers. comm., 1993) in a polymetamorphic micaschist (kyanite-bearing assemblage overprinted by andalusite-bearing mineral assemblage: Lelkes-Felvári et al. 1989).

All these radiometric age data refer to a widespread Variscan metamorphism in the basement of south Transdanubia.

Metamorphic petrological features. The major part of this basement is made up of amphibolite facies rocks, characterized in metapelites by the mineral assemblage: garnet + kyanite + staurolite + sillimanite (Szederkényi 1976; Árkai 1984; Török 1989, 1990). A garnet + andalusite + staurolite ± sillimanite assemblage was also reported (Lelkes-Felvári & Sassi 1981; Árkai 1984; Török 1990). Migmatitic rocks also appear in some areas. Greenschist facies rocks are subordinate. Different types of mylonites are also widespread in this basement.

The mineral assemblages can be clearly assigned to two, amphibolite facies stages or events of contrasting pressure character. Their reciprocal relationships can be deduced by some microstructural situations: late andalusite porphyroblasts enclose small, dismembered staurolite (Árkai 1984) and kyanite crystals (Lelkes-Felvári et al. 1989). This situation suggests that a Barrovian-type metamorphism was followed by a high thermal gradient metamorphism (Lelkes-Felvári & Sassi 1981; Árkai 1984). Thermobarometric calculations (Árkai 1984) assign 550-600 °C and 590-890 MPa to the older event or stage, that is a thermal gradient of 17-27 °C/km. The low pressure amphibolite facies event was followed by a subgreenschist facies to low temperature (450 °C) greenschist facies retrograde metamorphism, locally connected with mylonite formation. An identical evolution is suggested by an eclogite reported from a borehole (Ravasz-Baranyai 1969), which being largely altered into symplectite, indicates that it was affected by at least two metamorphic events: the older one under a relatively low thermal gradient and $P_{H_2O} = 0$, the younger one under a higher thermal gradient and/or $P_{H_2O} = P_{tot}$. A polymetamorphic evolution has been also reported concerning metaultramafic rocks, originally olivine-bearing pyroxenites (Balla 1985).

Problems. The age of the older, Barrovian-type metamorphism is completely unknown in this area.

Tokaj Mts. (locality 19 in Fig. 1)

General features. In the northeastern side of the Tokaj Mts., close to the boundary between Slovakia and Hungary, basement rocks occur mainly as fragments in detritic cover; moreover, some boreholes drilled metamorphic rocks in this area

(Pantó 1965; Lelkes-Felvári & Sassi 1981; Kisházi & Ivancsics 1988).

Two main groups may be distinguished within these rocks according to their metamorphic grade: a greenschist facies complex and an amphibolite facies complex. In the neighbouring Slovakia, the amphibolite facies rocks outcrop in a tectonic horst and are known from boreholes, while the greenschist facies rocks are known only as pebbles from Late Paleozoic conglomerates. Furthermore, the Upper Carboniferous siliciclastic sediments are affected by a very-low grade Alpine metamorphism (Lelkes-Felvári unpublished data).

Lithology. Metapelites and minor acidic metavolcanoclastics make up the greenschist facies complex. Pelitic and semipelitic rocks, basic horizons and granitoids are the protoliths of the amphibolite-facies complex.

Chronological data. The amphibolite and greenschist facies rocks occur as pebbles in the upper Carboniferous conglomerates: their metamorphism is therefore certainly pre-Alpine. As regards its radiometric age, only two data are available from the amphibolite facies complex: i) a K/Ar muscovite age of 227 ± 9 Ma from a micaschist, which can be interpreted as a Variscan cooling age rejuvenated by later hydrothermal effects, ii) a K/Ar amphibole age of 312 ± 13 Ma from an amphibolite, which is a Variscan cooling age (Balogh 1984).

Metamorphic petrological features. The mineral assemblages found in the greenschist facies complex correspond to the quartz-albite-muscovite-chlorite subfacies. Nothing can be said concerning the pressure values prevailing during this metamorphism.

Instead, the physical conditions of the amphibolite facies complex are well defined. In fact, the occurrence of the kyanite + staurolite + sillimanite assemblage indicates a thermal gradient lower than 40 °C/km (occurrence of kyanite) and higher than 25 °C/km (staurolite becomes unstable within the stability field of sillimanite). A value close to 27 °C/km and a temperature close to 670 °C can therefore be assumed (Lelkes-Felvári & Sassi 1981).

In the Slovak territory (Vozárová 1989), metapelites of the amphibolite facies complex are composed of quartz + biotite + almandine + plagioclase + microcline + sillimanite + staurolite, and migmatites also occur. Amphibolites consist of plagioclase + hornblende + sphene + almandine. Sericite pseudomorphs have also been reported in the metapelites, and could be referred to possible cordierite of late crystallization; however, as regards the main metamorphism, pressure conditions of 500 MPa and temperatures of 640-700 °C can be admitted (Vozárová 1995, pers. comm.). These mineral assemblages refer to a high thermal gradient amphibolite facies metamorphic event.

Problems. As concerns the amphibolite facies complex, the possible distinction of two contrasting amphibolite facies events is the most important goal, as well as the understanding of the apparently contrasting situations reported from the Hungarian and Slovak sides.

As regards the greenschist facies complex, the metamorphic thermal gradient has to be estimated by means of $d_{33\bar{1},060}$ measurements. A better definition of the metamorphic ages is a further important task.

IVb) South Hungarian Nappe Zone

Barcs West (locality 20 in Fig. 1)

General features. In this area, basement rocks are known only from boreholes. According to Árkai (1990), two tectonic units make up this basement: a Variscan to pre-Variscan polymetamorphic amphibolite facies unit *(a)*, described under locality 18, is tectonically overlain by a Mesozoic (Triassic?) unit *(b)*, which underwent prograde Alpine metamorphism.

Lithology. Unit *(a)* is made up of metapelites and metapsammites; unit *(b)* consists of metapelites, metapsammites, impure carbonates, with layers of acidic to intermediate metavolcanoclastics.

Chronological data. Biostratigraphic data are not available for the sedimentation ages of these sequences. The sedimentary rocks overlying this basement are Miocene in age.

As concerns radiometric data, the unit *(a)* gave a muscovite K/Ar age of 276 + 11 Ma and Rb/Sr age of 222 + 41 Ma, which can be both interpreted as rejuvenated Variscan ages (Balogh et al. 1990).

From unit *(b)*, a poorly defined Rb/Sr whole rock isochron from metarhyolites gave a Mesozoic (probably Triassic) age. Rb/Sr model ages of < 2 µm white mica refer to the Alpine (Cretaceous) regional metamorphism. Sericite K/Ar ages obtained from acidic metavolcanics scatter in the range 17-41 Ma, and those from intermediate metavolcanics in the range 26-29 Ma (Balogh et al. 1990). They were interpreted as Mesozoic (Cretaceous) metamorphic ages rejuvenated by a Tertiary (ca. 30 Ma) tectonothermal event.

Metamorphic petrological features. In unit *(a)* metapelites bear the mineral assemblage: quartz + plagioclase + muscovite + biotite + almandine. P-T conditions of about 900 MPa and 540 °C were estimated. In unit *(b)* the different lithologies contain the following minerals:

— metarhyolites: quartz, albite, sericite, potassium feldspar;
— phyllites: quartz, sericite, calcite, pyrite, rutile;
— carbonate phyllite: quartz, albite, sericite, chlorite, calcite, dolomite, tremolite, anhydrite;
— dolomite marble: quartz, albite, sericite, calcite, dolomite.

Temperatures around 300-350 °C were estimated. Sericite $d_{33\bar{1},060}$ values in phyllites point to medium pressure conditions during the subgreenschist to greenschist facies metamorphism (Árkai 1990).

Problems. Biostratigraphic data are necessary in order to constrain the chronology of the protoliths.

Concluding remarks

A general picture of the metamorphic history of the Hungarian basement may be attempted on the basis of the above data. Such a picture may be considered to be definitely established for some aspects, although it is rather vague for others. The effects of at least two regional metamorphic cycles have been definitely recognized, Alpine and Variscan, and some polymetamorphic situations suggest the possible existence of a third, older event.

Alpine metamorphism is more widespread than previously reported (Lelkes-Felvári & Sassi 1981), as pointed out by Árkai (1991). However, it never severely obliterated the pre-existing features: with a few exceptions, indeed, it commonly did not produce a complete microstructural and mineralogical renewal of the affected rocks. The Alpine metamorphic grade ranges from subgreenschist to greenschist facies conditions, locally reaching the lower amphibolite facies (locality 2). As concerns its pressure character, medium to low pressure conditions have been generally ascertained, with the following local exceptions: (i) Kőszeg Mts. (locality 1), where records of

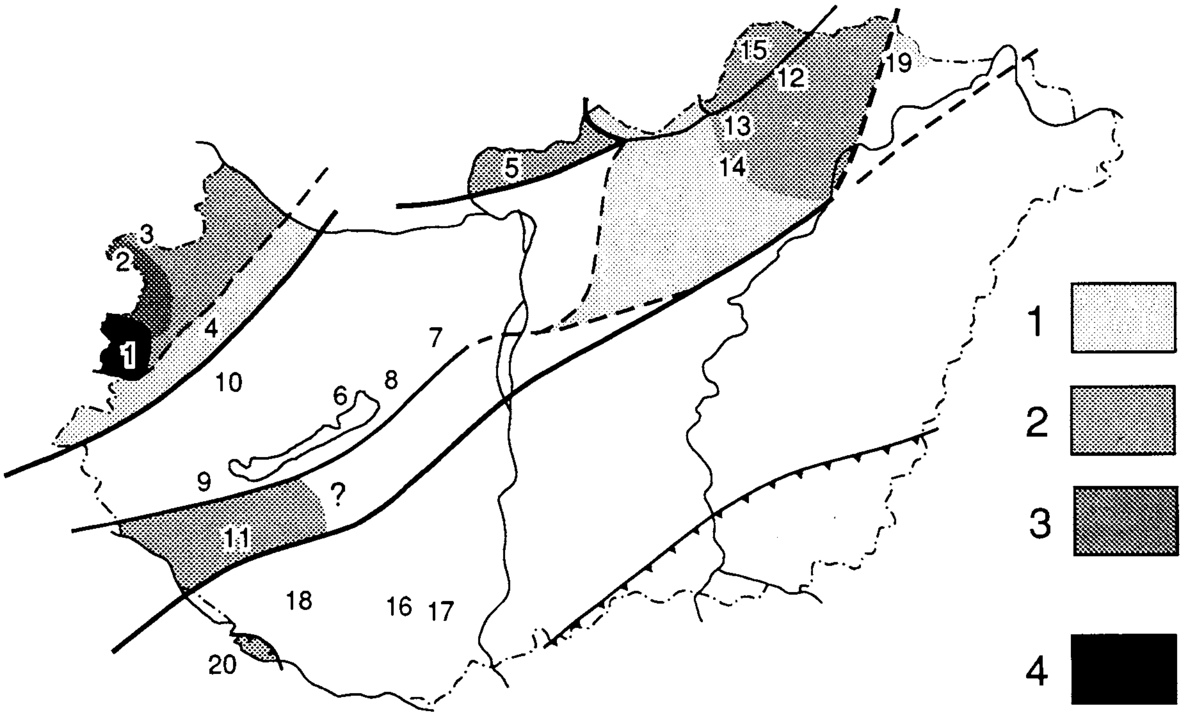

Fig. 2. Distribution and thermal features of the Alpine metamorphism in Hungary. Alpine metamorphic effects either occur as overprints in the previously metamorphic rock sequences, or affect monometamorphic Permo-Mesozoic rock sequences, as can be detected comparing Figs. 2 and 3. **Legend:** 1 — mainly subgreenschist facies; 2 — subgreenschist to greenschist facies; 3 — greenschist to amphibolite facies; 4 — glaucophanitic greenschist facies overprinted by greenschist facies.

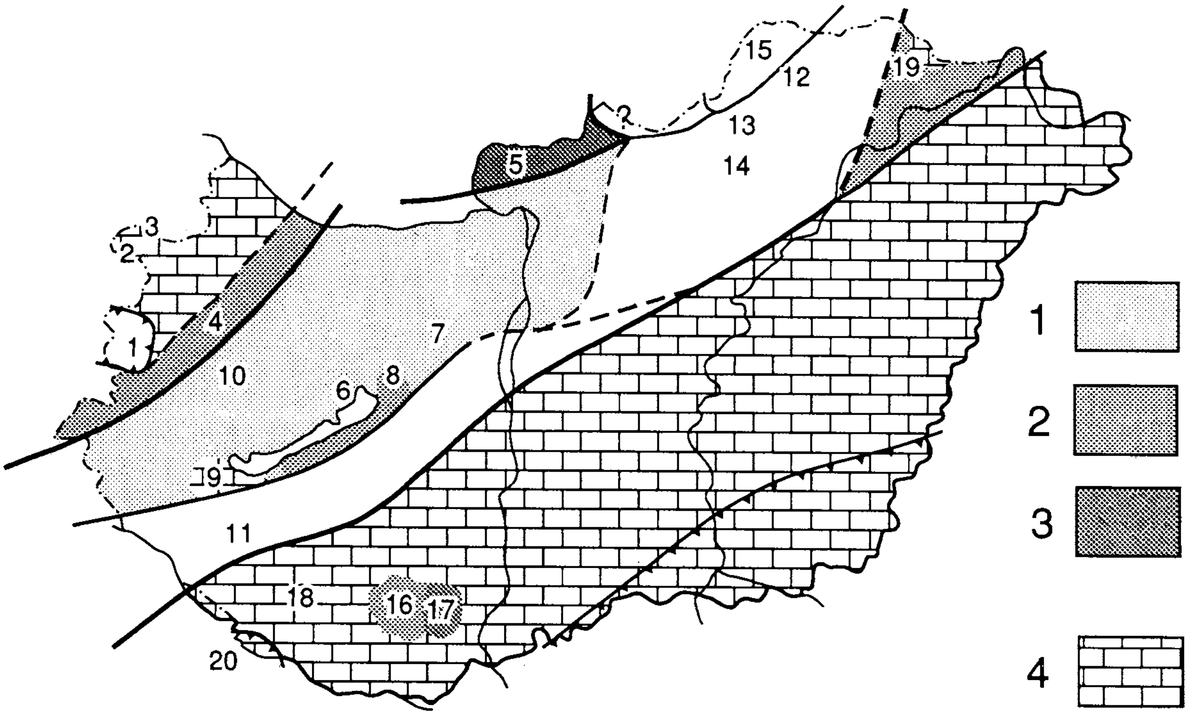

Fig. 3. Distribution and thermal features of the pre-Alpine metamorphisms in Hungary. **Legend:** 1 — Variscan, mainly subgreenschist facies; 2 — Variscan, subgreenschist to greenschist facies; 3 — Variscan, greenschist to amphibolite facies; 4 — polymetamorphic or polyphase amphibolite facies: pre-Variscan, or Eo-Variscan, intermediate pressure, amphibolite facies overprinted by Variscan, low pressure, amphibolite facies.

an early, high pressure, metamorphic stage have been detected in Pennidic rocks; (ii) deeper tectonic units of the Aggtelek-Rudabánya Mts. (locality 15), where a transitional medium to high pressure, greenschist facies was evidenced (locality 15). It is unclear whether and in what extent the above mentioned low pressure character is to be referred to the Alpine regional metamorphism or to late, contact to hydrothermal metamorphic effects in the Central Hungarian Unit.

The distribution and thermal conditions of the Alpine regional metamorphism are sketched in Fig. 2.

The *Variscan metamorphism* has been detected in the majority of the pre-Permian rock sequences in Hungary. Remarkable exceptions are the Dinaric type central Hungarian (Igal), the Aggtelek-Rudabánya and the Bükk units. In the former two units, rock sequences older than the main Variscan metamorphic phases are unknown. In the Bükkium, no significant difference could be demonstrated between the metamorphic P-T conditions recorded in the units older or respectively younger than the main tectonophases of the Variscan cycle. Consequently, in the Bükkium, possible Variscan regional metamorphic effects cannot be distinguished from the Alpine ones, which certainly affected the whole Paleo-Mesozoic sequence. The subsidence of the geosyncline, the flysch character of the Middle Carboniferous rock sequence as well as the lack of tectonic unconformities exclude the possibility of Variscan orogenic effects in the Bükkium; consequently, the occurrence of Variscan metamorphic effects in it is not probable (Árkai 1983), as recent K/Ar studies on white mica confirmed (Árkai et al. 1995).

The Variscan metamorphic grade covers the whole temperature field of metamorphism, up to anatectic conditions. Its pressure condition in the monometamorphic Variscan low grade metapelites turns out to be low, related to a thermal gradient close to 40 °C/km.

Disregarding the Alpine overprint (where it occurs), the amphibolite facies metapelites often display a *pre-Alpine polymetamorphic character.* The youngest mineral assemblages in them are characterized by the occurrence of andalusite in the rocks of suitable bulk composition, displaying a low-pressure character of the Variscan event, consistently with the above reported pressure estimates inferred from the greenschist facies monometamorphic metapelites. The oldest mineral assemblage is characterized by the occurrence of kyanite in rocks of suitable bulk composition, which may be either referred to an early Variscan stage or to a pre-Variscan event, as discussed by: Lelkes et al. 1984; Árkai 1984; Árkai et al. 1985. In any case, a medium pressure character must be assigned to this early Variscan stage or pre-Variscan event.

Fig. 3 summarizes the presently available data on the distribution and thermal conditions of the pre-Alpine metamorphism(s) in Hungary. The presently available isotopic chronological data (different analytical methods) indicate for the Variscan thermal climax the age in the range of 311-325 Ma, with cooling age in the range 286-321 Ma.

The possible occurrence of a pre-Variscan event in the Hungarian basements, as well as in the surrounding old basements along the Tethys, remains one of the major problems, which could be only clarified by means of specifically oriented radiometric research. The extensive use of the evaporation technique on the zircon xenocrysts has a very high potential both on this respect and for better understanding the nature and relationships of the low and very low-grade units vs. the higher grade ones.

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