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Evolution of the SE Bohemian Massif Based on Geochronological Data – A Review

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Bohemian Massif
Moldanubian zone
Moravian zone
European Variscides
Evolution
Geochronology

Österreichische Karte
Blätter 1–9, 12–22, 29–38, 51–56

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Entwicklung der südöstlichen Böhmischen Masse aus geochronologischer Sicht – ein Überblick

Zusammenfassung

Dieser Beitrag präsentiert und diskutiert radiometrische Altersdaten aus dem SE-Teil der Böhmischen Masse in Österreich.

Basierend auf dem Grad der variszischen Überprägung wird das Moldanubikum im W (komplett variszisch überprägt) dem Moravikum im E (nur partiell überprägt) gegenüber gestellt.

Das Moldanubikum lässt sich weiters in 3 tektonische Deckeneinheiten und in den variszischen Südböhmischen Pluton unterteilen. Jede dieser Einheiten zeigt eine charakteristische chronologische Entwicklung:

– Die Monotone Serie besteht aus einer poly-metamorphen Serie monotoner klastischer Sedimente eines spät- bis post-cadomischen aktiven Kontinentalrandes.
– Die höher liegende Bunte Serie besteht aus ebenfalls poly-metamorphen Sedimenten, die auf einem ca. 2 Ga alten Grundgebirge abgelagert wurden (oberes Proterozoikum bis unteres Paläozoikum). Cadomischer Plutonismus um 640 Ma ist wahrscheinlich.
– Die Gföhler-Gneis-Granulit-Einheit bildet die höchste Decke. Sie besteht aus Migmatiten und Granuliten, die aus altpaläozoischen Magmatiten hervorgegangen sind.

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Die prä-variszischen Relationen zwischen Bunter Serie und Monotoner Serie sind unbekannt. Die Gföhler-Gneis-Granulit-Decke wird als komplett eigenständiges Terrane interpretiert. Die gemeinsame variszische Entwicklung dieser moldanubischen Einheiten beginnt mit einer nicht exakt fassbaren Hochdruckmetamorphose und der Deckenstapelung nach 370 Ma (Oberdevon). Die Abkühlung nach einer mehr temperaturbetonten Metamorphose beginnt um 340 Ma (Visé) und dauert bis mindestens 290 Ma (oberstes Karbon). Eine generelle Tendenz zu jüngeren Abkühlaltern im Westen ist offensichtlich. Ursache dürfte die frühe Hebung verursacht durch die Aufschiebung des Moldanubikums auf das Moravikum sein.

Die Entwicklung des Südböhmischen Plutons beginnt mit dem partiellen Aufschmelzen cadomischer Kruste um 360 bis 350 Ma (Unterkarbon) und der folgenden Bildung und Intrusion geochemisch diverser Granitoide (Weinsberger Granit, Rastenberger Granodiorit) zwischen 350 und 320 Ma. Innerhalb dieser Intrusionen finden sich kleine grabbroide bis dioritische Körper mit ausgeprägter Mantelkomponente. Es folgt die Intrusion von geringen Mengen an I-Typ-Graniten und großen Mengen an S-Typ-Graniten (Mauthausner, Schremser und Eisgarner Granite) zwischen 330 und 300 Ma (mittleres Karbon). Das partielle Aufschmelzen der cadomischen Kruste und die gleichzeitige Bildung von Mantelschmelzen kann durch einen Krustenausdünnungsprozess erklärt werden. Post-kollisionale Lamprophyre mit Altern <316 Ma stammen von einem subkontinentalen Mantel ab. Die Abkühlung innerhalb der Plutonite folgt der großregionalen Abkühlung, kann aber zum Teil, bedingt durch die große Menge an latenter Wärmeenergie, auch etwas verzögert einsetzen.

Der Anteil cadomischer Kruste (oberes Proterozoikum und Kambrium), meist in der Form übernommener Zirkone in den variszischen Metamorphiten und Plutoniten identifizierbar, ist wesentlich höher als bis anhin angenommen. Demgegenüber fehlen altpaläozoische („kaledonische“) Gesteine, mit Ausnahme der exotischen Gföhler-Gneis-Granulit-Decke, vollständig.

Das cadomische Moravikum ist charakterisiert durch eine nur schmale Zone variszischer Überprägung entlang des Kontakts zum überschobenen Moldanubikum. In dieser Zone entspricht die post-variszische Abkühlung derjenigen des Moldanubikums. Im nicht überprägten Anteil des Moravikum/Brunovistulikums finden sich typischerweise Bildungsalter und Abkühlalter um 600 Ma bis 500 Ma.

Abstract

This paper summarises and discusses radiometric age data for the SE part of the Bohemian Massif in Austria.

On the basis of Variscan imprint a major division into a Moldanubian part in the W (completely overprinted during the Variscan) and a Moravian part in the E (only partly overprinted during the Variscan) is traditionally made.

Furthermore, a subdivision of the Moldanubian into 3 major litho-tectonic nappe series and a suite of Variscan intrusives is implied. Each of these units shows a distinctive chronological evolution:

– The Monotonous Series is built up by poly-metamorphic clastic sediments of a late- to post-Cadomian active continental margin.
– The overlying Varied Series is formed by Upper Proterozoic to Lower Palaeozoic meta-sediments deposited on a ~2 Ga crystalline basement. Invasion by Cadomian intrusives around 640 Ma is indicated.
– The highest nappe, the Gföhl gneiss-granulite unit, is formed by migmatites and granulites of Lower Palaeozoic age and mainly acid magmatic provenance.

Nothing is unambiguously known about the pre-Variscan relations of Monotonous Series and Varied Series, respectively. On the basis of absolute age data the Gföhl gneiss-granulite nappe is interpreted as a formerly completely independent terrane. The common Variscan evolution of the Moldanubian units starts with a postulated high-P event and nappe-stacking after 370 Ma (Upper Devonian). Cooling after a subsequent high-T metamorphic event begins at 340 Ma (Visean) and lasts at least until 290 Ma (uppermost Carboniferous), with a marked tendency to younger cooling ages from E to W. Cause is the early uplift in the E due to the thrusting of the Moldanubian zone onto the Moravian zone.

The evolution of the Variscan South Bohemian pluton begins with the partial melting of Cadomian basement series at 360 to 350 Ma (Lower Carboniferous) and the formation of large masses of geochemically diverse granitoids (Weinsberg granite, Rastenberg granodiorite) between 350 and 320 Ma. Incorporated into this complex are small gabbroic to dioritic intrusions with marked mantle components. The subsequent intrusion of small amounts of I-type granites and huge amounts of S-type granites follows (Mauthausen, Schrems, and Eisgarn type granites) between 330 and 300 Ma (Middle Carboniferous). The remelting of Cadomian crust and the production of mantle derived melts can be related to a crustal thinning process. Post-collisional lamprophyric dikes with emplacement ages <316 Ma are derived from a subcontinental mantle source. Post-magmatic cooling follows the general regional pattern but is somewhat delayed within the large pluton.

Remarkable is that Cadomian crust (Upper Proterozoic and Cambrian), now mainly present as zircon inheritance in Variscan metamorphites and plutonites, is far more widespread than previoulsy thought. And, except for the somewhat exotic Gföhl gneiss-granulite unit no Lower Palaeozoic (“Caledonian”) rocks are found.

The Cadomian Moravian/Brunovistulian unit is characterised by only a narrow zone of Variscan overprint near the overlying Moldanubian complex. In this zone post-Variscan cooling patterns resemble those of the nearby Moldanubian. The unaffected parts of the Moravian/Brunovistulian typically exhibit formation and cooling ages between 600 Ma and 500 Ma.

1. Introduction

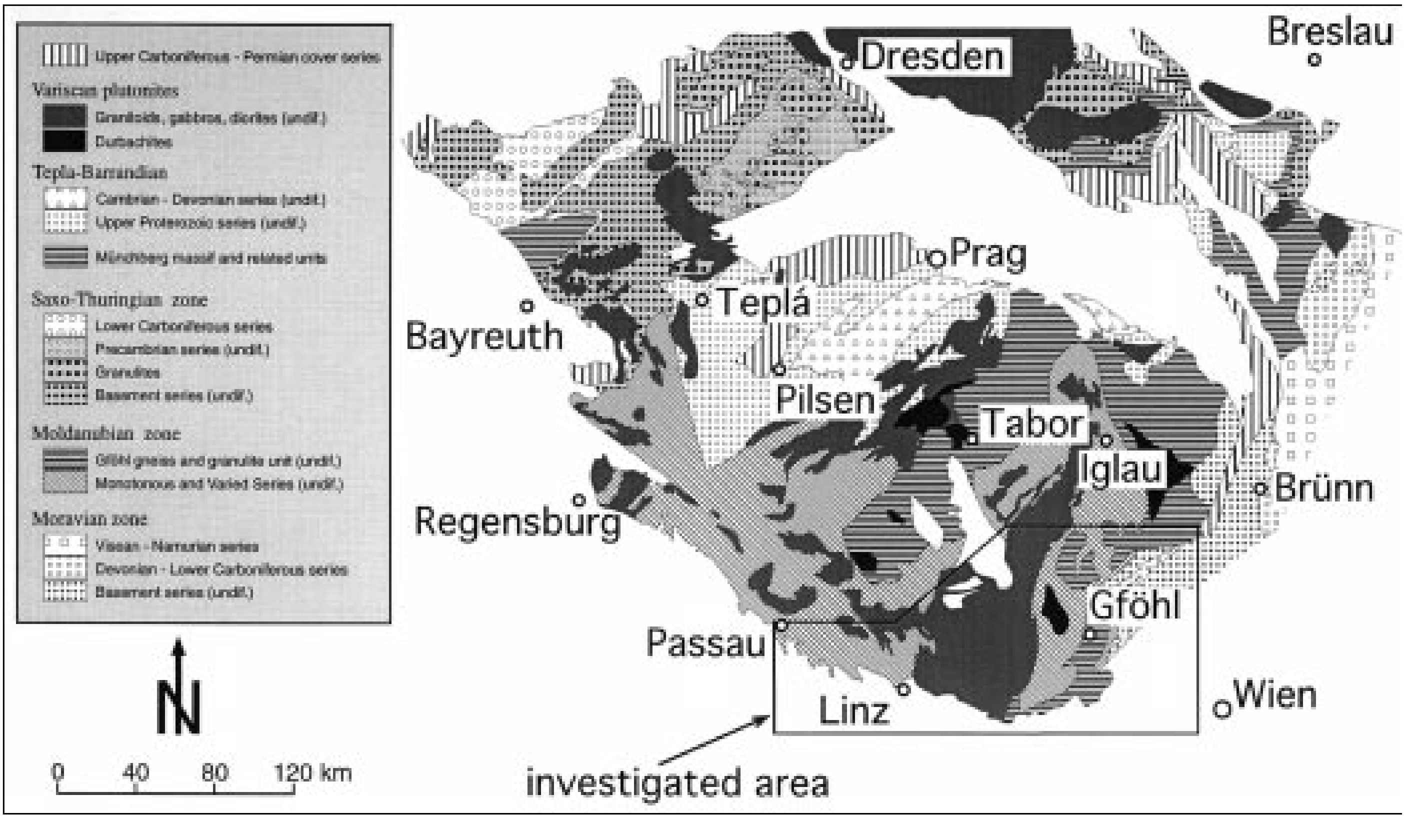
Since the revolutionary concept of Suess (1903, 1926), the deeply eroded, high grade metamorphic and intrusive rocks of the Bohemian Massif (Text-Fig. 1) were subject to many detailed studies. Many, often widely differing synthetic concepts were developed depending on the varying views about the age of the different rock units and the time of their metamorphic and structural overprint. Although there is some general agreement about the nappe structure of the Moldanubian and Moravian parts of the Bohemian Massif, no concise model regarding the number of continental pieces involved (microcontinents, terranes), possible oceanic sutures between these crustal blocks, their lithostratigraphic age, time of stacking and metamorphic overprinting has been presented.

This paper summarises the both published and new geochronological data from the SE Bohemian Massif (Text-Fig. 2).

In general, absolute age data can be interpreted to reflect either formation ages (magmatic ages or depositional ages) or cooling ages. In this respect the discussion proceeds from the oldest known magmatic ages to the youngest ages reflecting the post-Variscan cooling. Partly the presentation of the various lithological units is given from bottom to topmost units. The paper concentrates on the main trend lines of the evolution, but many aspects remained untouched. The investigations have thrown light on several problems, some of them have been solved, some have been newly raised and several need more efforts to be solved in future.

2. Geological Setting

The crystalline rocks of the Bohemian Massif represent a consolidated and deeply eroded part of the Middle-European Variscan orogenic system. In the SE part of the Bohemian Massif in Austria a division in 3 major units is widely accepted (Text-Fig. 2.):



Text-Fig. 1.
Simplified geological sketch map of the Bohemian Massif, modified after FUCHS & MATURA (1976) and MATTE et al. (1990).

2.1. Moravian Zone

The Moravian zone in the south-easternmost part of the Bohemian Massif forms two cupola like structures (Thaya and Svratka dome). The structurally lowermost part of the Moravian zone is formed by the Thaya batholite, a plutonic rock complex of granitic to granodioritic composition overlain by metapelitic and metapsammitic sequences of the Therasburg and Pernegg formations. Concordant orthogneiss bodies are intercalated, the most prominent of them being from bottom to top the Therasburg gneiss and the Weitersfeld Stengelgneis. The Moravian is topped by the Bites gneiss, a porphyric orthogneiss with intercalations of amphibolites in its topmost parts. The metamorphic zonation in the Moravian zone is clearly discordant to the lithological and tectonic zonation. Increasing metamorphic grades from the footwall units to the hangingwall units indicate tectonic inversion of the whole nappe pile (HÖCK, 1975). Metamorphic conditions in the highest units just below the overlying Moldanubian Zone are estimated to be in the range of 580–602 °C at 6–8 kb (HÖCK et al., 1990; HÖCK, 1994). Oldest metamorphic relics belong to the contact metamorphism in the roof of the Thaya pluton (FRASL, 1970), while the youngest overprint yielded retrogressive reactions in garnet, biotite, and staurolite. A slightly to non metamorphic sedimentary series of Devonian to Tertiary age forms the highest unit, especially in the surroundings of Brno.

The Moravian Zone is regarded as the westernmost part of the Brunovistulian which in turn represents the western part of the East European platform during Variscan times. Well preserved Cadomian ages are characteristic for this part of the Bohemian Massif. Thus, the Moravian forms part of the Cadomian consolidated crust that has partly been affected by tectonothermal processes of Variscan age. It is overlain by the higher grade metamorphic Moldanubian Zone. The tectonic contact along the prominent Moldanubian thrust zone (SUESS, 1903) is marked by a retrograde micaschist horizon (Glimmerschiefer zone, Outer Phyllite zone).

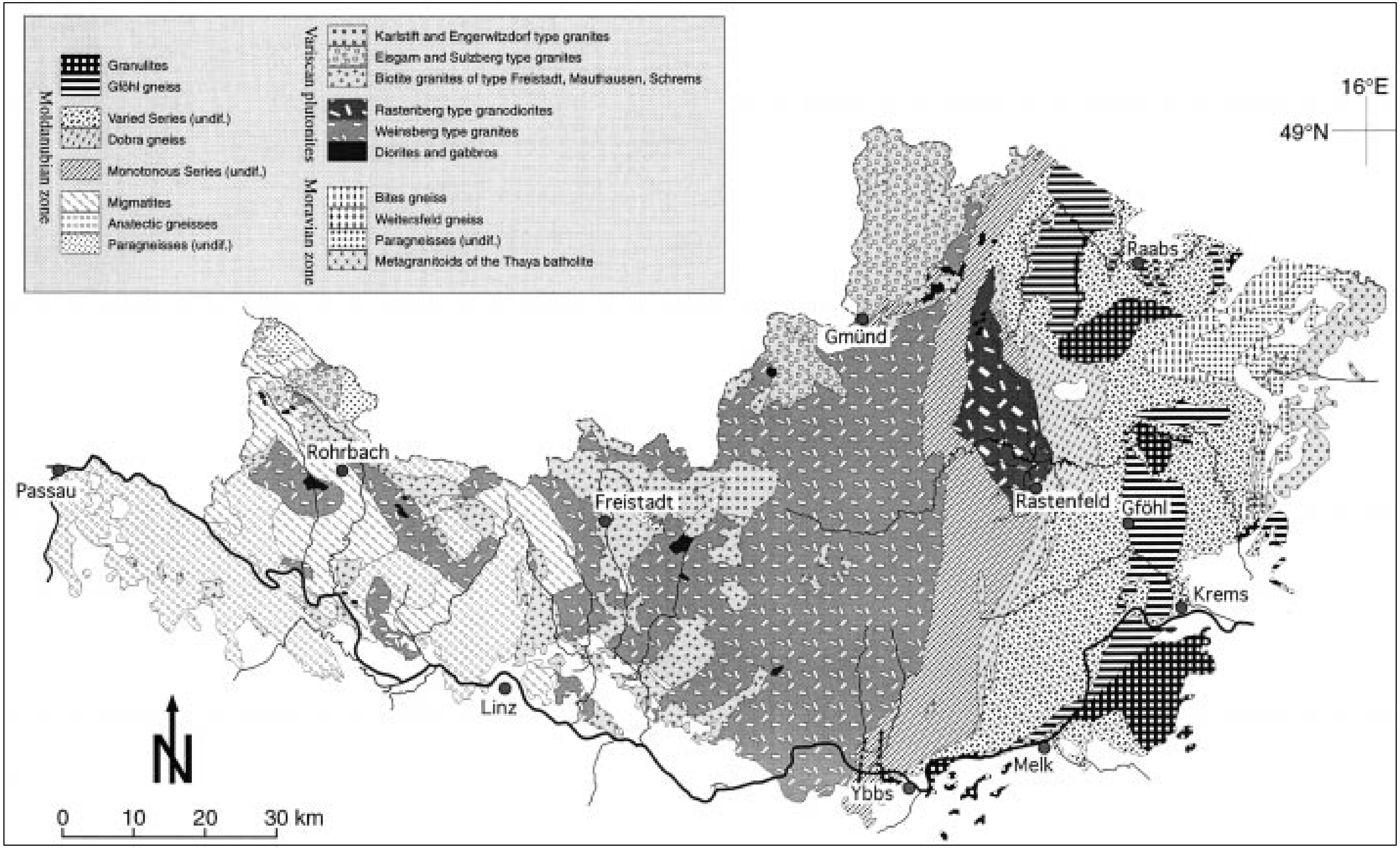
2.2. Moldanubian Zone

The Moldanubian Zone comprises the largest part of the southern Bohemian Massif in Austria. Within this zone a number of different basement series and late- to post-tectonic plutonic rocks can be distinguished mainly on lithological criteria. All of the tectono-stratigraphic units are separated from each other by more or less discrete, subhorizontal shear zones.

The Monotonous Series (Monotone Serie, Ostrong unit) forms the lowermost basement sequence. Major lithologies are masses of monotonous stromatitic to nebulitic garnet-free cordierite gneisses, cordierite-free sillimanite-biotite-plagioclase gneisses, often with lithological layering and some calcsilicate lenses thought to represent former shales and greywackes. Subordinate are lenses of orthogneisses, calcsilicate-gneisses and eclogite-amphibolites.

Low pressure / high temperature amphibolite facies metamorphism with cordierite bearing assemblages are thus typical for this unit. Local melt segregations point to the beginning anatexis due to extensive dehydration melting of muscovite at 700 °C and >4.5 kb (PETRAKAKIS, 1997). LINNER (1996) additionally describes relics of an earlier intermediate to high pressure metamorphic event with temperature around 570 °C and pressure >6 kb.

The Dobra gneiss forms the basis of the next higher unit in the east. This gneiss is of granitic to granodioritic com-



Text-Fig. 2.
Geological sketch map of the Austrian part of the southern Bohemian Massif, modified after FUCHS & MATURA (1976) and FRASL & FINGER (1991).

position, often with augen-structure and mostly concordant amphibolites, biotite-amphibolite, and biotite-gneiss intercalations.

The so called Varied Series (Bunte Serie, Variegated series, Drosendorf unit) overlies the Dobra gneiss. This rather inhomogenous rock suite is built up by partly migmatitic garnet-sillimanite-biotite-plagioclase gneisses, quartzites, more or less graphite-bearing marbles and calcsilicate rocks, and granitic orthogneisses (ex. Spitz granodiorite gneiss, Weiterndorf granite gneiss). Abundant amphibolites closely associated with ultrabasic rocks, marbles, and granitic gneisses (Rehberg and Buschandlwand units) are found within the Varied Series. The basic and ultrabasic metamorphites of the Raabs unit possibly belong to a disrupted ophiolite sequence (Raabs-Letovice complex) which would imply the existence of a major suture within the Moldanubian Zone (THIELE, 1984; FRITZ, 1995). For the Varied Series metamorphic conditions of 700 °C–800 °C at 7–9 kb and relictic mineral assemblages indicative for a higher pressure event have been reported by PETRAKAKIS (1997).

Within the amphibolites of the Varied Series in the vicinity of Weiterndorf (E Weitental) a granitic gneiss with presumably discordant contacts to its surroundings is found. In contrast to the country rocks, it contains primary muscovite relics within K-feldspars. This gneiss is thought to be the only orthogenic rock in the Varied Series which possibly shows some pre-metamorphic intrusive features.

The next higher units form characteristic klippen on top of the Moldanubian nappe sequence. The so called Gföhl gneiss, a widespread and monotonous alkalifeldspar rich orthogneiss of granitic composition builds up the lower part of these klippen. Locally transitions to acid granulites can be found. Generally, the Gföhl gneiss shows a strongly deformed fine-grained lithology without muscovite but frequent sillimanite. A migmatitic character is typical, textural relics of granites are very scarce (locally at quarry NW Florianikapelle, Eisenbergamt). Based on petrological investigations by PETRAKAKIS (1994) the migmatitic nature of Gföhl gneiss may best be interpreted as a product of anhydrous decompression melting during rapid ascent in a major thrust zone. Metamorphic conditions are 700–800 °C at 8–11 kb (PETRAKAKIS, 1997). According to this interpretation the Gföhl gneiss can be considered as one of the major deformation zones in the Moldanubian. In the most intense deformation zone, where the NS trending Gföhl gneiss unit is cut by the Kamp river, the flat syncline of Gföhl gneiss is progressively deformed to an isoclinal fold. Here, several late stage bands of prograde granulitic mineral assemblage and structures develop in which the biotite of Gföhl gneiss is replaced by garnet. In the same area several late stage granitic layers (cm–dm scale) have formed largely contemporaneously with deformation.

The highest unit of the Moldanubian Zone is formed by granulites. Light-coloured, acid varieties are prevailing. Within the granulites no structural relics have been preserved. More massive, less deformed light coloured varieties prevail in the Dunkelstein Wald area whereas strongly deformed platy and banded varieties (due to variations in biotite content) are typical for the St. Leonhard and Blumau occurrences (FRANK et al., 1990; FRITZ, 1990). In the Dunkelsteiner Wald small inclusions of basic granulites and garnet-pyroxenites are found. The granulite bodies are often underlain by a narrow zone of basic to ultrabasic rocks.Between Gföhl gneiss and granulites, migmatitic gneisses, amphibolites, pyroxene-gneisses, and a syntectonic syenite-gneiss body (Wolfshof syenite-gneiss) are found.

There is no argument from geochemistry that the granulites are residual rocks which lost a granitic melt during an anatectic event (VELLMER, 1992) although some mafic charnockitic layers do occur within the granulites, but their volume is only a few percent. According to CARSWELL (1991) the protolith of the pyroxene-free acid granulites was an acid igneous rock close to the wet granite minimum. The more basic, pyroxene-bearing varieties are probably derived from magmatic differentiates along the calc-alkaline igneous trend (PETRAKAKIS, 1997). But due to the pervasive overprinted nature of these rocks all the considerations about the nature of the precursor rocks are still rather speculative. Even alternations of sedimentary rocks, composed mainly of arkosic series, have been taken into account. The latter interpretation was influenced by the banded character of many occurrences, which now is clearly recognised as a tectonic feature. Metamorphic conditions for the major mineral assemblages are estimated to be around 760–780°C and 10–11 kb (SCHARBERT & KURAT, 1974; PETRAKAKIS & JAWECKI, 1995; PETRAKAKIS, 1997). Relictic high-pressure mineral assemblages with >800 °C and >13 kb are also reported for the granulites (CARSWELL & O'BRIAN, 1993; BECKER & ALTHERR, 1991; PETRAKAKIS, 1997).

2.3. South Bohemian Pluton

To the west of the Moldanubian basement series large parts of the Moldanubian Zone are occupied by the so-called South Bohemian pluton, a complex, 6000 km^2 sized batholite which was intruded into the gneisses of the Monotonous Series late-syntectonic to post-tectonic. It extends from Iglau (Czech Republic) in the north over a distance of 160 km to the Danube river near Linz in the south.

Four main groups of granitic intrusives besides some minor amounts of gabbroic and dioritic magmatites can be distinguished according to intrusion sequence, mineralogy, geochemistry, and isotope characteristics.

The widespread occurring coarse-grained to extremely coarse-grained peraluminous granitoids of the Weinsberg granite and the more easterly situated Rastenberg granodiorite, an independent intrusive body with a distinct durbachitic geochemistry that was intruded along the contact zone between the gneisses of the Monotonous Series and the Dobra gneiss, belong to the oldest group of rocks. These rocks typically exhibit K-feldspar megacrysts up to 20 cm length. ε_{Nd} and initial $^{87}Sr/^{86}Sr$-values are in the range of –4.3 to –5.6 and 0.706 to 0.709 for the Rastenberg granodiorite and –4.0 to –6.2 and 0.707 to 0.712 for the Weinsberg granite, respectively.

The second group is formed by metaluminous to slightly peraluminous fine-grained biotite granites (granites of type Mauthausen, Freistadt, and Schrems) exhibiting heterogeneous compositions and ages with ε_{Nd} and initial $^{87}Sr/^{86}Sr$-values in the range of –5.0 to –7.4 and 0.7053 to 0.7073, respectively.

The varieties of the strongly peraluminous muscovite bearing Eisgarn type granite form the third group. These rocks show the typical geochemical and isotopic characteristics of S-type granitoids. ε_{Nd} and initial $^{87}Sr/^{86}Sr$-values are in the range of –6 to –7 and 0.712 to 0.718, respectively.

The youngest group of rocks is formed by locally occurring, small sized bodies of highly fractionated leucogranites with varying degrees of mineralisations.

The south-westernmost part of the Bohemian Massif, characterised by the distinct NW–SE trending strike direction, is termed Bavarian zone. It is characterised by the occurrence of mostly migmatitic gneisses (Grobkorngneise) and nebulitic alkalifeldspar metablastites (Perlgneise), cordierite-sillimanite-garnet-gneisses and minor amounts of graphitic schists, calcsilicate rocks, and amphibolites. Several bodies of Weinsberg granite and of anatectic syntectonic granites (Schärding, Peuerbach) are also found.

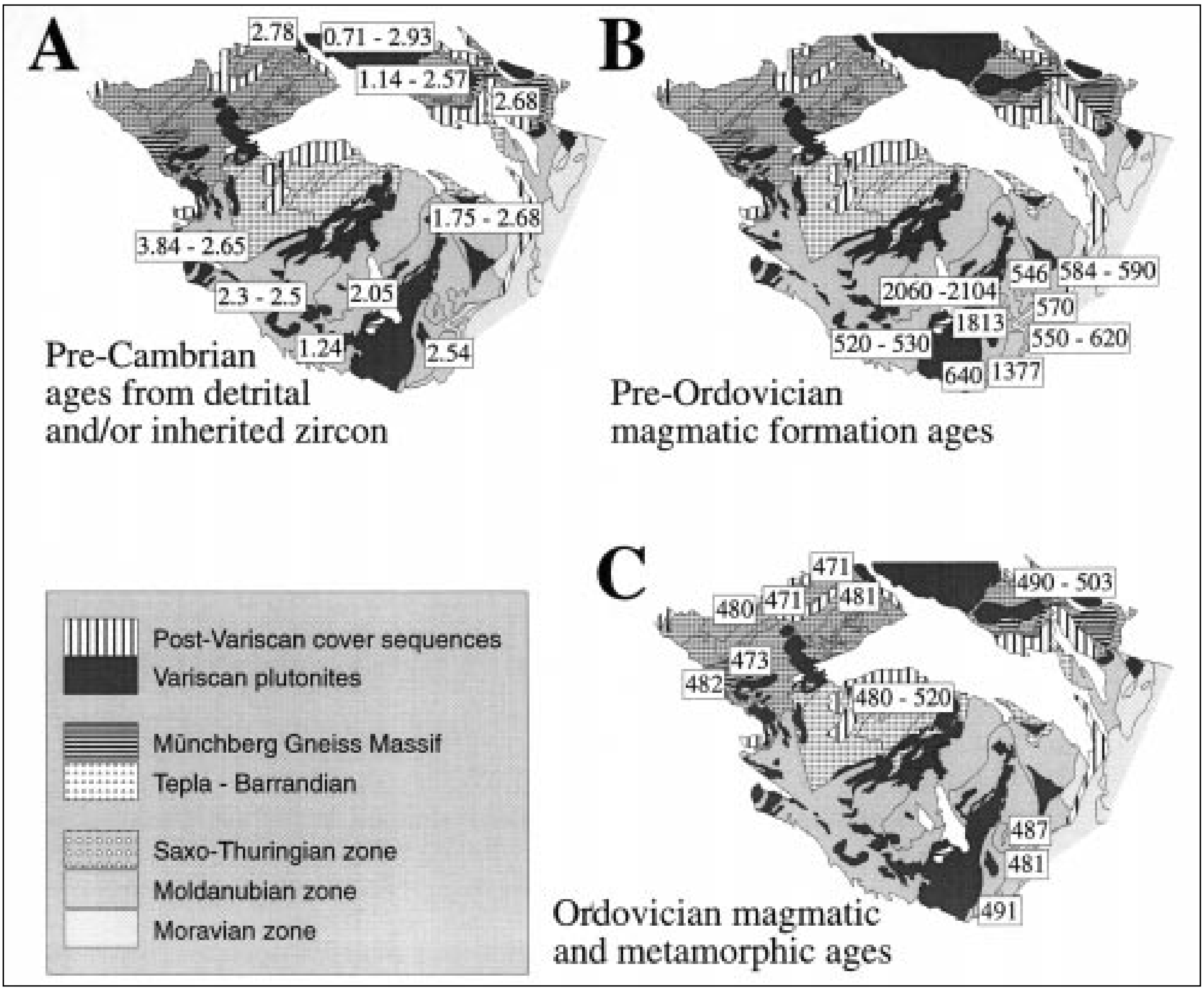
For a more complete and detailed overview and a discussion of the different possibilities of interpretations see FUCHS & MATURA (1976), GEBAUER et al. (1989), MATTE et al. (1990), ZOUBEK (1988), HÖCK (1975), FINGER et al. (1989), FRITZ (1995), FRITZ et al. (1996), FRITZ & NEUBAUER (1993), TOLLMANN (1985), THIELE (1984), FUCHS (1976, 1986), SCHARBERT & CARSWELL (1983), SCHARBERT & FUCHS (1981), FRASL & FINGER (1991), FRANKE (1989), HÖCK & STEINHAUSER (1990), FRASL (1991), LINNER (1996), KLÖTZLI & PARRISH (1996), KLÖTZLI et al. (1995), KOLLER et al. (1994), GERDES et al. (1996), HÖCK et al. (1990), PETRAKAKIS (1997).

3. Pre-Variscan Geochronology

Well constrained geochronological data from the pre-Variscan units of the SE Bohemian Massif are rather scarce although a substantial amount of data is provided. For a more complete account of the pre-Variscan ages available so far, the overview has to be extended to the total Bohemian Massif and the pre-Variscan crust of Europe. Text-Fig. 3 gives an overview of the available age data.

3.1. Information from Detrital and Inherited Zircons

The presence of Proterozoic and Archaean components in the rocks of the Bohemian Massif is mostly documented by the U/Pb systematics of detrital and/or inherited zircon (Text-Figs. 3A, 7). Archean components up



Text-Fig. 3.
Overview of pre-Variscan ages in the Bohemian Massif.
A: Pre-Cambrian ages (in Ga) from detrital and/or inherited zircons from all units of the Bohemian Massif.
B: Pre-Ordovician magmatic formation ages (in Ma) from meta-granitoids.
C: Ordovician magmatic formation and metamorphic ages (in Ma). In the SE Bohemian Massif Ordovician ages are restricted to the Gföhl and granulite unit.

to 3.84 Ga old have been found in Moldanubian paragneisses from north-eastern Bavaria using zircon ion-microprobe dating (GEBAUER et al., 1989). In addition, primary magmatic crystallisation ages for detrital zircons are reported at 3.13 Ga, 2.9 Ga, 2.76 Ga, and 2.65 Ga. Metamorphic overprints seem to have taken place around 2.59 Ga, 1.94 G, and 460 Ma. For all analysed samples Late Proterozoic ages cluster around 1 Ga to 600 Ma, providing good evidence, that the deposition of the metasedimentary precursors of the paragneisses of the Monotonous and Varied Series took place during or after the Cadomian orogenic cycle (GEBAUER et al., 1989). Ion-microprobe data on detrital zircons from Moldanubian metasediments from the Czech Republic give ages between 2.68 Ga and 1.75 Ga (KRÖNER et al., 1988). The authors interpret the ages as stemming from a significant early Proterozoic crustal-formation event between 2.0 and 2.2 Ga. From the northernmost part of the Bohemian Massif the Lusatian Granodiorite Complex in Saxonia exhibits evaporation ages of xenocrystic zircons in the range of 706±13 Ma to 2932±6 Ma (KRÖNER et al., 1994b). Detrital zircons from meta-greywackes from the same region provide ages between 1136±22 Ma and 2574±7 Ma. Inherited zircons found in the Rastenberg granodiorite of the South Bohemian Pluton are as old as 2540±47 Ma and average 2 Ga (KLÖTZLI & PARRISH, 1996). Similar results are reported by WENZEL et al. (1993) for the Meißen Massif where inherited zircon evaporation ages are as old as 2.78 Ga. U/Pb ages from inherited zircons as old as 2.68 Ga are found in orthogneisses from the Góry Sowie block, West Sudetes (KRÖNER et al., 1994a).

GRAUERT et al. (1973) report an upper intercept U/Pb age of detrital zircons from paragneisses from Bavaria of 2.3 Ga. Somewhat older ages for detrital zircons from the same rock series of 2.4–2.5 Ga are given by TEUFEL et al. (1985).

All ages substantiate some evidence for the reworking of material derived from Proterozoic and Archean crust into the magmatites of the Bohemian Massif.

3.2. Moldanubian Zone

3.2.1. Orthogneisses

The oldest preserved rocks, found so far in the Moldanubian part of the SE Bohemian Massif, are foliated amphibolite facies granitoid orthogneisses exposed in small tectonic lenses within the metasediments of the Varied group near the tectonic contact to the Monotonous group in Southern Bohemia, Czech Republic (Text-Fig. 3B). Single zircon evaporation dating and ion-microprobe dating point to intrusion ages of 2060±12 Ma to 2104±1 Ma for these rocks (WENDT et al., 1993). In the same tectono-stratigraphic position but in the southernmost part of the Moldanubian, the Dobra gneiss, an I-type granodioritic orthogneiss, exhibits an emplacement age of 1377±10 Ma (GEBAUER & FRIEDL, 1994). All these orthogneiss bodies are interpreted as representing slivers of the pre-Variscan (pre-Moldanubian) basement upon which the Varied Series was deposited.

For the muscovite granite gneiss of Weiterndorf, single zircon evaporation ages point to an Upper Proterozoic intrusion age of 640±20 Ma (KLÖTZLI, unpubl.). This orthogneiss exhibits discordant contacts to the surrounding amphibolites and paragneisses thus providing a minimum sedimentation age for at least parts of the Varied Series. A Rb/Sr whole rock errorchron (FRANK et al., 1990) yielded an age of 718±42 Ma. But, in respect of the low $^{87}Sr/^{86}Sr$ initial ratio of 0.704 and the evolved Rb/Sr geochemistry, mixing of magmas and therefore a too high apparent age cannot be ruled out.

Similar Proterozoic ages of 623±22 Ma are found in relictic zircons in the Rastenberg granodiorite further to the west (KLÖTZLI & PARRISH, 1996).

For the Gföhl gneiss an upper intercept age on zircons of 1813±160 Ma is given by VAN BREEMEN et al. (1982). This age may tentatively be interpreted as providing some information about the age of the precursor rocks of the Gföhl gneiss.

3.2.2. Monotonous Series

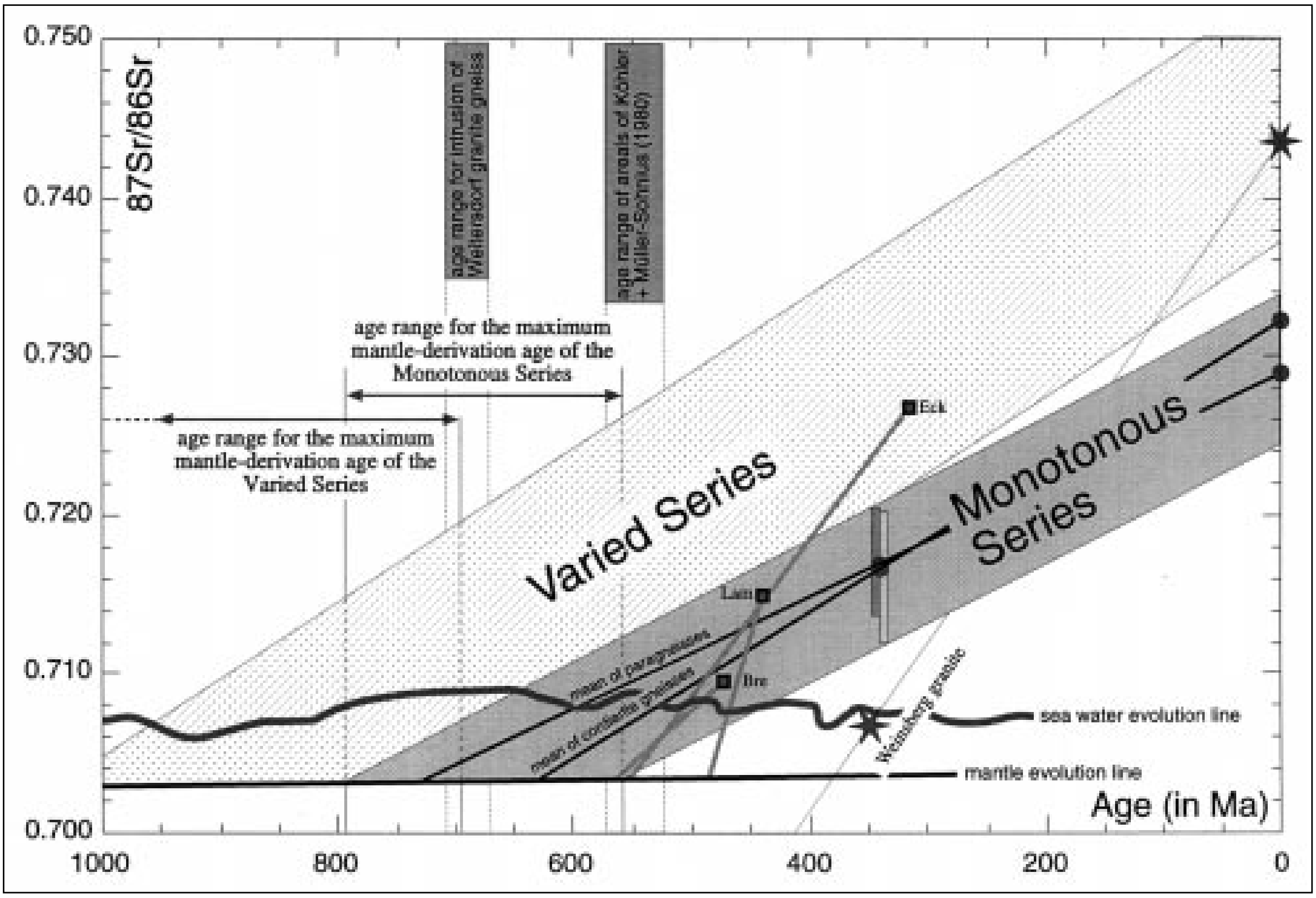
Only very limited geochronological information for the sedimentation age of the Monotonous Series is presently available. A set of representative whole rock samples are arranged along a trend line in the Sr-evolution diagram for which a maximum mantle derivation age in the uppermost Proterozoic (570–800 Ma) and possible sedimentation ages derived form the sea water Sr evolution line between 450 and 650 Ma can be calculated (Text-Fig. 4). This is in a marked contrast to the significantly higher $^{87}Sr/^{86}Sr$ ratios of metasediments analysed from the Varied Series (see below).

From "areal" Rb/Sr whole rock dating of paragneisses from the Monotonous Series of the Regensburg Wald region in Bavaria KÖHLER & MÜLLER-SOHNIUS (1980) provide some evidence for a mean sedimentation age of 544±29 Ma for these rocks, which is in complete accordance with the findings for the SE Bohemian Massif (Text-Fig. 4). But the possible interpretation of the data from KÖHLER & MÜLLER-SOHNIUS (1980) as representing an Early Cambrian metamorphic overprint cannot be completely neglected. The anatexis of the rock suite is dated at 420 Ma to 470 Ma based on normal Rb/Sr whole rock dating.

3.2.3. Varied Series

The stratigraphic ages of the sedimentary components of the Varied Series are largely unknown. In general, a Proterozoic age was suggested, yet is still speculative (Text-Fig. 4). On behalf of its lithology the series was compared to a similar rock sequence of the Islet Zone in the surroundings of the Central Bohemian pluton which in turn is compared to Ordovician to Devonian strata of the Barrandian. Accordingly, a Lower Palaeozoic age was assigned to it. The few investigated paragneiss samples seem to be higher radiogenic in respect to $^{87}Sr/^{86}Sr$ than the paragneisses and cordierite gneisses from the Monotonous Series. The possible range of mantle derivation ages is 700 to 1050 Ma. Sedimentation ages derived from the sea water Sr evolution line are in the range of 600 to 950 Ma. Although a significant overlap exists, the metasediments of the Varied Series seem to exhibit somewhat older mantle derivation and sedimentation ages than the metasediments of the Monotonous Series. But PACLTOVA (1981) found Silurian fossils in graphite bearing Moldanubian marbles around Cesky Krumlov (South Bohemia). Thus, the Varied Series could well be also of Lower Palaeozoic age, at least in parts.

The age of marine carbonates can be determined by the indirect method of comparing their $^{87}Sr/^{86}Sr$ isotopic composition with the $^{87}Sr/^{86}Sr$ values of the seawater evolution curve as far as it is reliably known. This method was applied to the marbles of the Varied Series. The investigations concentrated on samples from localities in the Lower Austrian Waldviertel, and carbonate occur-



Text-Fig. 4.
$^{87}Sr/^{86}Sr$ evolution diagram of the Monotonous and Varied Series. Shaded bands indicate the overall range in Sr isotopic evolution for both series. For the Monotonous Series the mean Sr evolution line for the paragneisses and the cordierite gneisses are shown as well.
Lines through Eck, Lam, and Bre represent mean Sr evolution lines of samples from the Bayrischer Wald (after KÖHLER & MÜLLER-SOHNIUS, 1980) indicating good coincidence with the Monotonous Series of the SE Bohemian Massiv.
Also shown are the mantle and seawater Sr evolution lines and the mean Sr evolution line of the Weinsberg granite (stars symbolise the mean isotopic composition of today and at the inferred magmatic formation age of ca. 350 Ma). Intercepts of Sr evolution bands with the mantle and seawater evolution lines give possible ages ranges for mantle and sedimentary model ages. Additionally, estimated age ranges for the intrusion of the Weitersdorf granitgneiss into the Varied Series and for the "areals" of KÖHLER & MÜLLER-SOHNIUS, (1980) are indicated as well.
For further discussion see text.

rences of minor size in Moravia between Iglau and Moravske Krumlov, as well as graphitic marbles around Česky Krumlov where PACLTOVA (1981) recovered Silurian microfossils.

In marbles with low $^{87}Sr/^{86}Sr$ ratios and high Sr concentration (>400 ppm) the original isotopic signature is preserved (FRANK et al., 1990). Parts of the investigated marbles exhibit $^{87}Sr/^{86}Sr$ isotopic compositions around 0.706 which strongly point to a Late Proterozoic (pre-Varangian glaciation) sedimentation age.

Further evidence for Late Proterozoic components in the Varied Series is the acidic Weiterndorf orthogneiss body with its presumably unconformable contacts to the surrounding amphibolites and mica schists. As already stated, single zircon $^{207}Pb/^{206}Pb$ ages indicate an intrusion age of 640±20 Ma. Thus sedimentation ages older than 620 Ma have to be assumed for at least parts of the Varied Series. Additionally, from the occurrence of amphibolites together with acidic rocks an important phase of magmatic activity during the uppermost Proterozoic in the Varied Series can be deduced. This interpretation is also supported by the occurrence of single magmatic zircons found in the Rastenberg granodiorite pointing to the incorporation of magmatic precursors of this age into the Variscan plutonites.

3.2.4. The Gföhl Gneiss-Granulite Dilemma

Both the Gföhl gneiss and the granulites form large bodies each with rather uniform but distinct lithological and geochemical characteristics, indicating that the bulk geochemistry of these rocks was produced by the formation of granitic melts of S-type affinity (VELLMER, 1992). Due to the high grade metamorphic and intense structural overprint, the detailed evolution of both rock series is difficult to assess and still a puzzling problem. At present, no unambiguous geochronological data is available (Text-Fig. 3C). Tab 1 summarises the analytical results.

The geochemical and mineralogical similarities of the two rock types became evident when the first Rb/Sr whole rock results were published. Ages of 491±24 Ma and 481±12 Ma (ARNOLD & SCHARBERT, 1973, recalculated to $\lambda_{Rb} = 1.42 \cdot 10^{-11}\ a^{-1}$) were found for large samples of Gföhl gneiss and felsic granulites, respectively. FRANK et al. (1990) report a Rb/Sr whole rock age of 487 22 Ma for large samples of Gföhl gneiss. If one accepts the reasonable assumption that these geochemically uniform rocks evolved in a closed system in respect to Rb and Sr, their present geochemical characteristics cannot have evolved from earlier than 500 Ma. Based on the hypothesis of a closed Rb/Sr-system among large sample volumes (>30 kg), these Early Palaeozoic ages are considered as

Table 1.
Comparison of available Rb/Sr age data from Gföhl gneiss and granulites of the SE Bohemian Massif.

Lithology Locality	System	Age (in Ma)	Initial $^{87}Sr/^{86}Sr$	Reference
Gföhl gneiss	whole rock	491 ± 24	0.7119 ± 0.0029	ARNOLD in SCHARBERT, 1977 [1)]
Gföhl gneiss, Krems valley	whole rock	487 ± 22	0.7095 ± 0.0030	FRANK et al., 1990
Gföhl gneiss	whole rock	482 ± 12	0.7099 ± 0.0015	FRANK et al., 1990
Gföhl gneiss, Wegscheid	thin slab	317 ± 8	0.7287 ± 0.0026	FRANK et al., 1990
Gföhl gneiss, Wegscheid	thin slab	335 ± 33	0.7262 ± 0.0031	FRANK et al., 1990
Gföhl gneiss, Hartvikovice	whole rock	570 ± 60	0.704 ± 0.003	VAN BREEMEN et al., 1982
Granulite, Dunkelsteiner Wald	whole rock	486 ± 12	0.7095 ± 0.0026	ARNOLD & SCHARBERT, 1973 [1)]
Granulite, Hochgreding	thin slab	450 ± 30	0.720 ± 0.015	ARNOLD & SCHARBERT, 1973 [1)]
Granulite St. Leonhard	thin slab	428 ± 16	0.7157 ± 0.0018	FRANK et al., 1990

[1)] Recalculated to $\lambda_{Rb} = 1.42*10^{-11}\ a^{-1}$

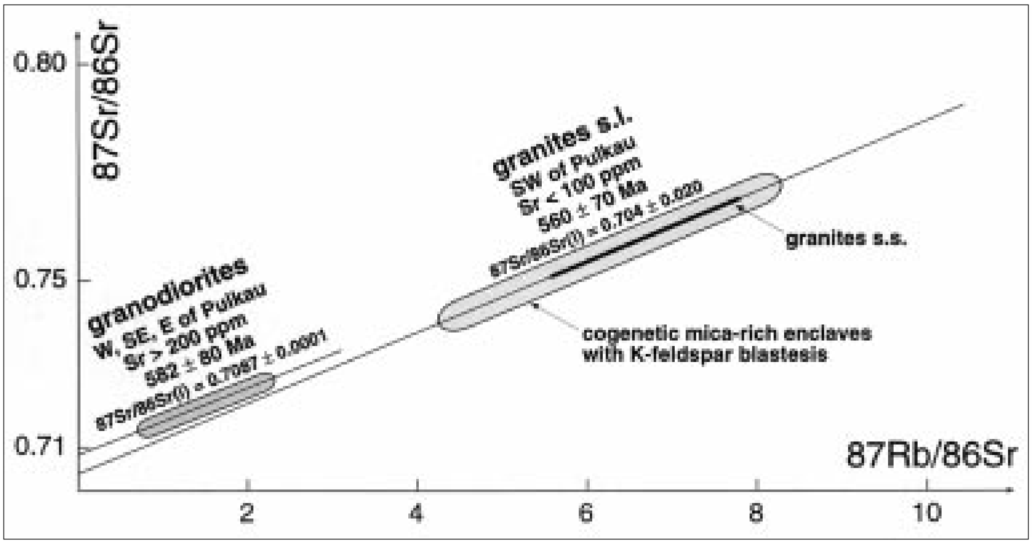
geologically meaningful, in general indicating a magmatic event during the Early Ordovician. It is striking that such ages on S-type granitic material are restricted to the rocks discussed here and no other orthogneisses of such age have been found in the Moldanubian of the SE Bohemian Massif until now. But beside the Moldanubian part of the Bohemian Massif Lower Palaeozoic ages are quite common: The occurrence of intermediate to acid volcanics in the Upper Cambrian–Lower Ordovician in the Barrandian SW of Prague support a distinct magmatic event in this region. GEHMLICH et al. (1996) report single zircon $^{207}Pb/^{206}Pb$ ages of metarhyolites of 471±13 to 481±4 from the Schwarzburg anticline and the Elbe Zone of the Saxo-Thuringian Zone. The authors interpret the ages as representing a major magmatic event during the Early Ordovician. KRÖNER et al. (1994c) reported zircon evaporation ages in the time span 490–503 Ma from the W-Sudetes. Augengneisses of the Lower Series of the Münchberg Gneiss Massif in the W show a Rb/Sr whole rock age of 482±20 Ma, associated metasediments a subsequent metamorphic overprint at 473±22 Ma (SÖLLNER et al., 1981).

Using the data of VAN BREEMEN et al. (1982) and assuming a realistic minimum initial $^{87}Sr/^{86}Sr$ ratio of 0.703 a maximum age of 595±45 Ma can be derived for the Gföhl gneiss and 540±50 Ma for the Sneznik gneiss, an equivalent of the Gföhl gneiss in the Czech Republic. This conclusion bears some discrepancy with the zircon dating by VAN BREEMEN et al. (1982), which shows a set of strong discordant analytical data (lower intercept at 341±4 Ma). These data can hardly be explained by a two stage Pb-loss at ca. 500 Ma and 340 Ma, as already the authors have pointed out. They would be more compatible with a formation of granitic rocks older than 500 Ma. This discrepancy is yet unsolved. Similar ages on granitic orthogneisses are known from the Black Forest and many other areas at the outer part of the Pangaea. Such Early Palaeozoic granite formation is not necessarily connected with a fully evolved orogenic cycle. The 500-476 Ma Afghanistan/North-Himalayan S-type granite belt is a prominent example of intense granite formation during a short period of compression without major crustal shortening (FRANK et al., 1990). Therefore it seems still possible that the rocks discussed also belong to this widespread event and were subsequently completely transformed and incorporated into the Variscan orogen.

ARNOLD & SCHARBERT (1973) investigated small samples from the banded granulites and determined a Rb/Sr whole rock age of 450±30 Ma. This age was interpreted as the time of the granulite facies metamorphism. Based on field observations and geochronological data FUCHS (1976, 1986) established a two stage model for the evolution of the SE Bohemian Massif. In his opinion good evidence for an older Caledonian nappe stacking event of the Moldanubian series, which were then subsequently thrusted onto the Moravian during the Variscan orogenic cycle, had been found. But the controversy about time and direction of the major orogenetic movements prevailed (THIELE, 1984; TOLLMANN, 1985; FUCHS, 1984). The Rb/Sr small scale information from banded granulites of 450±30 Ma (ARNOLD & SCHARBERT, 1973) and 428±16 Ma (FRANK et al., 1990) presumably only reflect a partial rejuvenation of the older large scale whole rock ages during the granulite facies to amphibolite facies tectonothermal event when only a fraction of the total Sr-inventory was equilibrated over distances of a few cm due to the low availability of fluid in this rather dry environment. It is a matter of debate whether these age values reflect any geological meaningful event or not. Interestingly, SÖLLNER et al. (1981) report an Rb/Sr whole rock age of 421±14 Ma from hornblende-free acid gneisses from the Upper Series of the Münchberg Gneiss Massif. The authors interpret the age value as reflecting the time of diagenesis or low-grade metamorphism.

3.3. Moravian Zone

The core of the Moravian zone on Austrian territory is formed by the Thaya pluton, a composite batholite of Cadomian age. Previous investigations reported zircon ages for the Brno pluton of 584±5 Ma (VAN BREEMEN et al., 1982), the eastern part of the big intrusion that is offset from the Thaya mass by strike slip movements along the Boskowiz furrow-Diendorf fault system. A Cadomian age has also been established for the Thaya granite by a 550±15 Ma Rb/Sr whole rock age by SCHARBERT & BATIK



Text-Fig. 5.
Rb/Sr evolution of Thaya batholite.
The encircled areas are defined by the sample spread of granodiorite (Iinital $^{87}Sr/^{86}Sr$ = 0.708) N of Pulkau valley and granitic types (Iinital $^{87}Sr/^{86}Sr$ = 0.704) from S of the Pulkau valley. The respective trend lines both indicate an age of approx. 600 Ma. The thick line represents the dark inclusions in the granite. The higher Sr initial ratio for the granodiorite indicates a complicated magmatic evolution for this pluton.

(1980). Further investigations on samples of distinct petrography reveal that a set of more or less parallel errorchrons can be constructed instead. Age differences of the individual rock types are obscured by the analytical and geological scatter of samples in a Sr-evolution diagram (Text-Fig. 5). Still, different initial $^{87}Sr/^{86}Sr$ isotopic ratios of approximately 0.708 and 0.704 for ages around 600 Ma can be deduced. Interestingly, the numerous dark inclusions found in the Sr poor granites are similar in composition to their host rock and lie on the same trend line (Text-Fig. 5) with the lower Sr initial. Obviously the types which cluster on the trend line above represent mixtures in regard of their intermediate Rb and Sr concentrations.

Based on $^{40}Ar/^{39}Ar$ cooling ages from micas and hornblende FRITZ et al. (1996) suggest a somewhat older intrusion age for the Thaya batholite of at least 620 Ma and of 590 Ma for the Brno pluton, respectively. Late stage pegmatites crosscutting the plutonic rocks near Brno show a cooling age of approx. 565 Ma.

The protolith age of the Weitersfeld Stengelgneis and the sedimentation ages of the paragneisses of the Pleissing nappe and Pernegg formation are presently unknown. Low Sr isotope ratios of the intercalated marbles in the Fugnitz calcsilicate schists point to late Proterozoic stratigraphic ages (SCHARBERT, unpubl.).

The magmatic formation age of the Bites gneiss is not well defined. Different methods and samples yield the following results (Text-Fig. 3B): 796±50 Ma (Rb/Sr whole rock [SCHARBERT, 1977]), 570±44 Ma (MORAUF & JÄGER, 1982), 574±60 Ma (Rb/Sr whole rock [VAN BREEMEN et al., 1982]), some of which might indicate metamorphic events. Rb/Sr muscovite ages around 630 Ma were measured on pegmatite layers within the Bites gneiss.

A pre-Cadomian origin for the Bites gneiss cannot be excluded, if the assumption holds true that this orthogneiss is equivalent to the Moldanubian Dobra gneiss (GEBAUER & FRIEDL, 1994; FRASL, 1970; MATURA, 1976). Using the data of VAN BREEMEN et al. (1982) and assuming a realistic minimum initial $^{87}Sr/^{86}Sr$ ratio of 0.703 a maximum formation age of 1030±200 Ma can be postulated for the Bites gneiss on the base of Sr isotope systematics.

VAN BREEMEN et al. (1982) report an U/Pb lower intercept age of 546±8 Ma for the granitic Keprník gneiss (Text-Fig. 3B). This age is interpreted as a magmatic formation or intrusion age.

3.4. Pre-Variscan Evolution: General Comments and Conclusions

Apparent Nd crustal residence ages for pre-Variscan rocks throughout the Variscan belt of Europe are in the range of 1.3 Ga to 3.0 Ga with a clustering of ages between 1.4 Ga and 1.7 Ga. This is somewhat contradictory to the distribution of zircon U/Pb ages where a marked age gap between 1.3 Ga and 1.7 Ga is found (GEBAUER & FRIEDL, 1994). This discrepancy might arise from the fact that the Nd model ages represent varying degrees of mixtures of Middle Proterozoic or older crust with juvenile late Proterozoic and younger crust resulting in a lowering of the model ages by some 100 Ma.

In line with the overall zircon U/Pb age data, two-stage lead evolution model ages for Moldanubian basement rocks of the Black Forest are in the range of 2.1 Ga to 2.7 Ga (KOBER & LIPPOLT, 1985).

A matter of debate is still the lack of Rb/Sr ages older than ca. 800 Ma from the Variscan crust of Europe (VIDAL et al., 1981; JÄGER, 1977; SCHARBERT, 1977). This probably reflects the immense amount of mixing of juvenile and rather primitive crust with older, at least pre-Cadomian European crust, which was recycled during the Cadomian, Caledonian (?), and Variscan orogenic events. Therefore, the older Sr isotope signatures were completely obliterated whereas these older signatures are still apparent in the Nd and Pb isotope systematics.

In conclusion: 2000 Ma–2500 Ma is a tentative age range for major formation events of basement rocks now incorporated either directly, in the form of metasediments or as single relictic zircons in the Bohemian Massif. According to GEBAUER & FRIEDL (1994) as much as 60 % of the precursor rocks of today's Variscan crust in Europe might have been generated prior to 2 Ga. Upper Proterozoic ages around 620–640 Ma point to a major magmatic event at that time. The Dobra gneiss seems to be a geochronological stranger, possibly originating from Baltica or Laurentia and not from Gondwana. The only comparable protolith age known so far might be the zircon U/Pb upper intercept age of 1422±184 Ma reported for the Moravian Keprník gneiss.

Beside the difference in the metamorphic pressure regime the Monotonous Series seems to be younger than the clastic portion of the Varied Series in Lower Austria. This is an additional proof for the tectonic emplacement of the Varied Series on top of the Monotonous Series.

Gföhler gneiss and granulites form a distinct "micro-terrane" with its own geochronological characteristics found in other places in the Bohemian Massif, characterised by Lower Palaeozoic magmatism and metamorphic overprinting. These phases are not found in the lithostratigraphic rock units below the Gföhler gneiss. Thus the amphibolite rich series between Varied Series and Gföhler gneiss (Raabs series or Raabs-Letovice complex [FRITZ & NEUBAUER, 1993; FRITZ et al., 1996; FINGER & VON QUADT, 1995]) may possibly represent a major Palaeozoic litho-tectonic boundary and suture between a possible Gföhler terrane and the Varied Series although no unambiguous age data for the ophiolitic (?) rock suite has been presented yet.

4. Variscan Metamorphism

For a detailed discussion of the P-T metamorphic evolution of the SE Bohemian Massif and some geochronological implications see PETRAKAKIS (1997).

The exact timing of the Variscan metamorphism in the SE Bohemian Massif, especially the question when the peak(s) of metamorphic temperatures were reached, is still an unsolved problem. Most of the work has focused on the genesis of the granulites and only little attention was paid to the time of metamorphism in the other lithological units.

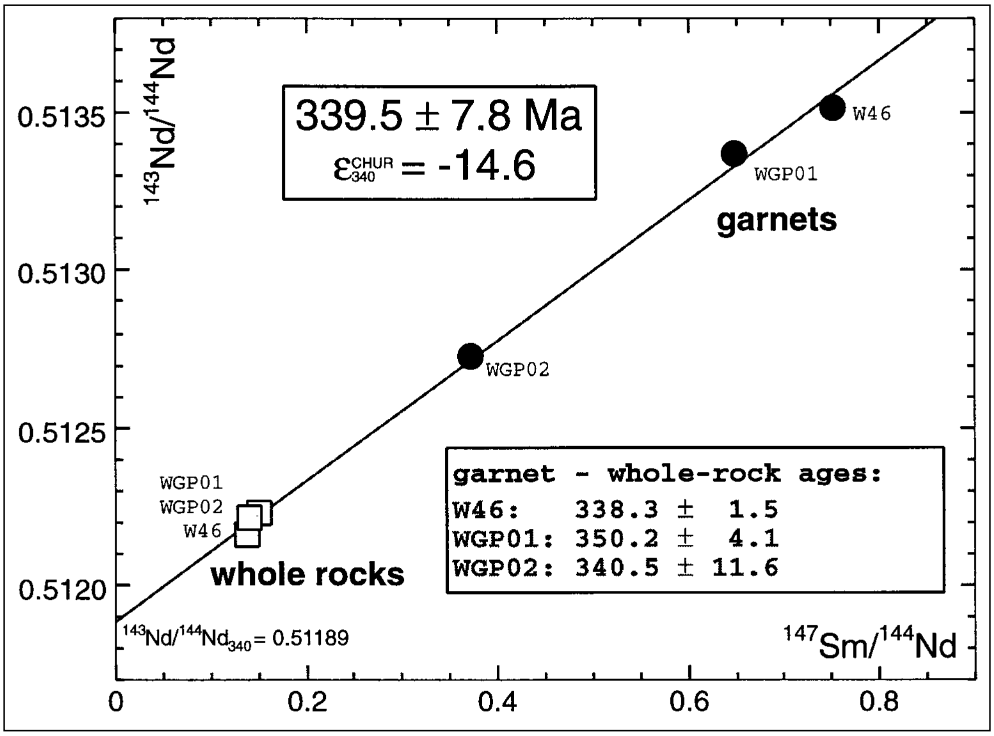
Garnet-whole rock Sm/Nd ages from granulites and from eclogitic inclusions from the St. Leonhard granulite body yielded consistent "isochron" ages of 338–350 Ma (THÖNI, unpubl.) with a mean age of 340±9 Ma (Text-Fig. 6).

U/Pb zircon lower intercept ages of 345±5 Ma for granulites from Lisov, Blansky les, and Mohelno are reported by VAN BREEMEN et al. (1982). SCHENK & TODT (1983) have given U/Pb monazite ages of 340±1 Ma for granulites from the Dunkelsteiner Wald. Strongly discordant $^{207}Pb/^{206}Pb$ zircon data for the same samples are in the range of 424–402 Ma providing some evidence for complex lead inheritance in these rocks (compare discussion in Chapter Gföhl gneiss and granulites). CARSWELL & O'BRIAN (1993) report Sm/Nd ages clustering around 340 Ma for granulites from the Dunkelsteiner Wald although ages as old as 370 Ma are given. Metamorphic zircon growth at 348±16 Ma is documented in two samples of dark granulites from Blansky les (WENDT et al., 1992). A corresponding Sm/Nd mineral-whole rock age of 340±20 Ma is also reported for these rocks (WENDT et al., 1992).

Reliable ages for the time of metamorphism in other tectonic units throughout the SE Bohemian Massif is rather scarce. The most complete work is from VAN BREEMEN et al. (1982). The authors report a lower intercept U/Pb age on zircon of 341±4 Ma for the Gföhl gneiss. Corresponding concordant U/Pb monazite ages are 337±3 Ma. These ages are interpreted as representing the down-temperature stage in amphibolite facies metamorphism. Similar ages are reported for the Vir gneiss (U/Pb monazite, 338±3 Ma) by the same authors.

All highly discordant data points of VAN BREEMEN et al. (1982) point to a lower intercept range of 370 Ma–340 Ma. FRIEDL et al. (1993) report concordant U/Pb monazite ages of 340±4 Ma for samples of Gföhl gneiss and gneisses from the Varied Series and 335±2 Ma for gneisses of the Monotonous Series. For the Wolfshof syenite gneiss the same authors report a zircon U/Pb age of 338±6 Ma. This age is interpreted as reflecting rock formation during high-T metamorphism.

In a dark variety of Svetlik gneiss a concordant titanite U/Pb age of 355 2 Ma is reported by WENDT et al. (1993). This titanite is clearly of metamorphic origin, the age thus timing some stage of the amphibolite facies metamorphism. 367 Ma and 347 Ma on zircon, respectively, are reported for high-grade metasediments of the Varied and Monotonous Series (KRÖNER et al., 1988). FRIEDL et al. (1993) give a zircon U/Pb age of 358 6 Ma for an amphibolite with within-plate-basalt affinity from the Varied Series. This age is interpreted as protolith formation reflecting ongoing extensional tectonics within the Varied Series, but this interpretation is definitely not in line with other well constrained geochronological and petrological data (see above and KRÖNER et al., 1988; WENDT et al., 1993; PETRAKAKIS, 1997). A more probable explanation of the various erratic mineral ages found lying between c. 370 Ma and c. 340 Ma might be that these could be attributed to different stages of a long lasting decompression after an earlier high-pressure event accompanying crustal stacking during the first Variscan compressional phases.



Text-Fig. 6.
Sm/Nd reference line of granulites from the SE Bohemian Massif of Austria.
Inset shows individual mineral – whole rock ages (data from THÖNI, unpublished).

The first zircon ages (VAN BREEMEN et al., 1982) and especially garnet Sm/Nd ages (CARSWELL & O'BRIAN, 1993) were interpreted as mineral formation ages. More recent age data suggest that at petrologically derived temperatures around 700°C and higher the U/Pb and Sm/Nd systems are completely or partially open. Thus, especially the Sm/Nd garnet ages should preferably be interpreted as cooling ages with a blocking temperature around 650°C–700 °C.

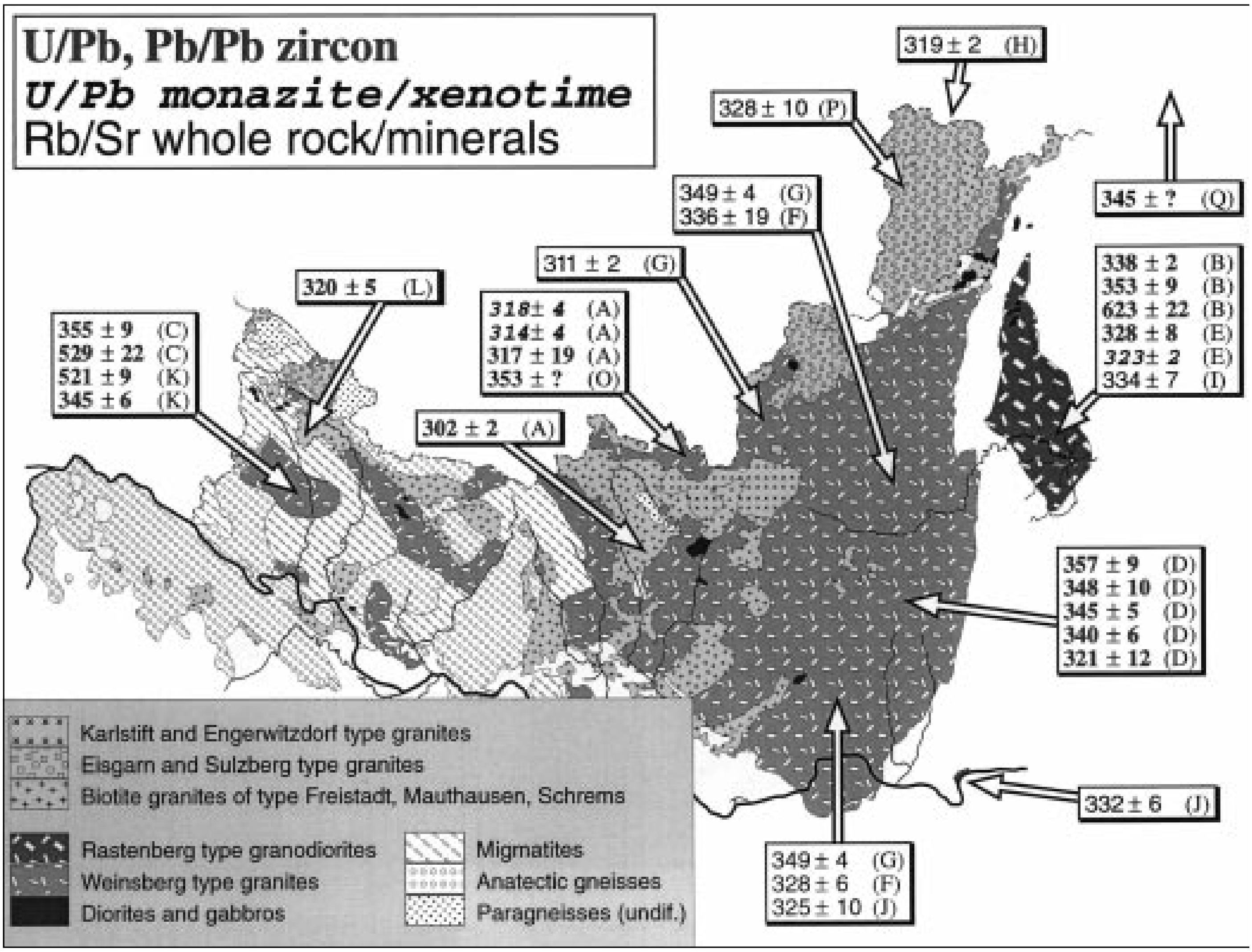
In re-interpreting all the available age data, the conclusion is that the Sm/Nd ages clustering around 345–340 Ma for the granulites and the zircon and monazite U/Pb ages from different gneisses represent the post peak-metamorphic cooling after the main Variscan metamorphic overprint. The onset of magmatic activity at 350–340 Ma gives further constraints for the timing of metamorphism and the subsequent cooling. Monazite U/Pb ages tend to be somewhat lower than zircon ages, consistent with the lower blocking temperature of approx. 700 °C for monazite.

Interestingly, no metamorphic cooling or formation ages older than ca. 360 Ma (except 370 Ma for a granulite from the Dunkelsteiner Wald [CARSWELL & O'BRIAN, 1993]) are found in the SE Bohemian Massif. This is in some contrast to the evolution of the W and NW part of the Bohemian Massif where a part of the 340 Ma granulite facies metamorphism of the Saxonian granulites (VON QUADT, 1993) an earlier high-pressure metamorphic event around 380 Ma is clearly documented in Saxony and the Münchberg massif (i.e. VON QUADT, 1993; MATTE et al., 1990).

5. Variscan Plutonism

The age discussion follows the intrusion sequence as found by field evidence. Text-Fig. 7 shows a compilation of the data available.

In the rocks of the Rastenberg granodiorite the wide - spread existence of late Proterozoic zircons with ages clustering around 623±22 Ma was demonstrated by KLÖTZLI (1993) and KLÖTZLI & PARRISH (1994a, 1994b, 1996). According to zircon typology studies, the growth of these zircons is thought to have taken place during a magmatic event. As up to 50 % of the investigated zircons show Cadomian ages, it is postulated that the amount of reworked Cadomian basement in the Rastenberg granodiorite is quite substantial. Erratic $^{207}Pb/^{206}Pb$ ages of inherited zircon crystals are as old as 2.54 Ga and average



Text-Fig. 7.
U/Pb and Rb/Sr age distribution of the South Bohemian Pluton.
Data from A: FRIEDL et al. (1992); B: KLÖTZLI & PARRISH (1996); C: KLÖTZLI et al. (1995); D: KLÖTZLI (1993); E: FRIEDL et al. (1993); F: FINGER & VON QUADT (1992) G: SCHARBERT (1987); H: BREITER & SCHARBERT (1995); J: FRANK et al. (1990); I: VELLMER (1992); K: KLÖTZLI et al. (2000); L: KLÖTZLI, unpubl.; O: FINGER, unpubl. P: SCHARBERT, unpubl.; Q: JANOUSEK et al. (1997).

2 Ga (KLÖTZLI & PARRISH, 1996). Individual dating of zircons in large K-feldspar megacryst and in the finer grained matrix has shown a marked age difference between the two occurrences: In the K-feldspars ages around 353±9 Ma, the above mentioned 623±22 Ma and single, older ages are found. In the matrix all the mentioned ages are found, but additionally, an age group of 338±2 Ma is present. This age group is formed primarily by zircons with a very distinct typology (KLÖTZLI, 1993; KLÖTZLI & PARRISH, 1996). The age of 338±2 Ma is thought to represent the time of intrusion of the granodiorite magma. The older ages represent some earlier magmatic and/or metamorphic events. In following this argumentation, at least parts of the K-feldspar megacrysts were not formed during the 338 Ma event but distinctly earlier, as has been postulated for the K-feldspar megacrysts in the Sarleinsbach variety of the Weinsberg Granite (KOLLER, 1994a, 1994b; KLÖTZLI et al., 1995, 2000).

In monzonitic to dioritic schollen, partly also with large K-feldspar crystals, remnants of relictic clinopyroxene are found. Biotite inclusions within the clinopyroxenes provide some evidence, that the schollen are former prograde, high-grade metamorphic rock. This leads to the assumption, that at least some large K-feldspar crystals or parts of the crystals and/or the above mentioned schollen possibly form a relictic mineral phase or assemblage within the normal Rastenberg granodiorite (KLÖTZLI & PARRISH, 1996; KLÖTZLI et al., 1995). A within error equal zircon age of 328±10 Ma and a monazite age of 323±2 Ma is given from the eastern part of the Rastenberg granodiorite by FRIEDL et al. (1993). VELLMER (1992) reports a Rb/Sr reference line of 334±7 for the main body of the Rastenberg intrusion. An age of 345 Ma, interpreted as the time of intrusion of post-tetonic ultra-potassic rocks, a suite of durbachites comparable to the Rastenberg granodiorite (including the Trebic massif), is given by JANOUSEK et al. (1997).

For the Weinsberg granite a number of geochronological data has been published some of which is quite contradictionary: Dark coloured varieties of the Weinsberg granite are found in the vicinity of Sarleinsbach (Mühlviertel, Austria) over an area of 10–15 km^2. These rocks show close structural relationships to the normal type of Weinsberg Granite with a more distinct quartz-monzonitic composition. Overall, an evolutionary trend to the normal Weinsberg Granite can be observed. In these rocks two different mineral assemblages, which are not in mutual equilibrium, are found. The older paragenesis is formed by a relictic charnockitic assemblage. Single zircon evaporation ages of 529±22 Ma and conventional U/Pb ages of 521±9 Ma provide good evidence, that this charnockitic relict assemblage is of Cadomian age (KOLLER et al., 1993, 1994; KOLLER 1994b; KLÖTZLI et al., 1995, 2000). The younger mineral assemblage crystallised from a granitic melt. Zircons belonging solely to the granitic assemblage are dated at 355±8 Ma, thus defining the time of magma formation of these varieties of Weinsberg granite rocks.

In the eastern part of the Weinsberg granite single zircon ages vary unsystematically between 357±9 Ma and 321±12 Ma (KLÖTZLI, 1993). In the NE of Freistadt (Plochwald) U/Pb zircon ages from late stage, acidic varieties of the Weinsberg granite are between 353 Ma (FINGER, pers comm.) and 317±19 Ma (FRIEDL et al., 1992). Monazite and xenotime U/Pb ages from the same locality are 318±4 Ma and 314±4 Ma, respectively (FRIEDL et al., 1992).

The youngest magmatic age reported so far for the South Bohemian Pluton is an U/Pb monazite age of 302±2 Ma for the Freistadt granodiorite (FRIEDL et al., 1992).

Rb/Sr whole rocks analyses of uncontaminated Weinsberg granite define a reference line of 349±4 Ma (SCHARBERT, 1987), interpreted as time of intrusion for the major amount of the Weinsberg granite magma. On the other hand the frequent occurrence of paragneiss schollen, the distinctly lower Rb and higher content of common and radiogenic Sr were arguments for SCHARBERT (1987) to interpret many other samples as being contaminated. On the basis of zircon typological studies FINGER & VON QUADT (1992) reinterpreted the existing Rb/Sr data. In a segment N of a line between Freistadt – Königswiesen and SE of Weitra – Zwettl the authors recognised a single zircon population formed in a palingenic melt that had evolved from an anatectic source. Reassessing the whole rock Sr evolution of this northern part of the Weinberg Granite and including K-feldspars in the regression an age value of 328±6 Ma can be deduced. Using the samples from the NE and SW an age of 336±19 Ma is obtained. But care should be taken in calculating a Rb/Sr isochron with K-feldspar. Due to its specific low closure temperature its age might possibly differ from whole rock ages. SCHARBERT (1987) therefore interpreted two sets of identical K-feldspar Rb/Sr ages from both age "provinces" as cooling ages around 324 Ma. The main body of Weinsberg Granite must be older than the 328 Ma Eisgarn type granite as can be concluded from field evidence. Yet evident is that the whole Weinsberg Granite forms a very complicated composite batholite with a prolonged magmatic history. In the socalled Nebelstein intrusion autometamorphic alteration followed immediately after the crystallisation as can be deduced from identical Rb/Sr whole rock and $^{40}Ar/^{39}Ar$ muscovite ages of 311 Ma. This indicates very fast cooling, even quenching and can occur only if the country rocks, i.e. Weinsberg type granite, had cooled already to temperatures around 450 °C as can be concluded from its apparent muscovites $^{40}Ar/^{39}Ar$ cooling ages in the range of 310 Ma more to the south. A similar situation must have existed during the intrusion of the Homolka granite body further to the north. Here all ages are several million years older as is exemplified by Rb/Sr whole rock ages of 319±6 Ma and muscovites Ar/Ar ages of 317 and 315 Ma, respectively (BREITER & SCHARBERT, 1995) while micas from the Eisgarn granite cluster around 320 to 325 Ma. South, more or less along the axis of the main pluton the areas of similar cooling temperature realms become younger and younger. This demonstrates the prolongated cooling of large plutons. A number of related but younger granitoids point to the fact that the heat volume was high enough to produce additional melt fractions accompanied by considerably younger intrusions. Examples are the vulcano-tectonic zone in the central Moldanubian pluton, the Hirschenschlag red biotite granite at the Austrian/Czech border, the Schrems intrusion (KOLLER et al., 1993). This intrusion was hot enough to remelt Weinsberg and Eisgarn type granites which recrystallised as fine grained types beside the Schrems granite proper. Other examples are Nebelstein and Plochwald, and many other small stocks of variable texture, grain size, and degree of fractionation which penetrate the Weinsberg pluton and maintain its heat volume over a long time of several million years.

From previous investigations (SCHARBERT, 1992) it is known that re-melting of Weinsberg type granite and mixing with other melts has produced a variety of younger fine grained granites of remarkable size. An example is the Mauthausen type granite for instance which developed as a homogenous granite from melt mixing and gave a perfect yet erroneous isochron age much older than its country rocks. All stages of mixing between Weinsberg type inclusions and newly developed fine grained granites can be observed in areas of less perfect melt homogenisation.

Using all the available data the following tentative geochronological evolution for the South Bohemian Pluton can be given. Magma generation by anatexis of pre-existing rocks of partly Cadomian age (relictic charnockites near Sarleinsbach, 529 Ma and relicts in the Rastenberg granodiorite, 623 Ma) began at 350 Ma–360 Ma. This event is found in zircons throughout the South Bohemian Pluton (Sarleinsbach, Plochwald, Weinsberg, Rastenberg [KLÖTZLI et al., 1995]). The subsequent intrusion of individual granitoid plutons is documented by the zircon ages of 338 Ma and 345 Ma, and the Rb/Sr age 334 Ma for the durbachitic rocks along the eastern margin of the South Bohemian Pluton (Rastenberg granodiorite, Trebic massif [KLÖTZLI & PARRISH, 1996; VELLMER, 1992]). The probably somewhat lower zircon age of 328 Ma reported by FRIEDL et al. (1993) together with the monazite U/Pb age of 323 Ma may be attributed to a slight post-intrusive rejuvenation of the U/Pb system due to the reheating during the intrusion of a fine grained granite along the eastern boundary of the Rastenberg granodiorite. For the Weinsberg granite no such definitive intrusion age can be given. U/Pb and $^{207}Pb/^{206}Pb$ ages which can be attributed to the intrusion event are in the range of 345 Ma to 321 Ma and vary unsystematically (KLÖTZLI, 1993) demonstrating the complex magmatic evolution and intrusive history of this large plutonic complex. The end of this intrusion cycle is clearly defined by the intrusion of the Plochwald type late stage acidic rocks with ages around 325±10 Ma (Rb/Sr whole rock [FRANK et al., 1990]) to 314±4 Ma (U/Pb monazite [FRIEDL et al., 1992]). The zircon U/Pb age of 317±19 Ma found in these rocks has been interpreted as an intrusion age of the Weinsberg granite (FRIEDL et al., 1992). As the granites of the Plochwald type definitely belong to a younger rocks suite within the Weinsberg granite, we conclude that this interpretation is not in line with the geological setting of the rocks. But the age of 317±19 Ma fits perfectly well into the age range for these late stage rocks defined by the Rb/Sr isochron age of 325 ±10 Ma (FRANK et al., 1990).

In concordance with the field relations the ages given for the Eisgarn (328 Ma) and the Homolka granites (319 Ma [BREITER & SCHARBERT, 1995]) are interpreted as the time of intrusion of these rocks. The late stage greisen formation in late stage intrusives near the roof of the Weinsberg granite in the area of the Nebelstein took place around 311 Ma (SCHARBERT, 1987; GÖD & KOLLER, 1989).

The Rb/Sr reference line of 349±4 Ma reported by SCHARBERT (1987) for the Weinsberg granite has led to some debate about the interpretation of Rb/Sr isotope systematics in such complex intrusive rock suites. In the view of the now available U/Pb age information, a reinterpretation of the data satisfying all former interpretations (SCHARBERT, 1987; FINGER & VON QUADT, 1992; FRIEDL et al., 1992) seems possible: The zircon ages of 350 to 360 Ma are thought to reflect the onset of melt generation in the deeper crust which eventually led to the intrusion of the granitoid magmas. The time between the first melt generation and the actual intrusion events can be considerably long because the first minor amount of melt generated cannot escape its host rock. Thus it seems reasonable to assume that the Rb/Sr reference line of 349 Ma reflects some stage in this long-lasting process of melt generation. The reference lines calculated by FINGER & VON QUADT (1992) then represent some later stage in this magmatic maturation process where already a certain regional individualisation of magmatic activity has taken place. In this sense one might think of the Rb/Sr isotope system of the Weinsberg granite as reflecting something like the "areal" approach to Rb/Sr systematics used by KÖHLER & MÜLLER-SOHNIUS (1980) for paragneisses of the Moldanubian. This then would imply, that the actual intrusion events in the large Weinsberg granite composite pluton cannot be detected using the Rb/Sr system.

The amount of thermal reworking (melting) of crust is remarkable. It is a question whether the big masses of granites are the sole source of heat necessary to maintain the long lasting and repeated melt formation one can observe in the southern part of the South Bohemian pluton, especially in the Weinsberg granite domain or whether a deep seated heat plume added energy for these processes.

Dikes of leucogranitic composition crosscutting the rocks of Monotonous Series, Varied Series, and Gföhl gneiss-granulites exhibit an Rb/Sr whole rock age of 332±6 Ma (FRANK et al., 1990), this age is another important time marker for the tectonic evolution of the Moldanubian. Post-collisional, wide spread lamprophyric dikes with mostly kersantitic composition exhibit cooling ages $<$316 Ma (RICHTER et al., 1994).

6. Late to Post-Variscan Cooling

The medium to low temperature cooling history, deduced from Rb/Sr and especially $^{40}Ar/^{39}Ar$ data from micas and amphiboles from the eastern Moldanubian region is generally closely linked with the high temperature cooling, following the thermal peak of metamorphism around 370-350 Ma.

Oldest muscovite ages of 341±2 Ma were found from a two-mica granite from the coarse clastic Kulm beds of Visean age (352 Ma–333 Ma) near Brno. A Gföhl gneiss boulder yielded an biotite $^{40}Ar/^{39}Ar$ age of 336±2 Ma. These ages reflect the high level cooling of Moldanubian rocks immediately before erosion. These comparably old cooling ages are approximately contemporaneous with intrusion ages given for the most easterly situated plutons (Rastenberg, Trebic) and only very little younger than the U/Pb and Sm/Nd ages post peak-metamorphic cooling ages of the Gföhl gneiss and the granulites (345–340 Ma). This small time span between metamorphism and erosion is only possible if one assumes very high cooling rates for at least parts of the Moldanubian basement series during the Visean. With a magmatic formation of the two-mica granite at $\sim$350 Ma at $\sim$700 °C and a minimum depositional age of 333 Ma, overall cooling rates of $>$25 °C/Ma result.

A detailed discussion of the post-Variscan cooling history of the investigated region can be found in FRANK & SCHARBERT (2000).

7. Evolutionary Model and Conclusions

The south-eastern part of the Bohemian Massif is built up from a deeply eroded, high grade metamorphic and ductile level of the European Variscan crust. As already stated in the introduction, the structural evolution or the tectonic framework of the Moldanubian and Moravian zones are still a matter of gross debate. FRANKE (1989) and MATTE et al. (1990) present a model involving the stacking of 3 different crustal segments during the Variscan collision: Moravian Zone, Monotonous and Varied Series, and Gföhl and granulite terrane. FRITZ & NEUBAUER (1993) presented a model where an Upper Proterozoic continental block comprising the Moravian Zone, the Monotonous Series, and Varied Series collided with the Lower Palaeozoic Gföhl gneiss and granulite terrane. A similar model was presented by FINGER & VON QUADT (1995). In these models, the ophiolite-like rock assemblages of the Raabs-Letovice complex are interpreted as remnants of a Lower Palaeozoic ocean situated between two microcontinents which was closed during the Variscan orogenesis.

To completely understand the tectonic and lithologic evolution of this region, the information from structural geology besides the geochronological information is very important. But since the evolution of the discernible structures are linked to late metamorphic stages, one is often not in the position to unravel the complete set of successive tectonic phases from these data.

One of the key points in the understanding the area seems to be the regional syntaxial nature of the rock units indicated by the regional bending of all orogenic zones in the Bohemian Massif. The necessary rigid indenter probably was the Brunovistulian spur of the East European foreland. Unfortunately the continuation of the orogenetic zones of the Variscan orogen to the South is obscured by the very intense tectonic-metamorphic reworking of the crust within the Alpine-Carpathian-Dinarid mountain belt. FINGER et al. (1996) report preliminary monazite age data from drill cores of basement rocks from the Molasse zone of NE Austria. All reported ages are in a Variscan age range of 355 to 292 Ma proposing that the Cadomian Brunovistulian does not find a continuous continuation to the south of the Thaya cupola. Instead the Variscan Moldanubian zone or the Variscan rejuvenated part of the Brunovistulian seems to continue beneath the E and W Molasse zones.

As a corresponding feature to the large scale syntaxial structure the Monotonous Series in the centre of the Moldanubian realm forms a cupola like structure, plunging below the older Varied Series und other tectonic units to the N, NW and E.

According to the age data already discussed, the base of the Dobra gneiss or of the Varied Series, where the Dobra gneiss is missing, has to be considered as a major tectonic thrust plane, where Proterozoic rock units, locally associated with mid-Proterozoic basement slivers, overly the Monotonous Series. The latter can be considered as a late Proterozoic (to Cambrian?) clastic sediment pile, possibly an active continental margin (LINNER, 1996), probably with a first metamorphic overprint in the Early Palaeozoic. Although reasonable arguments for a late Proterozoic age of the marble rich Varied Series in the Weitental area of Lower Austria exist, other marble occurrences in the same area and from Cesky Krumlov are considered to be of Silurian age. Based on the Sr-isotopic evolution, the Varied Series could represent a crustal sequence consolidated during the Cadomian orogenic cycle, whereas the Monotonous Series could represent the erosional products of this Cadomian continental crust, respectively.

The Gföhl and granulite nappes are derived from a completely different crustal section, characterised by the Lower Palaeozoic magmatism and metamorphic overprinting, otherwise not found in the lower nappes of the SE Bohemian Massif. This "terrane" might have been separated from the underlying Varied Series by an oceanic realm now found as relicts of ophiolitic (?) rocks in the Raabs-Letovice complex. No unambiguous age data is provided for the internal evolution of the Gföhl and granulite "terrane".

Each Variscan lithotectonic unit is characterised by its specific pressure regime. Low pressure amphibolite facies is typical for the Monotonous Series, whereas for the overlying Varied Series and the Gföhl unit intermediate to high pressure conditions were attained (PETRAKAKIS, 1997). Although the details of this gradation are unknown, it is obvious from all available age data that the rock forming metamorphic mineral assemblages must be attributed to the Variscan orogenic cycle. LINNER (1996) has provided good evidence that the low pressure metamorphism of the Monotonous Series was not caused by the intrusion of the Weinsberg composite batholite, as this mineral assembladge clearly is overprinted by the intrusion of the plutonites. Equilibrium mineral parageneses due to migmatisation in the rocks of the Monotonous Series pre-date the movements along the thrust zone between the Monotonous Series and the overlying rock suites.

The exact time of superposition of the Gföhl and granulite nappe onto the Varied Series and thus the closing of the hypothetical Lower Palaeozoic ocean is not known, but the present pile of tectono-stratigraphic succession was completed at the time of intrusion of the durbachitic rocks of the Trebic and Rastenberg plutons around 345 to 338 Ma (KLÖTZLI & PARRISH, 1996). Based on geochronological data PETRAKAKIS (1997) favours a model evolution where P_{max} due to crustal stacking was attained at or before 370 Ma. In his model, all ages around 340 Ma found in the granulites of the Moldanubian Zone must be attributed to post-peak-metamorphic reequilibration. But, it is still an unresolved problem whether the Variscan nappe stacking took place according to a 3 terrane model (i.e. FRANKE, 1989 or MATTE et al., 1990) or according to a 2 terrane model (FRITZ & NEUBAUER, 1993).

The polarity of thrusting, especially of the Gföhl nappe, was subject of a long controversy. Unilateral medium to very long distance transports from the NW were proposed by THIELE (1984), TOLLMANN (1982) and MATTE et al. (1990). The outer and tectonically higher portions of the Moldanubian zone are interpreted as a relictic collision and nappe stacking zone where the polarity of movements was initially directed southwards. This tectonic setting was (probably almost immediately) subsequently overprinted and transformed during the long lasting NNE directed transpressional regime, which developed between the rigid Brunovistulian spur of the East European platform and the ductile evolving Variscan metamorphic belt. During this regime not only the outer parts of the Variscan orogen have been squeezed off but also the innermost part of the Moldanubian became deformed and the cupola structure plunging NE was formed. On the contrary, the results of structural observations of SCHULMANN et al. (1994) of the pre-transpressional – transtensional HT-structures in Moldanubian rocks along the Thaya section show an opposed sense of transport to the proposed model. But the question remains if the structures described by SCHULMANN et al. (1994) really do belong to the first emplacement of the higher units.

Closely connected to this problem is the question whether the Lower Palaeozoic mafic remnants have been fully overprinted by the high grade Variscan metamorphism or not.

Despite all the uncertainty these results opens a new field of speculation. Usually the oceanic environment of the Rhenohercynian oceanic basin which was formed in Early Devonian time is thought to terminate N of the Moldanubian realm and therefore the Ligerian–Moldanubian terrane was not separated by oceanic crust from the East Silesian Massif. The existence of oceanic crust in the eastern part of the Moldanubian would open the possibility of an oceanic pathway to the south. It may not be necessarily the exact continuation of the Rhenohercynian basin, but the linkage of the Moldanubian with the East European platform would be weakened by such a palaeogeography, which in turn should influence the tectonic evolution of the orogen considerably.

The igneous rocks of the South Bohemian pluton exhibit a complex evolution. In general it starts with the remelting of lower crustal igneous (Sarleinsbach) or possible metamorphic rocks (Rastenberg) of presumably Cadomian age. Incorporated into this complex are older small gabbroic to dioritic intrusions. All the gabbros show a dominant sub-continental mantle component (VELLMER, 1992; KOLLER & NIEDERMAYER, 1981). The remelting of a Cadomian crust and the production of mantle derived basaltic melts, are linked with high heat flow and thus are more likely related to a crustal thinning process accompanied by magmatic underplating than to a collisional stage (BÜTTNER & KRUHL, 1997). Subsequently the intrusion of small amounts of I-type granites, forming dikes and locally stock like bodies, and huge amounts of S-type granites followed. The latter clearly are related to a syn-collisional stage of the Variscan orogen, formed by a continental collision. In contrast the younger and mineralised granites seem to be related to a more post-collisional orogenic stage (KOLLER et al., 1993, 1994; BREITER & FRYDA, 1994). Also syn- to more likely post-collisional are the widely spread lamprophyric dikes with mostly kersantitic composition and ages $<$316 Ma. There are arguments for an origin from a K-rich sub-continental mantle source for these dikes.

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