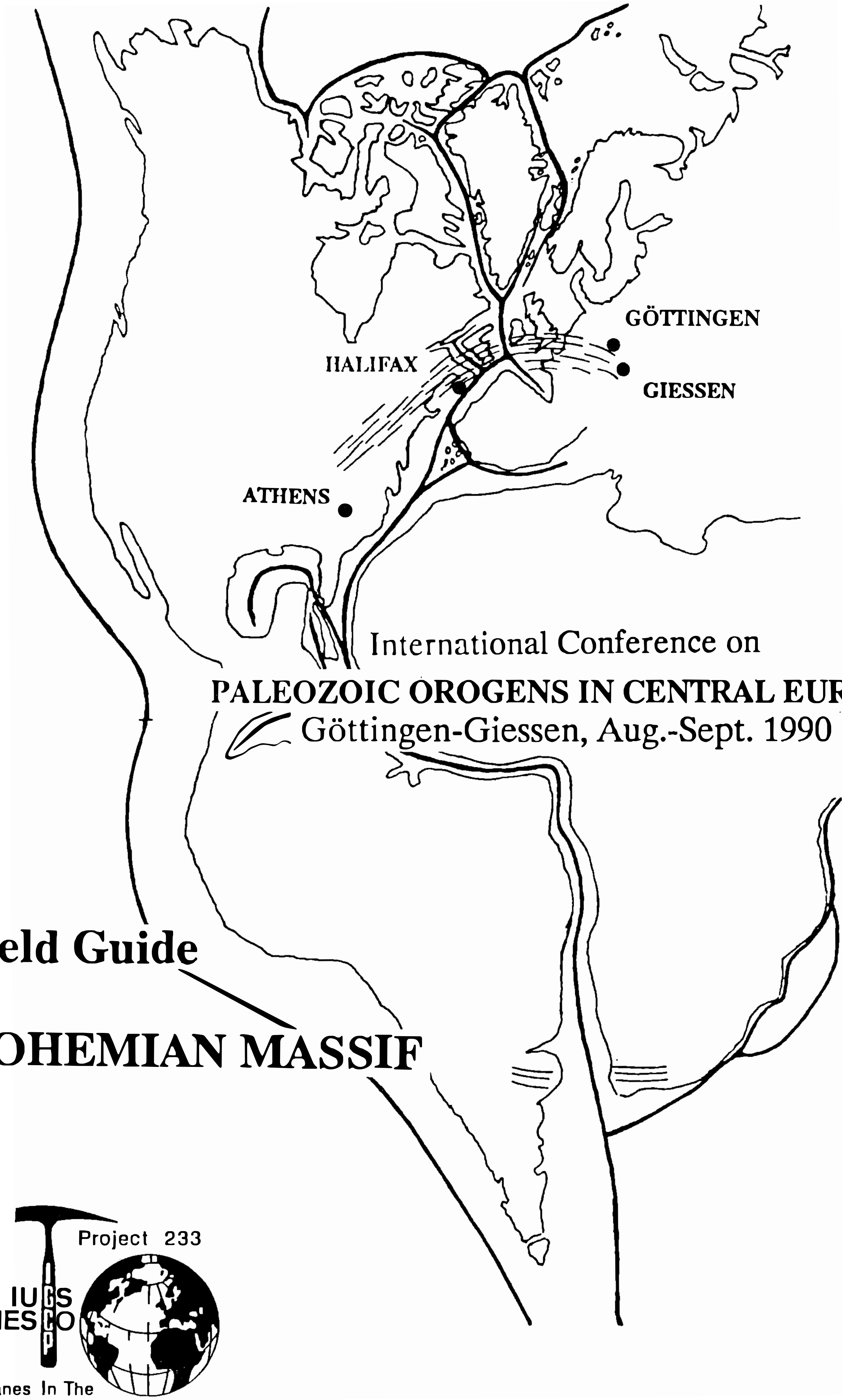
TERRANES IN THE CIRCUM-ATLANTIC PALEOZOIC OROGENS



International Conference on

PALEOZOIC OROGENS IN CENTRAL EUROPE

Göttingen-Giessen, Aug.-Sept. 1990

Field Guide

BOHEMIAN MASSIF

Project 233

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Terranes In The
Circum-Atlantic Paleozoic Orogens

IGCP 233
TERRANES IN THE CIRCUM-ATLANTIC PALEOZOIC OROGENS

Conference on

PALEOZOIC OROGENS IN CENTRAL EUROPE - GEOLOGY AND GEOPHYSICS

Göttingen-Giessen 1990

FIELD-GUIDE to post-conference excursion:

BOHEMIAN MASSIF

with contributions by:

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compiled by Wolfgang FRANKE

cover: after A.WEGENER 1915

FOREWORD

This guide-book presents a cross-section through the western part of the Bohemian Massif, the central part of the Variscan Belt. Geological research in this area reflects part of the history of our science. As early as 1897, F.E.SUESS discerned "Intrusions-Tektonik" (in modern terms: emplacement of granitoids in a post- collisional, extensional regime) and "Wander-Tektonik" (long- distance nappe transports. F.E.SUESS, in 1912, also published a cross-section through the Saxothuringian/Moldanubian boundary region, whose essential features are still valid, and F.KOSSMAT (1927) based his classical subdivision of the Variscan Belt largely on observations in the Bohemian Massif. These mobilistic views of Variscan geology coincided with A.WEGENER's conception of the continental drift hypothesis. This fruitful line of thinking was interrupted by the political desaster before and during world war II, and is now being successfully retraced by modern studies.

If it is possible, today, to propose geotectonic models, this is thanks to the thourough and long-term studies of several pioneer working groups, e.g., detailed mapping carried out by the Bayerisches Geologisches Landesamt (G.STETTNER & Co.), the biostratigraphic work of the Paläontologisches Institut Univ. Würzburg (J.GANDL & Co.), petrological studies by the Mineralogical Institute Univ. Munich (initiated by the late G.FISCHER), and, in Austria, petrological studies by G.SCHARBERT and detailed mapping by G.FUCHS, A.MATURA and O.THIELE. Their results have laid a solid foundation.

Our attempts to interpret the Bohemian Massif has, until very recently, been greatly hampered by mutual ignorance and misunderstandings due to the political boundaries which cut across the structural trend - imagine, for comparison, an iron curtain separating the Western from the Eastern Alps, or the Southern from the Northern Appalachians! We are therefore happy to welcome numerous colleagues from Eastern Germany, Poland, and the Czecho-Slovakian Federal Republic, and we are looking forward to a future meeting with an integrated view of the Bohemian Massif.

The present guidebook is a cooperative effort. Though we have given all contributors a chance to present their own data and interpretations, we have tried to produce a balanced, organized survey. Unfortunately, a number of contributions came in so late that thourough copy-editing and coordination with co-related papers was not possible.

The first part of the guidebook covers general aspects such as the plate tectonic framework, structural features, petrological and geochemical data, mineral deposits and geochronological data, while the second part introduces into the regional geology of the individual geological units and describes the stops.

We have described much more stops than we can expect to visit; in this way, the individual guides had the chance to present more local information. We will make our selection of stops according to the preferences of the participants.

Since we hope that at least some visitors might wish to come back for a second look, we have given precise topographic coordinates (R = East, H = North) which refer to the grid on the official topographic maps 1 : 25.000 or 1 : 50.000 (TK 25, resp. TK 50, ÖK in Austria). The last threenumbers read as meters.

The compilation of this guide-book would have been impossible without the help of the staffs at our institutes; we would like to thank Brigitte Lins, Thomas Hofmann, Christoph Pauli, Joachim Seibert, and Achim Volp (Giessen); Matthias Krienert, Amke Lottmann, Andreas Mann, Heinz Ocklenburg, Detlef Peters, Henning Sprenger, Klaus Ullemeier, Stefan Urban, Axel Vollbrecht, and Ulrike Wössner (scientific assistance), and Gudrun Asic, Karl Faber, Cornelia Kaubisch, and Gisela Neugebauer (technical assistance), all at Göttingen. Lastly, it remains to express our sincere gratitude towards the following institutions and companies, who have helped to fund the meeting and the fieldtrips:

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Giessen/Göttingen, 30.07.1990 W.FRANKE
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TECTONOSTRATIGRAPHIC UNITS IN THE W PART OF THE BOHEMIAN MASSIF AN INTRODUCTION

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The Bohemian Massif in Germany, the Czecho-Slovakian Federal Republic, Poland and Austria is one of the largest outcrops of Variscan basement in Europe. It comprises an almost complete cross-section through the Variscan Belt of East-Central Europe (Fig.1). Nevertheless, the geotectonic development of this region is far from being understood. Besides the political problems, this is due to the large portion of crystalline rocks often of unknown age, and to an extremely complex tectonic history, which spans at least 130 Ma, comprises large-scale thrusting on both flanks of the bilateral Variscan orogen, and was further complicated by at least two sets of important strike-slip faults. One of these

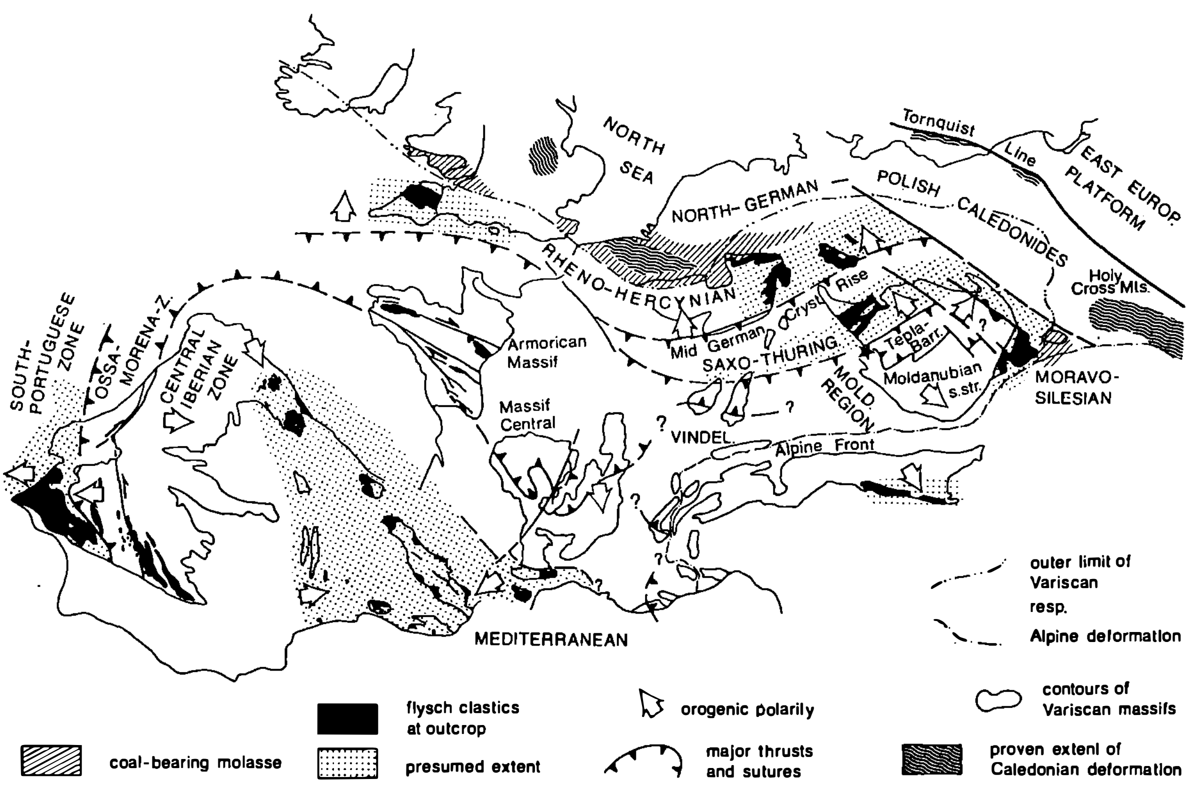


Fig. 1: Structural subdivision of the European Variscides (from FRANKE 1989).

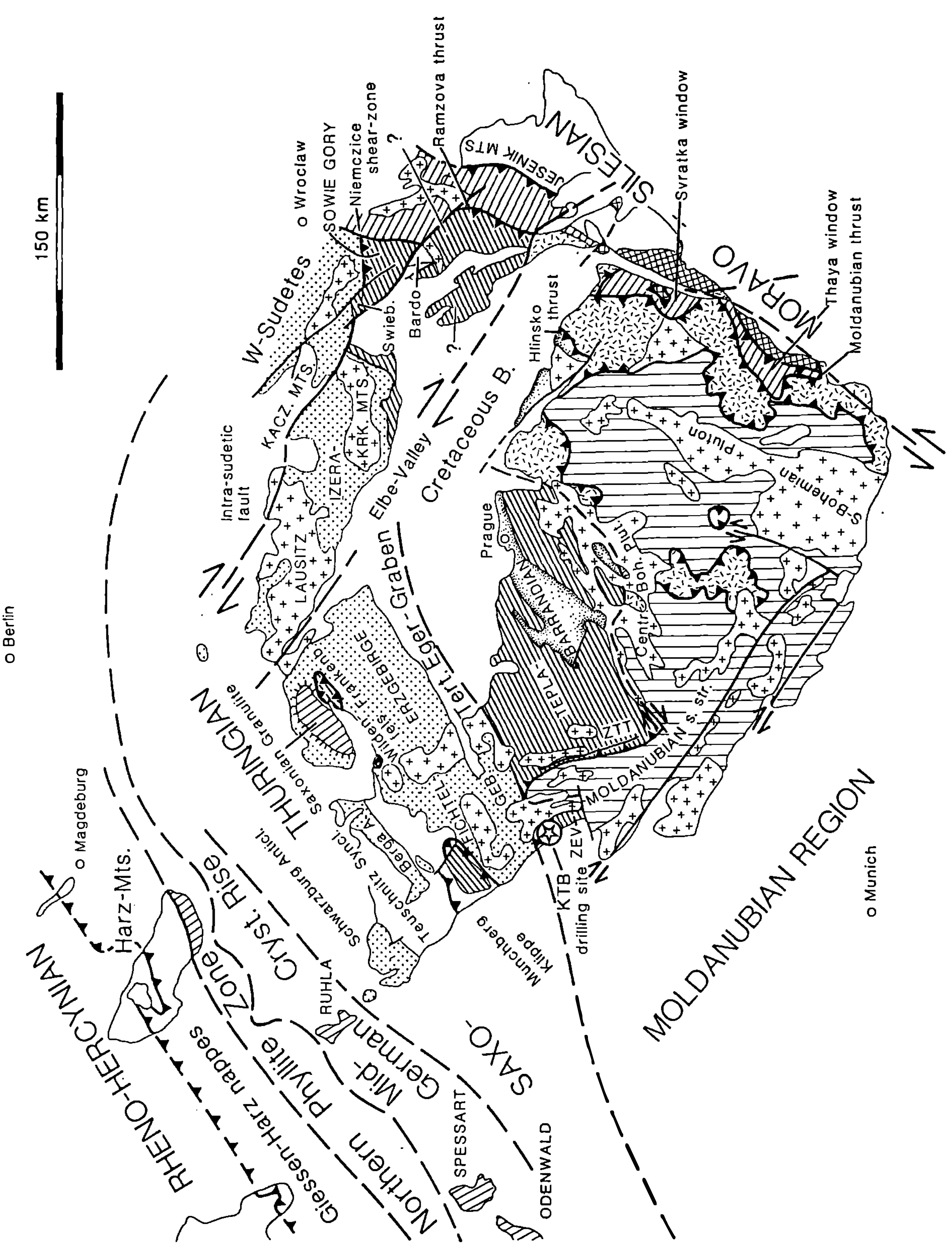
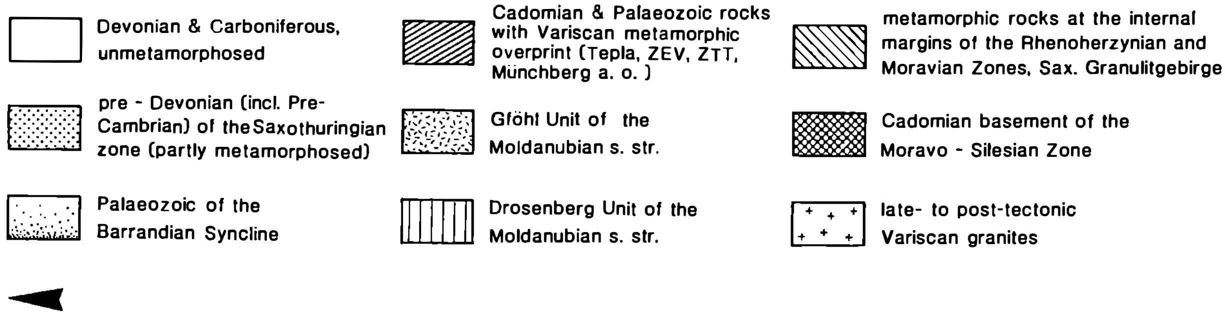


Fig. 2: Structural sketch map of the Bohemian Massif and area adjacent to the NW (after FRANKE 1989).



fault systems parallels the SW margin of the East-European Platform, and has brought about important dextral offsets along the Elbe Valley Lineament and the Inner-Sudetic Fault. This prevents simple "long-strike" correlation of the W part of the massif with tectonic units at the eastern margin (W-Sudetes, Fig. 2); the geology of the area to the NE of the Elbe Lineament is therefore not treated here.

SAXOTHURINGIAN TERRANE

The NW part of the ST Zone is occupied by the Mid-German Crystalline Rise, the active southern margin of the Rhenohercynian Basin (see the field-guide to the pre-conference excursion). The Crystalline Rise is exposed around Ruhla (Fig. 2). Greenschist-grade sedimentary and volcanic rocks exposed further south, in the Schwarzburg Anticline (Fig.2), already belong to the main, sedimentary part of the ST belt, which is defined here as the ST terrane. The SE-facing Schwarzburg A. has been thrust over the very low-grade sequences to the SE.

The infill of the ST basin probably rests upon a Cadomian basement, which is possibly exposed in the Eastern Erzgebirge, but has nowhere been identified further west. Crustal extension occurred mainly in the Cambrian and Ordovician, and is documented by thick marine clastic sequences and by Cambro-Ordovician bimodal volcanic rocks which have been extruded in an intra-plate setting (BANKWITZ et al. 1989, WIRTH 1978, see also the contribution by OKRUSCH et al.).

Like in the Rhenohercynian basin, it is important to distinguish between a main, autochthonous sequence ("Thuringian" facies realm) and an allochthonous sequence ("Bavarian" facies), which is contained within the Münchberg nappe pile (Fig. 2). As it is a rule in orogenic belts, the allochthon contains the deeper water facies: an Ordovician volcano-sedimentary sequence, Silurian and Devonian cherts with graptolites and radiolarians, and a Lower Carboniferous wildflysch which represents trench and slope environments (BEHR et al. 1982, FRANKE 1984a,b).

The Cambro-Ordovician of the "Thuringian" autochthon consists of neritic quartzites or sandstones with slates, hemipelagic Late Ordovician through Devonian sequences, and a relatively distal Lower Carboniferous flysch.

In addition to the Cambro-Ordovician bimodal volcanic rocks, there is a further volcanic episode in the Frasnian, again characterized by intra-plate products (alkali-basalts and intra-plate tholeiites, WIRTH 1978). Within the volcanic belt, a narrow, NE-trending tectonic uplift has produced conglomerates and greywackes, which contain only clasts derived from the "Thuringian" type Ordovician through Frasnian sequences. This uplift is in line with the Saxonian Granulite Antiform (Fig.2), and probably records the uplift of the granulites, possibly in the form of a metamorphic core complex (FRANKE 1989a,c).

In the Münchberg Klippe, the "Bavarian" type volcano-sedimentary nappes are overlain by greenschists developed from Proterozoic island-arc volcanics, epidote-amphibolites of unknown derivation and age, and a variety of higher-grade metamorphic rocks, which include eclogites (see the contributions by OKRUSCH et al. and BLÜMEL et al.) derived from Cambrian MORB-type basalts (GEBAUER & GRÜNENFELDER 1979). All these metamorphic units have undergone early Variscan metamorphism, partly with medium or even high pressure (see the contribution by AHRENDT). Their lithologies, metamorphic facies and ages are largely identical with the Tepla-Barrandian (or Bohemian) further south, and must be interpreted as a tectonic outlier of this unit (see below). It is possible that MORB-type eclogites represent part of a Saxothuringian ocean, whose extent, however, must have been fairly limited (see the discussion in FRANKE 1989 a,b).

Equivalents of the Münchberg Klippe exist at Wildenfels and Frankenberg in E-Germany (Fig.2), though their allochthonous position is still being questioned by E-German colleagues.

The Cambro-Ordovician magmatic rocks in both the Thuringian and Bavarian facies reflect a major episode of crustal extension, which has affected most of the Variscan Belt. Time-equivalent magmatic sequences are present in the Münchberg metamorphic nappes and also in various structural levels of the Tepla-Barrandian terrane (see below).

Tectonic deformation and metamorphism are polyphase. The Münchberg crystalline rocks have imported earlier increments of the Variscan tectonometamorphic development: high- and medium-pressure metamorphism at about 390 Ma (or even earlier), and subsequent rapid cooling (see the contribution bay AHRENDT). The autochthon underwent deformation and metamorphism during and shortly after the emplacement of the Münchberg nappes, in Lower Carboniferous time.

The first and, in most of the area, main deformation (D1) has formed NW-facing folds and thrusts, both in the low-grade parts of the Münchberg nappe pile and in the autochthon. Toward the NW (Teuschnitz Syncline, Berga A.), D1 gradually fades out. D2 has brought about S- to SE-facing backfolds and minor thrusts (FRANKE 1984 a,b, STEIN 1988). D3, with subvertical axial planes, is responsible for the major Fichtelgebirge/Erzgebirge Antiform.
In most of the area, the Palaeozic sediments have not attained greenschist grade. Only in a transverse zone with high heat-flow (FRANKE 1984a), and in the core of the Fichtelgebirge-Erzgebirge Antiform, the Ordovician sequences exhibit higher grades (up to staurolite in the Fichtelgebirge, see MIELKE et al. 1979 and the contributions by BLÜMEL and BLÜMEL et al.), which requires some tectonic overburden, and suggest southward thickening of the allochthonous wedge.

TEPLA/BARRANDIAN (BOHEMIAN) TERRANE

The largely crystalline areas to the SE of the ST were termed "Moldanubikum" in KOSSMAT's (1927) classical subdivision of the Variscan Belt in Germany. Meanwhile, it is possible to discern two subunits with a clearly different tectono-metamorphic history: the Tepla-Barrandian (or Bohemian of Czechoslovakian authors) and the Moldanubian proper (Moldanubian s.str. in Fig.2; see Fig. 3 for a close-up).

Stratigraphy and petrology

The Tepla/Barrandian contains, in its south-central part, an unmetamorphosed Palaeozoic sequence (the Barrandian Syncline, named after the pioneer geologist Joachim BARRANDE). At its base, Lower Cambrian fluvial conglomerates overstep a weakly folded and metamorphosed Cadomian basement. The basal clastics are overlain by Ordovician quartzites, Silurian and Lower Devonian carbonates, and are topped by a Middle Devonian clastic sequence. In the Upper Cambrian through Silurian, there are intercalations of bimodal intra-plate volcanic rocks. It is possible that the Barrandian sequence represents the southern shelf of the Saxothuringian basin, but it might also have been connected with the Moldanubian s.str. (see below).
Following the proposals of KETTNER (1917), SVOBODA et al. (1966) and HOLUBEC 1968), the pre-Cambrian basement is subdivided into three lithological units: the "pre-spilitic" sequence (mainly pelites), the "spilitic" group (mafic volcanic rocks and pelites), and the "post-spilitic" group (flysch-type clastic sediments). Local microfloras indicate a Proterozoic age (KONZALOVA 1981).
Toward the NW and W, metamorphism of the TB basement is seen to increase up to kyanite grade (VEJNAR 1982, see also the contribution by BLÜMEL). The TB, as a

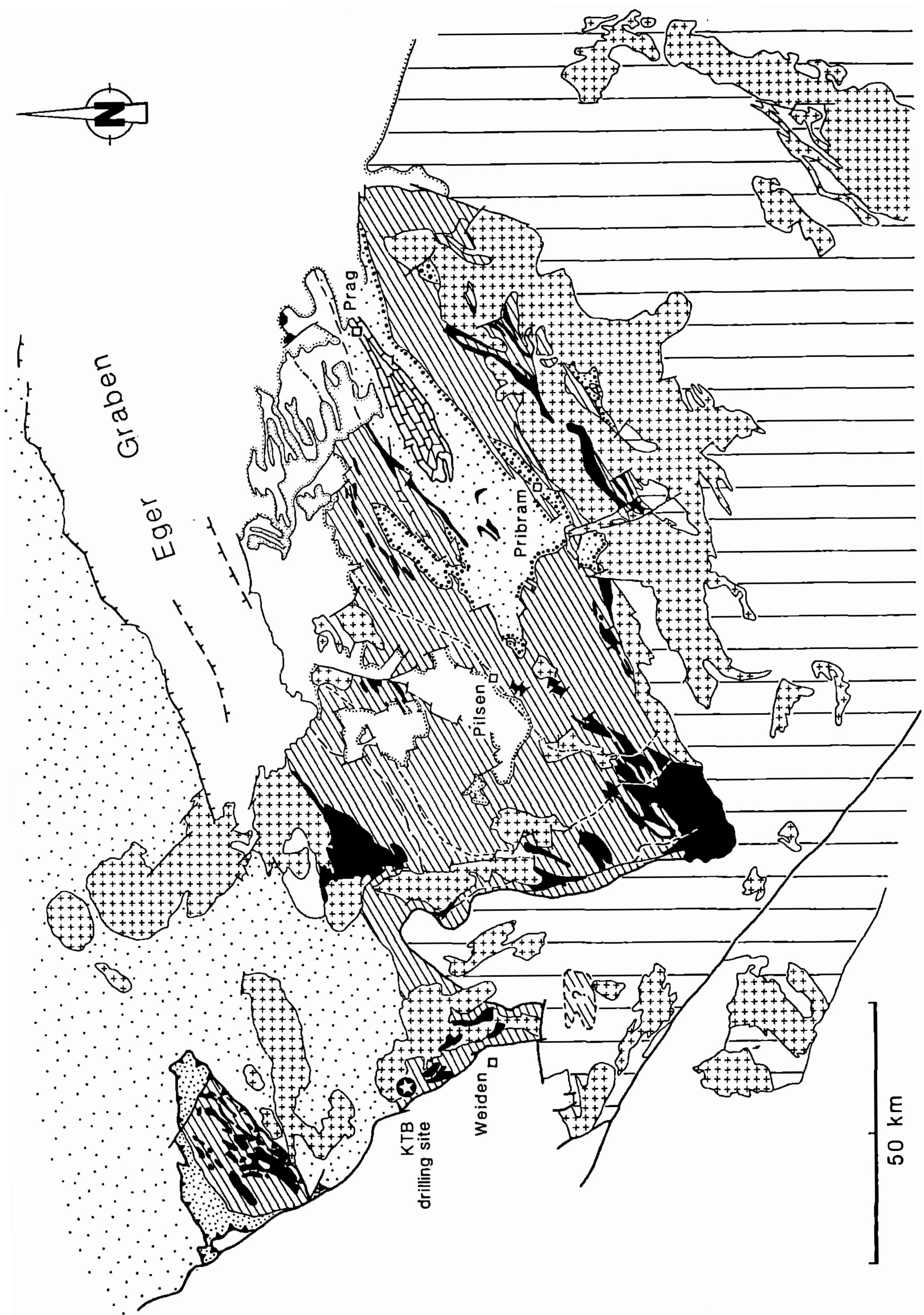
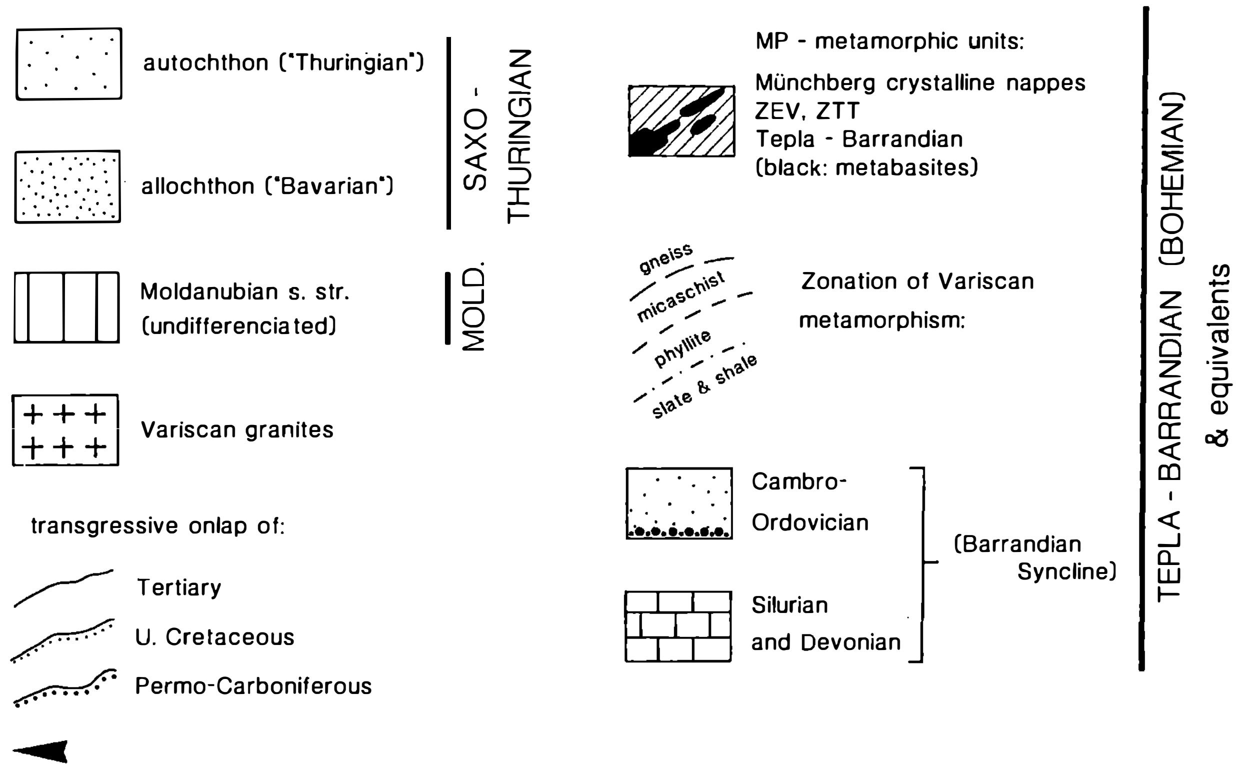


Fig. 3: Structural sketch map of the Tepla-Barrandian and adjacent terranes.



whole, exhibits a synformal structure, with the Barrandian Palaeozoic in its core. The western margin of the TB is called the Zone of Tepla-Domazlice or Tepl-Taus (ZTT). Mafic rocks in the ZTT have yielded early Variscan hornblende ages around 390 Ma (SCHÜSSLER et al. 1989b, see also the contribution by AHRENDT), which clearly demonstrate that the strong metamorphism encountered at the margins of the TB block is Variscan and not Cadomian. In the southern part of the ZTT, i.e., in the SW corner of the TB, the hornblendes have been reset to ages around 330 Ma, probably due to the widespread Lower Carboniferous low-pressure metamorphism (see below and the contribution by BLÜMEL.

An outlier of the Tepla-Barrandian occurs at the western margin of the Bohemian Massif, in the Zone of Erbendorf-Vohenstrauß (ZEV). Like the ZTT, the ZEV consists of various meta-basaltic and meta-sedimentary rocks, which have undergone the same early-Variscan medium- and high-pressure metamorphism as the ZTT and the crystalline rocks in the Münchberg nappe pile (TEUFEL 1988, HANSEN et al. 1989, see also the contribution by AHRENDT). Intrusion of an orthogneiss body has been dated at 457 +/- 2 Ma (TEUFEL 1988). The geochemical characteristics of the numerous metabasites are highly variable (N- and E-MORB as well as intra-plate, see SCHÜSSLER et al. 1989a, and the contribution by OKRUSCH et al.).
The German Continental Deep Drilling (KTB) is being carried out near the northwestern end of the ZEV (see the description of stops).

S of the ZEV, near Oberviechtach, there are occurrences of eclogites retrograded into granulites and amphibolites (O'BRIEN 1989), and serpentinites derived from sub-oceanic mantle rocks (von GEHLEN & SCHMITT 1989). Sm/Nd isochrons give 427 +/- 5 Ma, and 423 +/- 8 Ma for the eclogite metamorphism, and Rb/Sr-WR, Sm/Nd-WR, plus U/Pb data on zircons suggest derivation from magmatic protoliths crystallized at about 1.25 Ga (QUADT & GEBAUER 1988). These rocks probably represent an outlier of the ZEV, which rest as tectonic klippen on the Moldanubian paragneisses (but see an alternative view in the contribution on the Moldanubian Region by BLÜMEL).

A separate terrane composed of Palaeozoic protoliths?

At least part of the amphibolites and metasediments in the Münchberg Klippe and in the various parts of the Tepla-Barrandian have Proterozoic protoliths and represent recycled Cadomian basement. This is evident, e.g., from the trend of metabasic units, which can be traced from the amphibolite-grade at the western margin of the ZTT toward the Proterozoic very-low-grade terrains which underly the Cambrian conglomerates of the Barrandian Syncline (Fig. 3). The presence of pre-Cambrian rocks in the ZEV is also suggested by Nd model ages from the KTB hole (v.DRACH & KÖHLER 1990). However, there is also evidence of Palaeozoic magmatic rocks: The Münchberg eclogites were derived from Cambrian MORB-type basalts (see above), a metagabbro in the KTB pilot hole has a crystallization age of 480 Ma (U/Pb, QUADT 1990), and metabasic rocks with MORB-type geochemistry from the southern part of the ZTT have a U/Pb zircon-age of 530 Ma (GEBAUER & GRÜNENFELDER 1982). Further MORB-type rocks, partly with high-pressure metamorphism, occur in the Marianske Lazne mafic complex at the northern end of the ZTT; it can be expected that these rocks will likewise turn out to be derived from Early Palaeozoic protoliths. Lastly, PFLUG & PRÖSSL (1989) have detected, in graphite-bearing paragneisses of the KTB pilot hole, a microflora which can be assigned to the Late Silurian or Early Devonian.

It is possible that these occurrences of Palaeozoic protoliths represent intrusions into, resp. a stratigraphic onlap on, a Barrandean-type Cadomian basement, and that all these rocks, together, were later caught up in the Variscan orogeny. However, it is also possible that the Palaeozoic magmatic and sedimentary rocks belong to a separate terrane which is tectonically inserted between the Saxothuringian and the Barrandian (MATTE et al.1990).

Tectonic boundaries

The SE margin of the Tepla-Barrandian is a subvertical, NE-trending dextral shear-zone (Rajlich 1987, 1988), which is now largely masked by the Central-Bohemian Pluton (intrusion at 331 +/- 4 by U/Pb, van BREEMEN et al. 1982). "Metamorphic Islets" in the roof of the granite contain metamorphosed equivalents of the Barrandian Palaeozoic (CHLUPAC 1981, 1986). Further E, in the Zelezne Hory, the Barrandian has been thrust over the Moldanubian rocks to the SE (Hlinsko Thrust, Fig. 2).
Near the SW margin of the TB , there is a subvertical, SSE-trending fault-zone, partly with extensive vein-quartz ("Bohemian Pfahl"), which probably post-dates the dextral shear-zone at the SE-margin of the TB, and a still earlier ductile deformation at the SW margin (see below).

The ZTT and ZEV are interpreted as a nappe emplaced on the Moldanubian s.str. (BLÜMEL 1983). The Moldanubian sequences are exposed in the core of a late, NS-trending antiform (D4 of STEIN 1988). The boundaries between the Moldanubian and the ZTT resp. ZEV exhibit strong ductile shearing. If one presumes that these shear-zones represent the refolded, originally subhorizontal thrust of the ZTT + ZEV over the Moldanubian, shear criteria consistently indicate transport toward the SW (HEINICKE 1987, KLEEMANN et al. 1989, MASCH 1988, STEIN & KLEEMANN 1990). Thrusting is more or less coeval with the Lower Carboniferous low-pressure metamorphism, and has been dated, in one of the shear-zones, by U/Pb on monazite and xenotime, at 333 +/-3 Ma (TEUFEL 1988). At another locality, Rb/Sr dating in a high-temperature mylonite at the eastern margin of the ZEV has yielded 305 +/- 9 Ma (BAUMANN et al. 1990).

The NW margin of the Tepla-Barrandian, and its contact with the Saxothuringian to the NW, are largely masked by the Tertiary infill of the Eger Graben, and by late Carboniferous, post-tectonic granites. Only at the NW end of the ZEV it is possible to observe what may be interpreted as the primary relationship between the TB and the ST: very low-grade, fossiliferous Palaeozoic sediments of the southern Fichtelgebirge (in the "Thuringian" facies typical of the ST autochthon) are overthrust by amphibolite facies rocks and gabbros retrograded into greenschists (MATTHES & OLESCH 1989). Their calc-alkaline geochemistry resembles that of the Münchberg greenschists, see OKRUSCH et al. 1989, and the contribution by OKRUSCH et al.). The metabasites are tectonically overlain by the gneisses and amphibolites of the ZEV.

At the northern end of the D4-antiform, a deeper structural level is exposed, so that the medium- and high-grade sequences of the ZTT and ZEV are absent. In this area, Saxothuringian metasediments are in direct contact with metasediments, which have conventionally been interpreted as belonging to the Moldanubian sensu stricto. These metasedimentary sequences have undergone the same low-pressure metamorphism in Lower Carboniferous time (SCHREYER 1966, BLÜMEL 1982), which is synchronous with the D2 resp. D3 deformation in the Fichtelgebirge and the Moldanubian s.str. (STEIN 1988). This metamorphism is interpreted as a syn- to late-collisional feature, which postdates the emplacement of the Tepla-Barrandean (+ Münchberg, ZEV,ZTT) unit with its early Variscan medium- and high-pressure metamorphism over the Saxothuringian metasediments (BLÜMEL 1983, 1986). The low-pressure metamorphism is probably grossly synchronous the emplacement of the Tepla-Barrandian units over the Moldanubian s.str.. The Münchberg crystalline rocks do not show any low-pressure metamorphic overprint, probably because they had already been upthrusted into a high tectonic level. In the SE part of the ZEV, and in the S part of the ZTT, resetting of hornblendes to about 330-320 Ma may be taken to reflect the low-pressure event.

In an alternative interpretation (MATTE et al. 1990), the "Moldanubian" metasediments of the boundary region are tentatively assigned to the Saxothuringian Zone. However, this variant does not solve the main problem: apparently, rocks belonging to the Tepla-Barrandean unit have been thrust towards the NW (over the Saxothuringian of the Fichtelgebirge), towards the SW (over the Saxothuringian or Moldanubian metasediments within the D4 antiform), and are also involved in SE-ward thrusting (Zelezne Hory, see above) over parts of the Moldanubian Zone (s.str.). The sequence of these tectonic events, and especially their geodynamic causes, are largely unknown.

MOLDANUBIAN s.str. - GFÖHL and DROSENDORF TERRANES

The Moldanubian s.str. occupies the SW and SE parts of the Bohemian Massif (with the exception of the Moravo-Silesian Terrane at the SE margin of the Massif). Within the Moldanubian s.str., it is possible to discern two clearly distinct terranes: the Gföhl Terrane has been thrust toward the SE over the Drosendorf Terrane.

The name of the Gföhl Terrane (Gföhl Unit of TOLLMANN 1982) is derived from the Gföhl Nappe in Austria (FUCHS & MATURA 1976, THIELE 1976, see also the contribution by WEBER). It consists of sillimanite-bearing para- and orthogneisses, partly anatectic, with inserts of amphibolites and metagabbros. At the bottom of the unit, there are tectonic intercalations of granulites, eclogites, and garnet peridotites. Other eclogites occur as boudins in the amphibolites or, together with the peridotites, within the anatectic gneisses (DUDEK & FEDIUKOVA 1974, MISAR et al. 1984, DUDEK & MISAR 1985). The highest position in the pile is occupied by large sheets of acid granulites (SCHARBERT 1988, MATTE et al. 1985). The age of the protoliths of the high-grade rocks is largely unknown; an anorthositic gabbro in the Austrian Waldviertel has been emplaced at 600 Ma (GEBAUER & GRÜNENFELDER 1982; see some further data in the contribution by WEBER).

The age of the high-grade metamorphism was supposed to be "Caledonian" (FUCHS 1976) or older (e.g., CHALOUPSKY 1988, ZOUBEK et al. 1988). ARNOLD & SCHARBERT (1973) have reported a Rb/Sr WR-isochron of 446 +/- 35 Ma. Recent radiometric studies have only yielded ages less than 370 Ma (see the compilations in FRANKE 1989c and MATTE et al. in press, and AFTALION et al. 1989). It cannot be excluded, however, that the peak of metamorphism is older, and that the zircon ages obtained, e.g., by KRÖNER et al. (1988) reflect part of the retrograde path.

The allochthonous nature of the Gföhl Terrane is evident from the presence of high-grade metamorphic rocks over the less metamorphosed units of the Drosendorf Terrane. The Gföhl Terrane occupies areas adjacent to the SE margin of the Tepla-Barrandian Terrane, a number of klippen in the central part of the Moldanubian zone, and the SE part of the Moldanubian Zone, adjacent to the Moravo-Silesian Belt (see Fig. 2 and below). Strong mineral lineation, other extensional fabrics, and clasts in the granulites, in the basal shear zones, and partly also in the underlying Drosendorf sequences indicate transport towards the SE to E (NEMEC 1965, MATTE et al. 1985, 1987, RAJLICH 1987, TOLLMANN 1982; see also the contribution by WEBER).

The Drosendorf Terrane consists mainly of a "monotonous" pelitic series (named "Ostrong Unit" in the Austrian Waldviertel, see the contribution by WEBER) with some orthogneiss and "variegated" intercalations of metabasites, graphitic schists and marbles. Mineral assemblages are usually biotite-garnet-staurolite, and partly also kyanite or sillimanite (see the contribution by BLÜMEL).

The Drosendorf sequences have conventionally been attributed to the Precambrian (e.g., ZOUBEK et al. 1988), but recent findings of microfloras have revealed that at least part of the protoliths are Palaeozoic, partly as young as Silurian/Devonian (ANDRUSOV & CORNA 1976, GUNIA 1985, PACLTOVA 1981, PFLUG & REITZ 1987). Detrital zircons from the Drosendorf metasediments indicate thermal events between 2.3 and 2.6 Ga (GRAUERT et al. 1973, 1974; van BREEMEN et al. 1982, TEUFEL 1987), but also at about 530 Ma (TEUFEL 1987) and 560 Ma (GRAUERT et al. 1973). The latter ages indicate, like the microfloras found at other localities, a Palaeozoic age of the host rocks. It is uncertain at present, whether the Palaeozoic

portions of the Drosendorf Terrane represent a separate basin, or else was connected with the Barrandian Palaeozoic.
Though the Palaeozoic clastic and carbonate sediments require an extensive continental basement, pre-Variscan crust has, so far, only been detected in meta-granitoids (Dobra Gneiss of the Drosendorf Terrane, see the contribution by WEBER). Detrital zircons with Cadomian ages (GEBAUER et al. 1989) are ubiquitous in clastic sediments and meta-sediments of the Bohemian Massif, but cannot be assigned to specific source regions.

Rb/Sr and U/Pb data indicate thermal events between 450 and 530 Ma (GEBAUER 1975, GRAUERT et al. 1974, KÖHLER 1981, KÖHLER & MÜLLER-SOHNIUS 1976,1985, GOROCHOV et al. 1983). These ages likewise occur elsewhere in crystalline parts of the Variscan Belt and are usually referred to as a "Caledonian" event, although the adjacent unmetamorphosed sequences do not record any orogenic activity during this time span. As far as the respective isotope data reflect real geological events, they might relate to a thermal episode in an extended crust (see, e.g., WEBER 1984).

Relics of kyanite in the Drosendorf Terrane (BLÜMEL 1982, WAGENER-LOHSE & BLÜMEL 1986, see contribution by BLÜMEL), and some radiometric data may be taken to suggest that at least parts of the Drosendorf Terrane have undergone, like the Tepla-Barrandian, an Early Devonian medium-pressure metamorphism (Rb/Sr WR-age of 384 +/- 26 Ma in the Drosendorf-type Moldanubian E of the ZEV, TEUFEL 1987; Rb/Sr-WR 393 Ma +/-12 Ma, HOFMANN 1985; U/Pb zircon 400 Ma, GEBAUER 1975; see also KÖHLER et al. 1989).

The youngest, and the dominant, metamorphic event in the Drosendorf Terrane is the Lower Carboniferous low-pressure metamorphism (approx. 320-330 Ma) of varying grade (up to anatectic). Ever since this event has been recognized (SCHREYER 1966), it has more and more turned out to be the main phase of metamorphism in the area (see the contributions by BLÜMEL and AHRENDT). The low-pressure metamorphic event probably correlates with the SE-ward thrusting of the Gföhl over the Drosendorf Terrane.

It must be stated, that our present knowledge about the P/T paths, metamorphic ages, and especially protolith ages in the Tepla-Barrandian, Gföhl and Drosendorf Terranes is still very fragmentary. It is possible that further geochronologigal studies will necessitate a much more differentiated treatment.

MORAVO-SILESIAN TERRANE(S) (or BRUNNO-VISTULIAN T.)

Along the "Moldanubian Thrust" recognized already by F.E.SUESS (1897), the already assembled Gföhl and Drosendorf Terranes were brought in tectonic contact with the Moravian or Moravo-Silesian Terrane, which occupies all of the southeastern margin of the Bohemian Massif. Within the Moravo-Silesian Terrane, it is possible to distinguish between a Cadomian basement, Palaeozoic cover sequences, and metamorphic rocks of uncertain affinity.

The Cadomian basement is exposed at the base of the tectonic pile in the Thaya (= Dye = Messern) and the Svratka (= Tishnov = Schwarzawa) windows, and in the Brno Massif to the E of the latter (Fig.2). It consists of an extensive granite body, the Brno granite, which is largely undeformed and has been dated by U/Pb on zircons at 584 +/-5 Ma, resp. 585 Ma by 207/206 Pb (van BREEMEN et al. 1982, and at 551 +/-6 by Rb/Sr WR (SCHARBERT & BATIK 1980). Deformed and metamorphosed equivalents of the Brno Granite probably occur in the windows (Bites-Gneiss, 570 Ma Rb/Sr WR, SORAUF & JGER 1982), and - to the NE - in the Keprnik-Orthogneiss of the Hruby Jesenik Mts. (546 +/-5 Ma by U/Pb on zircons, van BREEMEN et al. 1982). The Dobra Gneiss of the Drosendorf Terrane might be another equivalent (see the contributions by FRASL et al. and by WEBER).

The unmetamorphosed, eastern portion of the Brno Massif is overstepped by terrestrial to shallow-marine, Old-Red-type clastic sediments of Lower and Middle Devonian age, followed by Middle Devonian through Frasnian reef carbonates, condensed Upper Devonian to Tournaisian carbonates, and Tournaisian to Namurian flysch. Toward the NE (long-strike), the Devonian carbonates are replaced by basinal facies with early flysch, pelagic shales, and (locally) spilite/keratophyre volcanic rocks.
Toward the SE and E, the Moravo-Silesian basin was bounded, in Lower Carboniferous time, by a carbonate platform (BELKA 1987), which was gradually overstepped by the N- and E-ward migrating front of synorogenic clastic sedimentation. In Namurian time, flysch accumulation gave way to the deposition of coal-bearing molasse in the Silesian coal district. A recent summary of the sedimentary record has been published by DVORAK (1989).
The Devonian and Carboniferous sediments have also been detected in deep wells under the Carpathian nappes further S (DVORAK 1978, 1982).

Metamorphosed Devonian clastic sediments and volcanic rocks have been dated with fossils in the Hruby Jesenik Mts. (CHLUPAC 1987, 1989). In the Svratka and Thaya windows, the granitoids of the Cadomian basement are structurally overlain by metasedimentary and metavolcanic rocks. It is uncertain, whether these rocks represent Cadomian crust intruded by the Brno pluton, or else the unconformable cover of the pluton, which has later been affected by the Variscan orogeny (see the contribution by FRASL et al.).

As laid out in ENGEL et al. 1983 and in FRANKE 1989a,b, the Palaeozoic sedimentary record of the Moravo-Silesian terrane corresponds, in all its essential features, to the Rhenohercynian Belt of Germany (represented, in Fig. 2, by the Harz Mts.). The most crucial point is the Devonian extensional phase, which is common to both these regions, whereas all the other major Variscan basins originated from rifting already in Cambro-Ordovician time. It is therefore probable that the Rhenohercynian and Moravo-Silesian were originally connected by an arc-structure around the eastern margin of the Bohemian Massif, and were separated by late Variscan indentation and wrenching (LORENZ 1976, but see alternative options in the contribution by FRASL et al.).

This concept implies a dextral offset between the Moravo-Silesian Terrane and the main part of the Bohemian Massif. In fact, the Moldanubian thrust and the underlying crystalline rocks are part of a low-angle, NW-dipping shear zone, with an important N- to NE-ward translation of the Moldanubian over the Moravo-Silesian (FRITZ & STEYRER 1990, RAJLICH 1987, MATTE & RAJLICH 1988, MATTE et al. 1990, SCHULMANN 1990; see also the stops presented by FRITZ & STEYRER in the contribution by FRASL et al.). In its NE part, in the Hruby Jesenik, the shear zone has been refolded around N- and NE-trending axes (MATTE et al. 1990). The age of this transpressional event is constrained by the stratigraphic ages (post-Namurian, pre-Permian), and by 40/39 Ar plateau-ages of 305-310 Ma on biotites and amphiboles in the Hruby Jesenik (MATTE et al. 1990). It should be noted however, that clearly older ages have been reported from the Moldanubian thrust zone at the W margin of the Thaya window (see the contribution by DALLMEYER et al.).

LATE- AND POST-VARISCAN EVENTS

In addition to the ductile nappe thrusts on both sides of the Tepla-Barrandian Terrane, and to the dextral, ductile strike-slip faults at the SE margins of the Tepla-Barrandian and the Moldanubian Terranes, there is a further set of subvertical, ductile to brittle faults, which have affected all of the Bohemian Massif. These late faults have locally masked or reactivated older terrane boundaries, but, on the large scale, represent a new set of fractures. Some of these faults trend NW, parallel with the SW margin of the Bohemian Massif: the Bohemian "Pfahl" ("Pfahl" is the local term for extensive quartz veins exposed in cliffs), the Franconian Line (which forms the SW margin of the Variscan basement further to the NW), the Rundingen Shear Zone, the Bavarian "Pfahl" (e.g., BEER 1981), and the Donau Fault (see Fig. 2). Other faults trend SW-NE, and probably represent, together with the NW-trending ones, a conjugate set in a regime of NS-directed compression (e.g., the Rodl Shear Zone, BRANDMAYER et al. 1990, WALLBRECHER 1989, or the important sinistral Diendorf Fault at the SE margin of the Moravian windows).

Permian depocenters lined up along the Franconian Line probably represent pull-apart basins (see, e.g., EMMERT 1981, SCHRÖDER 1988, SCHMOLL et al. 1989, WEBER & VOLLBRECHT 1989). The same NW-trending faults have also been reactivated in a transpressional regime during the Alpine collision (BACHMANN et al. 1987, MEYER 1989, SCHRÖDER 1987). Cretaceous basins along the Elbe Lineament and at the SW margin of the Bohemian Massif likewise relate to these activities. The boundary between the Tepla-Barrandian and Saxothuringian terranes has been reproduced by the Tertiary Eger Graben (Fig.2).

SUMMARY AND OPEN QUESTIONS

The central and key position within the Bohemian Massif is occupied by the Tepla-Barrandian terrane, a Cadomian basement overstepped by Palaeozoic sediments. As stated by TOLLMANN (1982), and later adopted by various authors, the TB probably correlates with the Armorican Massif in France. The TB has been thrust (Fig.4), in Lower Carboniferous time, towards the NW over the Saxothuringian Terrane, towards the SW over a part of the Moldanubian s.str., which probably forms part of the Drosendorf Terrane, and towards the SE over the Gföhl Terrane. The Gföhl T., in its turn, has been emplaced over the Drosendorf T. to the ESE.

Metabasites in basal parts of the TB and in the Gföhl T. represent Palaeozoic thinned continental and and/or oceanic crust. These crustal-scale necks have predisposed the thrust zones, which now mark the terrane boundaries.

Still in Lower Carboniferous time, the newly assembled Gföhl and Drosendorf Terranes have been offset, along a dextral shear zone,
against the Moravo-Silesian Terrane at the SE margin of the Bohemian Massif. Later NS-compression has created further important shear zones, which trend NW and NE.

Many urgent questions remain to be answered. The confusing multitude of local names highlights the lack of facts regarding the protolith ages and palaeogeographic subdivision of the metamorphic sequences:

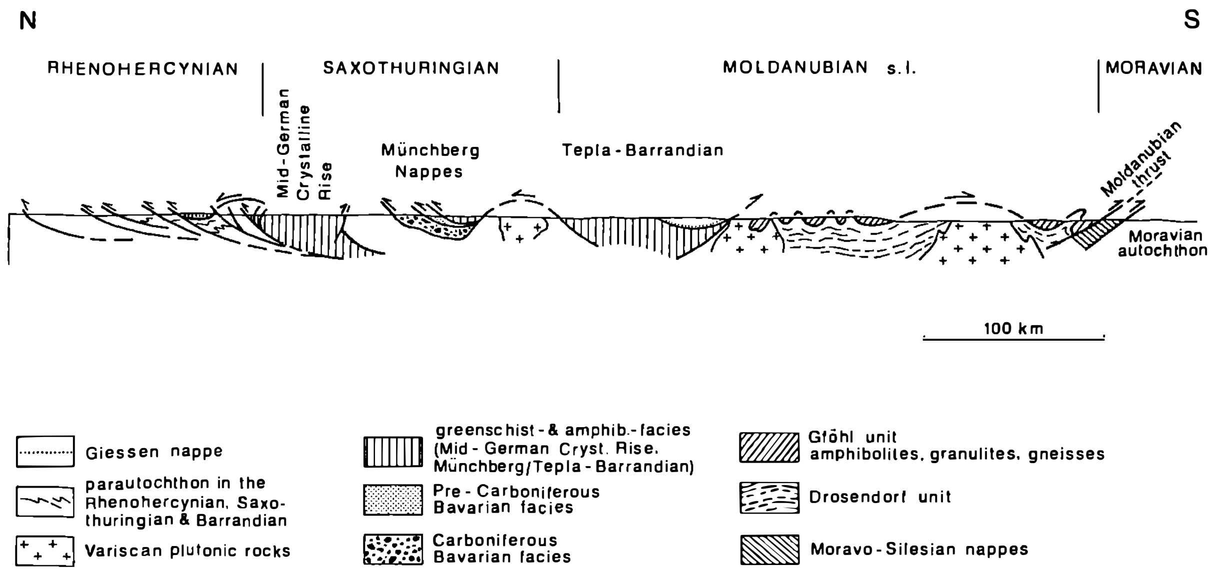


Fig. 4: Diagrammatic cross-section through the Variscan Belt in E-Central Europe (after BEHR et al. 1984, modified after TOLLMANN 1982).

- Are there further portions of pre-Variscan basement, which have so far remained undetected because of the strong Variscan overprint?

  What is the character and geometry of the Cadomian orogeny?
- Various parts of the Tepla-Barrandian Terrane (the Münchberg Klippe, the ZEV and its outliers at Oberviechtach, the ZTT) and the Gföhl Terrane contain metabasites developed from early Palaeozoic protoliths, mostly of MORB-type composition. It appears that these rocks represent one Saxothuringian and one Gföhl "ocean". Is this correct, i.e., could we do with just one ocean, or do we need more than two?
- What are the palaeogeographic affiliations of the metamorphosed Palaeozoic sediments contained within the Moldanubian s.str.?

Other unsolved problems concern the tectono-metamorphic history:

- All the relative displacements of the TB Terrane towards the NW, SW and SE occurred during the Lower Carboniferous. What is the exact sequence of events? What is the geotectonic significance of the contrasting thrusting directions ? (backthrusting? "flip" of continental subduction?)
- Where is the root-zone of the Gföhl nappe(s)? (see also the discussion in the contribution by WEBER).
- To exhume the high-pressure metamorphic rocks, up to 80 km of crust have to be removed. Where are the products of erosion, or else the tectonic indications of gravitational spreading and crustal thinning?

- Does the Moravo-Silesian Terrane represent the southeastern foreland of the bilateral Variscan Belt, or (as proposed above) the southeastern part of a Rhenohercynian/Moravo-Silesian arc?
- What is the geotectonic significance of the various sets of late ductile shear zones?

Further questions are welcome.

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PRE- TO EARLY VARISCAN MAGMATISM IN THE BOHEMIAN MASSIF

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Pre- to early Variscan magmatites of basic and acid character are widespread in different tectonic units of the crystalline basement at the northwestern margin of the Bohemian Massif. During one or more phases of orogenic activity they suffered metamorphic overprint under different P-T conditions. In recent years, an increasing data base has been elaborated which allows to discriminate the meta-magmatites of the different tectonic units by their geochemical characteristics, and to estimate the possible paleotectonic environments in which the respective protoliths have been initially emplaced. However, owing to the absence of age criteria, the relative position of these environments in time and space is so far unknown.

THE MÜNCHBERG NAPPE PILE

The anchimetamorphic Paleozoic sediments of the Bavarian lithofacies forming the lowermost nappe unit contain intercalations of tholeiitic to alkaline basalts, trachyandesites and minor keratophyres (WIRTH 1978).

The overlying tectonic unit of the Prasinite-Phyllite-Series consists predominantly of quartz phyllites, prasinites and minor serpentinites. The prasinites show structural and mineral relics which clearly indicate basalts and related pyroclastites as protoliths. The chemical composition is generally subalkaline with calcalkaline tendency, possibly indicating an island arc or back-arc environment (OKRUSCH et al. 1989). The assemblage

actinolite + epidote + chlorite + albite + quartz + sphene + opaques

indicates p-t conditions of the greenschist facies. K-Ar dating on muscovites from the adjacent quartz phyllites yielded a narrow range of 358 to 369 Ma presumably pertaining to the age of metamorphism (KREUZER et al. 1989).

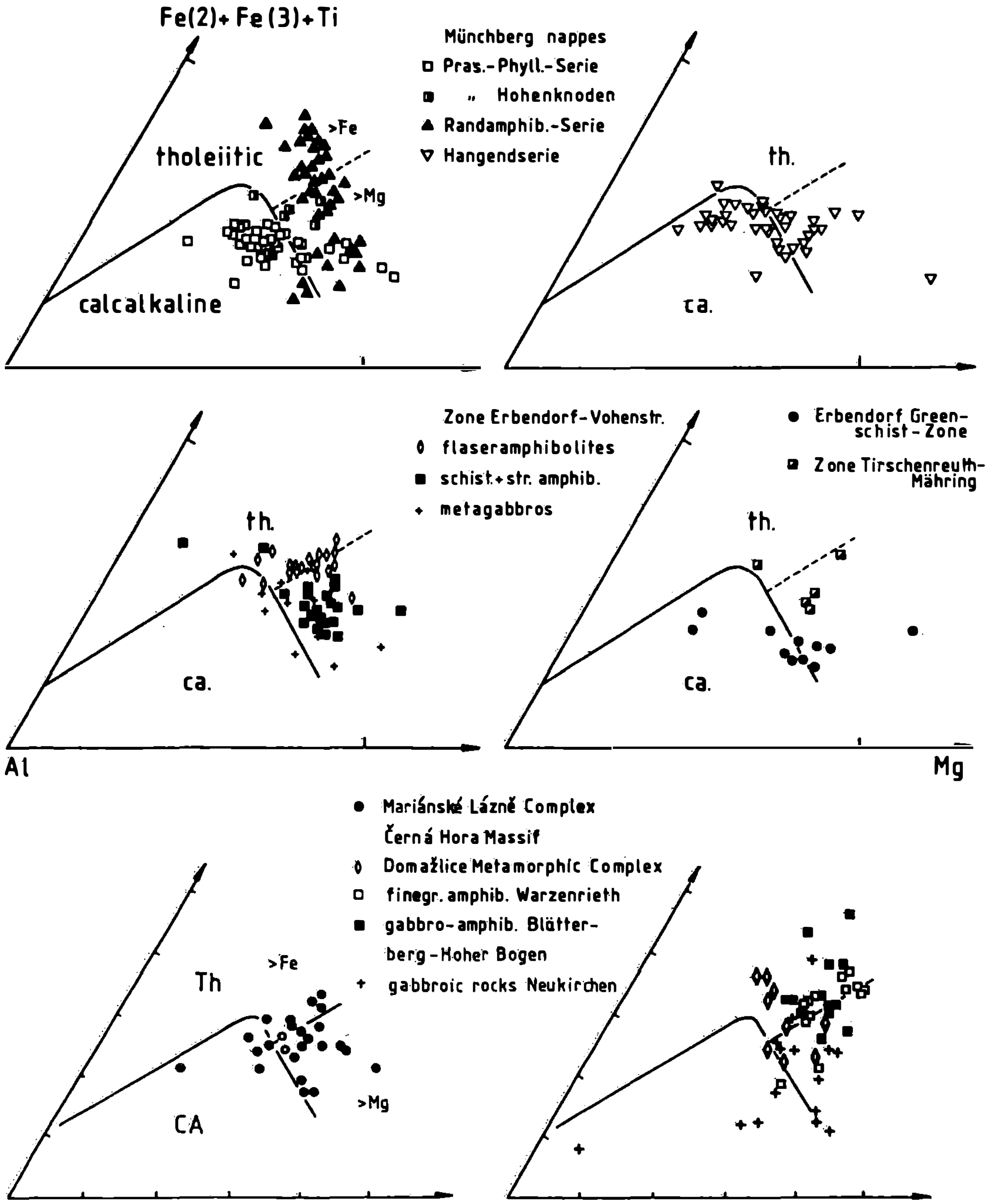


Fig.1: Position of analysed metabasites from different tectonic units of the western margin of the Bohemian Massif in the JENSEN (1976) cation-plot, discriminating between tholeiites (Th) and calc-alkaline basalts (CA)

The so-called Randamphibolite-Series, next higher up, consists predominantly of amphibolites with the assemblage

hornblende + andesine +- gross.-rich almandine +- epidote + sphene + opaques

indicating a distinctly higher metamorphic grade. The chemical composition of the amphibolites conforms to subalkaline, tholeiitic basalts which exhibit a pronounced differentiation trend from Mg-rich, Ti- and Zr-poor to Fe, Ti- and Zr-rich compositions (OKRUSCH et al. 1989).

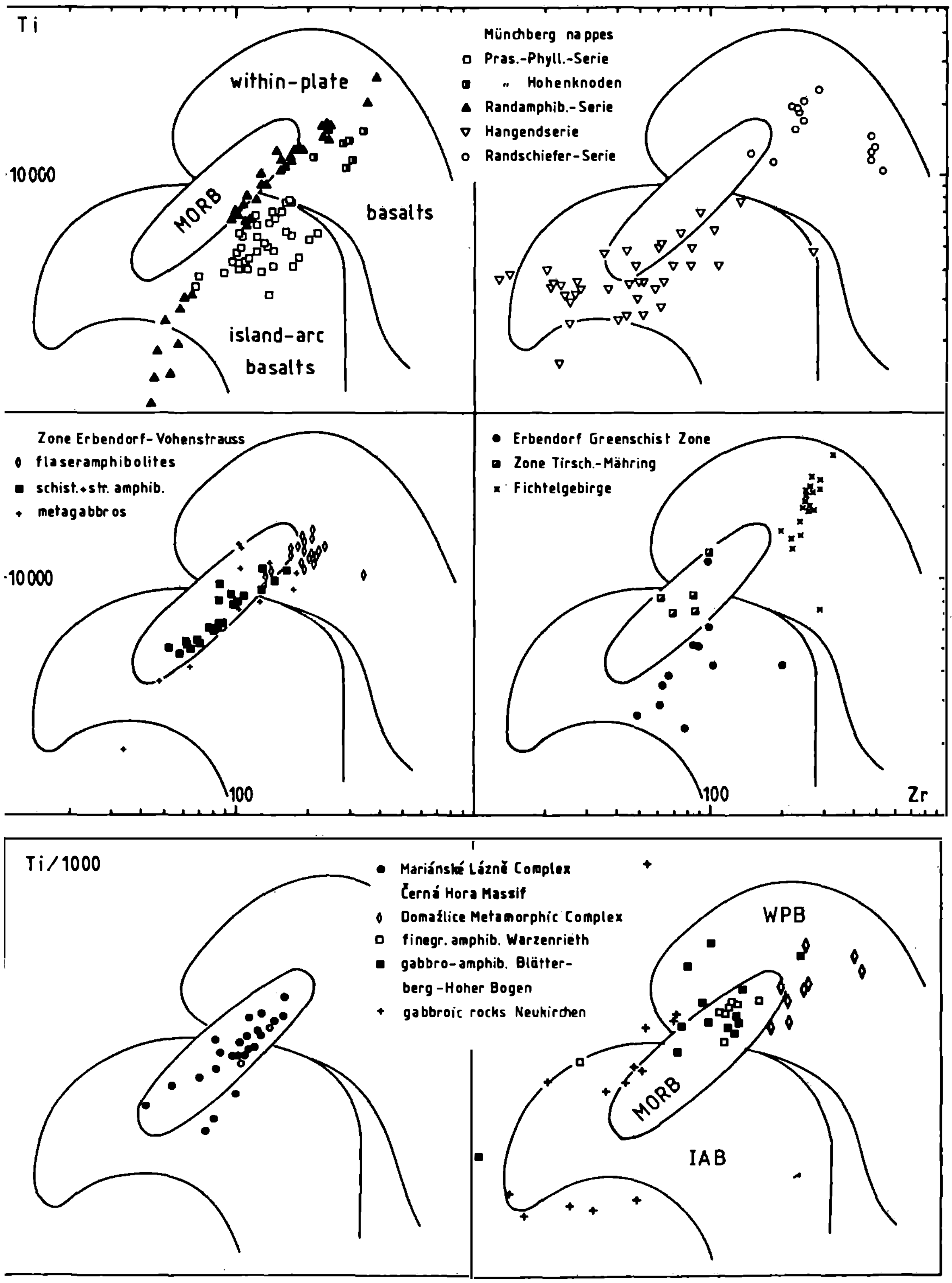
The Liegend-Series higher up in the nappe pile contains a high amount of pre-Devonian granitoids. These intrusives were affected by high to medium pressure stages of metamorphism which transformed them to mainly biotite-muscovite augengneisses with in part well preserved igneous relicts. The former contact aureoles are marked by meta-hornfelses. Isochemical conditions provided, the leucocratic to mesocratic intrusive rocks with a sodium predominance can be classified by their chemical composition as tonalites, granodiorites, granites and quartz-rich granites. Following the chemical classification of CHAPPELL & WHITE (1974) the granitoides clearly plot into the field of S-type granites.

Intercalated are subordinate metagabbros to meta-gabbronorites still exhibiting igneous structures as well as mineral relics of An-rich plagioclase, hyperstene, clinopyroxene, brown hornblende, ilmenite and pyrrhotine. The bulk rock compositions conform to a high-Al basaltic character. Regional metamorphic overprint yielded the assemblage

oligoclase + hornblende +- garnet +- zoisite +- white mica + quartz + rutile/sphene.

Radiometric U-Pb dating on zircons and monazites from the meta-gabbro as well as Rb-Sr total rock dating of the orthogneisses point to an important igneous event at about 500 Ma (GEBAUER & GRÜNENFELDER 1979; SÖLLNER et al. 1981).

The uppermost unit of the Münchberg nappe pile, the Hangend-Series, is famous for the widespread occurrence of eclogitic relics (MATTHES 1978). They are conformably intercalated within a variegated sequence of amphibolites, banded hornblende-gneisses, paragneisses, calc-silicate rocks and marbles.



Metabasites like Fig. 1, compared with compositions of modern basalts different environments (after PEARCE 1982).

The eclogites with the critical assemblage

garnet + omphacite + zoisite +- kyanite +- phengite + rutile

testify to at least one high-pressure event which reached pressures in excess of 20 kbar in a temperature range of 600 - 650 ^{o}C (for a review see OKRUSCH et al. in press). Isothermal uplift, leading to various symplectitic breakdown assemblages, was followed by a renewed phase of prograde metamorphism under amphibolite facies conditions indicated by the assemblage

oligoclase/andesine + hornblende + quartz +- almandine +- zoisite +
rutile/sphene + opaques,

typically present in the amphibolites and banded hornblende-gneisses. The eclogites can be divided in two groups: dark eclogites have chemical compositions similar to normal-MORB, whereas the light, often kyanite-bearing eclogites are high-Al basaltic in character; some of them may be derived from plagioclase-rich gabbroic cumulates (STOSCH & LUGMAIR 1987). Despite of some geochemical similarities, the light eclogites cannot be derived from the metagabbros of the Liegend-Series (MATTHES & SEIDEL 1977). The amphibolites and banded hornblende-gneisses conform to subalkaline basalts with a calc-alkaline trend.

Bulk rock Sm-Nd data suggest igneous formation of the eclogite protoliths at roughly 460 Ma. Recent Sm-Nd, Rb-Sr and Ar-Ar dates on eclogite minerals cover a wide range between 449 and 380 Ma (STOSCH & LUGMAIR 1987, 1990; MÜLLER-SOHNIUS et al. 1987; KREUZER & SEIDEL 1989). The amphibolite-facies metamorphism in the Randamphibolite-, the Liegend- and the Hangend-Series was radiometrically dated at about 380 Ma (e.g. KREUZER et al. 1989).

THE FICHTELGEBIRGE CRYSTALLINE COMPLEX

This complex, currently regarded as autochthonous, consists of pelitic to psammitic metasediments, calc-silicate rocks and marbles and contains intercalations of orthogneisses and minor metabasites. The sequence underwent low-pressure metamorphism ranging from the greenschist to the amphibolite facies, dated at about 330 to 320 Ma.

Granitoids occur as metamorphic granitic intrusives (orthogneiss from Wunsiedel, Selb, Pfaffenreuth) and as metavolcanics (so-called "epi-orthogneisses" in the western Fichtelgebirge). The orthogneisses are medium-grained muscovite-biotite gneisses, frequently containing tourmaline. From their chemical composition a classification as granites and mainly alkalifeldspar-granites can be calculated. They are peraluminous granitoids of S-type character with only a weak potassium predominance. A somewhat uncertain Rb-Sr isochron gave a minimum intrusive age for the Wunsiedel orthogneiss which would be concordant to the Cambrian to early Ordovician age of the surrounding metasediments.

The metavolcanics are highly deformed, partly mylonitic muscovite gneisses, missing considerable amounts of biotite. Volcanic relics have been described by several authors. These "epi-orthogneisses can be classified as rhyolites and alkalifeldspar-rhyolites according to their chemical composition, although there are strong hints for severe postmagmatic alterations in some cases. Less altered meta-rhyolites are leucocratic, peraluminous acid volcanics.

According to their rare earth element patterns all granitoids of the Fichtelgebirge are medium to highly differentiated with deep Eu-anomalies. The S-type character gives hints on collision events with strong contribution of continental crust to the formation of granitic melts.

The rare metabasites are characterized by the assemblage

hornblende + plagioclase + biotite +- quartz + sphene + ilmenite +
sulphides.

Relics of ophitic texture as well as igneous augite and serpentinized olivine point to a basaltic protolith which, according to the major and trace element chemistry, is alkaline-basaltic in character (SCHÜSSLER et al. 1989).

THE ERBENDORF GREENSCHIST ZONE (EGZ)

Situated between the autochthonous Fichtelgebirge in the north and the (?)allochthonous zone of Erbendorf-Vohenstrauss in the south, the EGZ appears to be in a tectonic position similar to the Prasinite-Phyllite-Series of the Münchberg nappe pile. Interestingly, the metabasites in both tectonic units exhibit striking similarities in their chemical composition. The amphibolites and metagabbros forming the predominant constituents of the EGZ conform to Mg-rich tholeiites and calc-alkaline basalts, indicating an island arc or back-arc environment (SCHÜSSLER et al. 1989; OKRUSCH et al. 1989). Another similarity is the widespread occurrence of serpentinites, whereas metasediments are subordinate. The main phase of regional metamorphism took place under conditions of the lower amphibolite facies with the assemblage

hornblende + oligoclase + epidote + opaques

in metabasites. However, the secondary, greenschist-facies minerals albite, epidote, chlorite and calcite are frequently formed, due to a strong retrogressive overprint. Additional contact metamorphism was caused by the intrusion of late-Variscan granites (e.g. MATTHES & OLESCH 1986).

ZONE OF ERBENDORF-VOHENSTRAUSS (ZEV)

The ZEV consists of pelitic metasediments with intercalations of calc-silicate rocks, graphite quartzites and graphite schists. Predominant meta-igneous rocks are amphibolites, metagabbros and meta-ultramafics. Minor orthogneisses of acid composition have not been geochemically studied so far.

Flaseramphibolites showing the assemblage

hornblende + oligoclase/andesine +- garnet +- salite + sphene + ilmenite + sulphides

prevail in the northern and central parts of the ZEV. They were also penetrated by the KTB pilote hole. Typical for this rock type is the breakdown of garnet to symplectitic aggregates of hornblende and plagioclase during a late stage of regional medium-pressure metamorphism. In their bulk rock chemistry,, the flaseramphibolites from surface outcrops and the first 500 m of the pilote hole exhibit a tholeiitic composition with marked enrichment of the incompatible trace elements conforming to an enriched-MORB or within-plate character. The enrichment is less distinct in the southernmost occurrences of the flaseramphibolites and in the depth between 1160 and 1610 m of the pilote hole (PATZAK et al. 1989, SCHÜSSLER 1990). In the Windisch-Eschenbach area, the flaseramphibolites are clearly affected by the thermal influence of the late-Variscan Falkenberg granite, leading to the formation of two types of secondary hornblende and of a new, An-poor oligoclase. The major and trace element patterns of these contact-metamorphosed flaseramphibolites are markedly disturbed (SCHÜSSLER et al. 1989).

In the southern part of the ZEV, schistose and striped amphibolites with the assemblage

hornblende + andesin/labradore + sphene + ilmenite + sulphides predominate. In their geochemical character they are similar to normal-MORB compositions.

The metagabbros exposed in the southwestern corner of the ZEV and penetrated by the KTB pilote hole are characterized by a coarse-grained, massive ophitic structure formed by platy plagioclases intergrown with large, colourless magmatic clinopyroxenes which are, however, widely replaced by metamorphic hornblendes. The structures testify to a plutonic protolith, presumably intruded into relatively shallow crustal levels. Interesting features in the metagabbros of the pilote hole, indicating a multistage metamorphic history under (?)granulite- and amphibolite-facies conditions are coronas of pyrope-rich garnet between igneous plagioclase and pyroxene, and symplectites of hornblende + plagioclase (e.g. PATZAK et al. 1989). Several generations of differently coloured hornblendes are frequently observed in the metagabbros of the ZEV. In their geochemical character the metagabbros are transitional between the schistose and striped amphibolites and the flaseramphibolites. Some of the investigated samples are depleted in incompatible elements and have higher Mg/Fe ratios and Cr contents. They are derived from a more primitive type of gabbroic protolith.

K-Ar dating of hornblendes and micas (KREUZER et al. 1989) and U-Pb dating of zircons and monazites (TEUFEL 1988) yielded age data of about 380 Ma for the western part of the ZEV, supposed to date the last metamorphic event under medium-pressure, amphibolite-facies conditions. In contrast, ages of around 325 Ma prevail in the eastern part of the ZEV. They are either due to the Variscan low-pressure event which affected the neighbouring units of the Fichtelgebirge crystalline complex and the Moldanubian s. str., or, alternatively, are caused by the intrusion of the post-tectonic Leuchtenberg granite.

THE ZONE OF TIRSCHENREUTH-MÄHRING (ZTM)

The rare amphibolites of the ZTM and the adjacent Moldanubian s. str. are very similar to the schistose and striped amphibolites of the ZEV in their normal-MORB-like geochemistry and in their mineral assemblage

hornblende + andesine +- salite +- garnet + sphene + opaques.

Radiometric data point to a last metamorphic event between 330 and 320 Ma (SCHÜSSLER et al. 1989; KREUZER et al. 1989).

THE ZONE OF TEPLA-DOMAZLICE

This zone which has been tentatively parallelized with the Münchberg gneiss complex and the zone of Erbendorf-Vohenstrauss contains a great variety of metabasites. First results of geochemical and geochronological investigations (SCHÜSSLER et al. in press; KREUZER et al. in press) are summarized here:

So far analyzed, various amphibolites, metagabbros, and eclogitic relics of the Marianske Lazne metabasic complex as well as amphibolites from the Cerna Hora massif exhibit a uiform geochemical character which compares well with modern normal midocean ridge basalts. In their chemical composition, these metabasites are similar to the amphibolites of the northern Moldanubian s. str. and to schistose and striped amphibolites from the zone of Tirschenreuth-Mähring and the southern part of the zone of Erbendorf-Vohenstrauss.

Greenschists and amphibolites from the Domazlice metamorphic complex show an alkaline-basaltic tendency conforming to modern within-plate basalts or basalts from anomalous midocean ridge segments. In their chemical character, these metabasites compare well with the flaseramphibolites of the zone of Erbendorf-Vohenstrauss. Fine-grained amphibolites in the Warzenrieth area and gabbro-amphibolites in the Bätterberg - Hoher Bogen area show normal-MORB character. The metamorphosed gabbroic rocks in the southern part of the Neukirchen - Kdyne (meta-)igneous complex are subalkaline, tholeiitic, and exhibit a magmatic differentiation trend. They differ from the neighbouring amphibolites by generally lower contents of incompatible elements.

K-Ar dating on hornblendes and micas from the zone of Tepla-Domazlice revealed a pattern of dates which significantly deviates from the mid-Carboniferous to early Permian one that is found in the adjacent Moldanubian s. str. and Saxothuringian. Especially for the Marianske Lazne metabasic complex the dates resemble the early Devonian pattern determined for the Münchberg gneiss complex and the western part of the zone of Erbendorf-Vohenstrauss. This supports the idea that all three units are remnants of a huge complex which suffered a metamorphic overprint under medium-pressure conditions, probably in the early Devonian. Strong rejuvenation is found in the southern part of the zone of Tepla-Domazlice by which micas and hornblendes were reset to mid-Carboniferous ages. This feature is due to an influence of the last, low-pressure metamorphic event which affected the neighbouring Moldanubian s. str. at that time.

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VARISCAN SYN - AND POSTTECTONIC MAGMATISM

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Orogenic magmatism generally takes place in four steps:
(1) partial-melting of various source-rocks of oceanic and continental affiliation, (2) aggregation of the melts to magmas, (3) ascent of magmas diapirically or by stoping accompanied by various modes of differentiation and (4) emplacement of magma within different levels of the orogenic edifice. In this evolutionary scheme the arrival of magmas in a deforming or quiet crustal domain is the last step and the crystallization / deformation relationship is ultimately of minor importance. Moreover, complications may arise in case of locally restricted deformations. Nevertheless on a more local scale it is helpful to employ the emplacement-deformation ratios pre-, syn-, posttectonic. At the given erosion level in the area (basement mainly of amphibolite facies) granitoids clearly predominate and the few gabbroids are preferrentially emplaced within one of the two main metamorphic units of the area (see A5). Similarly volcanites of kersantitic or rhyolitic composition are rare in the Variscan internal zone. They decorate fracture patterns mainly of N-S orientation (BEHR et al.1989).

SYNTECTONIC MAGMATISM

Only few magmatites are syntectonically emplaced, then being bound to shearzones or antiforms.
In the Bavarian Moldanubicum flaser-granites accompany the Bavarian Pfahl shearzone toward SW over a distance of ca. 35 km (Fig. 1). They are cut by dikes of undeformed granite (FISCHER 1967).
A more problematic example of syntectonic Variscan intrusion occurs outside the excursion area: the "Rotgneis" in the Saxothuringian of the eastern Erzgebirge. This partly concordant, partly discordant meta-granitoid (containing red k-feldspar phenocrysts) is located within dome structures in Variscan paragneiss of proterozoic deposition ("Preßnitzer Serie"), leaving aureoles with k-feldspar in the non-anatectic wallrock. For at least part of the Rotgneis rocks, FRISCHBUTTER (1988) has suggested shear heating as the reason for melting. Variscan deformation in amphibolite facies produces a foliation which in turn is folded with southerly facing axial planes (FRISCHBUTTER 1988).

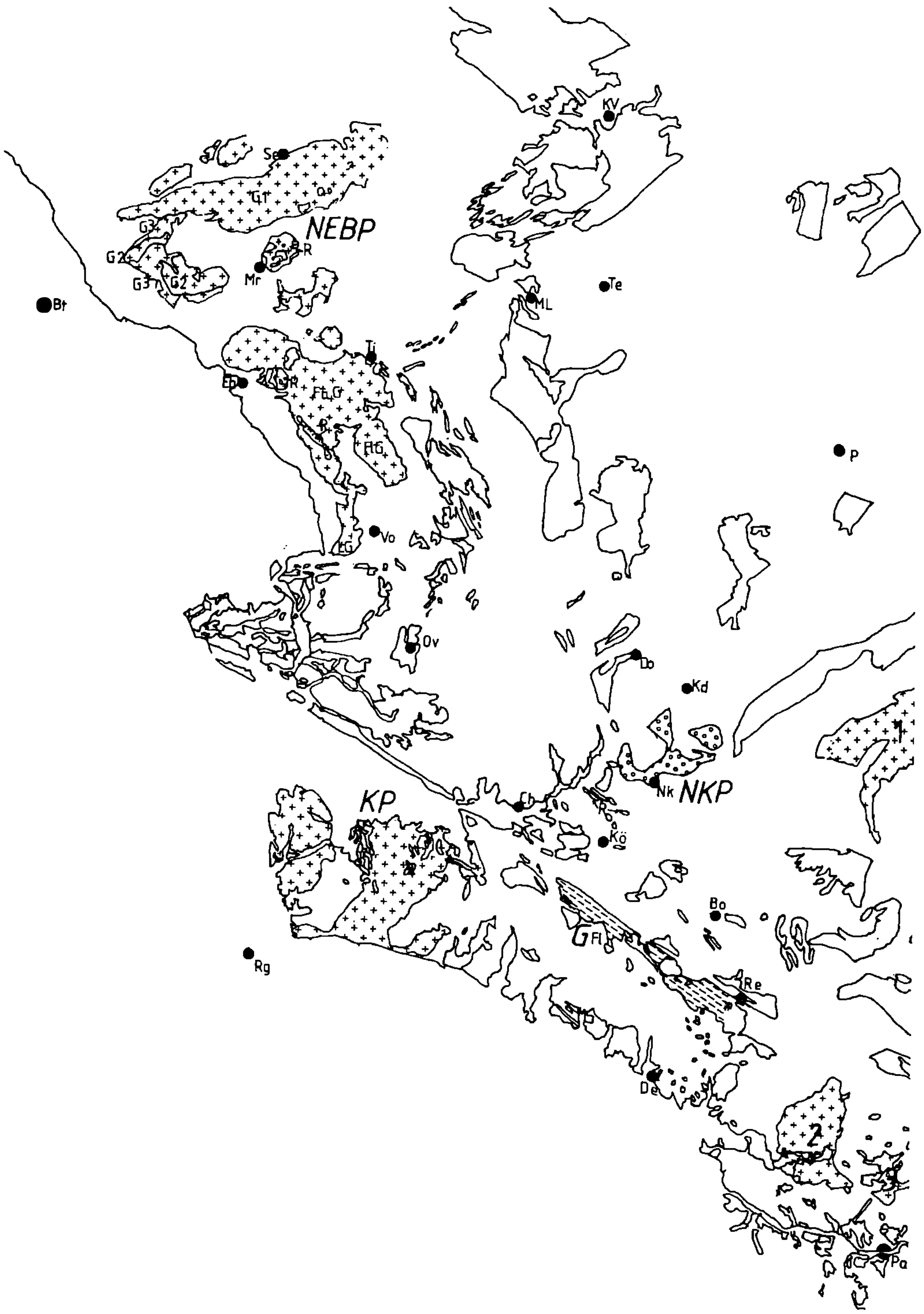


Fig.: 1 : Distribution of syn- and post-tectonic granitiods and gabbroids at the western margin of the Bohemian Massiv.

NEBP NE-Bavarian Pluton, NKP Neukirchen-Kdyně Pluton, KP Kristallgranit Pluton, G_{Fl} Flasergranit, R Redwitzit (all discussed in A4). Further Plutons: 1 Central Bohemian Pluton, 2 Fürstenstein Pluton, 3 Hauzenberg Pluton.
Bt Bayreuth, Eb Erbendorf, Mr Marktredwitz, Se Selb, Ti Tirschenreuth, Kv Karlovy Vary (Karlsbad), ML Mariánské Lázně (Marienbad), Vo Vohenstrauß, Ov Oberviechtach, Te Teplá (Tepl), P Plzeň (Pilsen), Do Domazliče (Taus), Kd Kdyně (Neugedein), Nk Neukirchen, Ch Cham, Kö Kötzting, Bo Bodenmais, Re Regen, Rg Regensburg, Dg Deggendorf, Pa Passau

Alternatively, the Rotgneis might represent Early Palaeozoic intrusions related with Cambro-Ordovician rifting. More geochemical and geochronological studies are needed to solve this problem.

Metagranitoids termed "Rotgneis" occur also in the northern part of the Saxothuringian Belt, i.e., in the Spessart Mountains. Here they are two-mica gneisses (±garnet), chemically characterized by normative corundum and ratios of $Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O) > 1.1$, which contain megacrysts of K-feldspar and xenoliths of the wallrock (OKRUSCH 1983). Their Rb/Sr whole-rock age has been dated at 424 ±18 MA (LIPPOLT 1986). The S-type signature of the Rotgneis might be taken to suggest emplacement after a compressive event (OKRUSCH & RICHTER 1986), but a late Ordovician/Silurian orogenic event is nowhere detectable in the area. Alternatively, the Rotgneis intrusion might relate to an early phase of Rhenohercynian rifting (FRANKE 1989).

SYN- TO POST-TECTONIC MAGMATITES

Major posttectonic pluton areas in the western Bohemian Massif are:

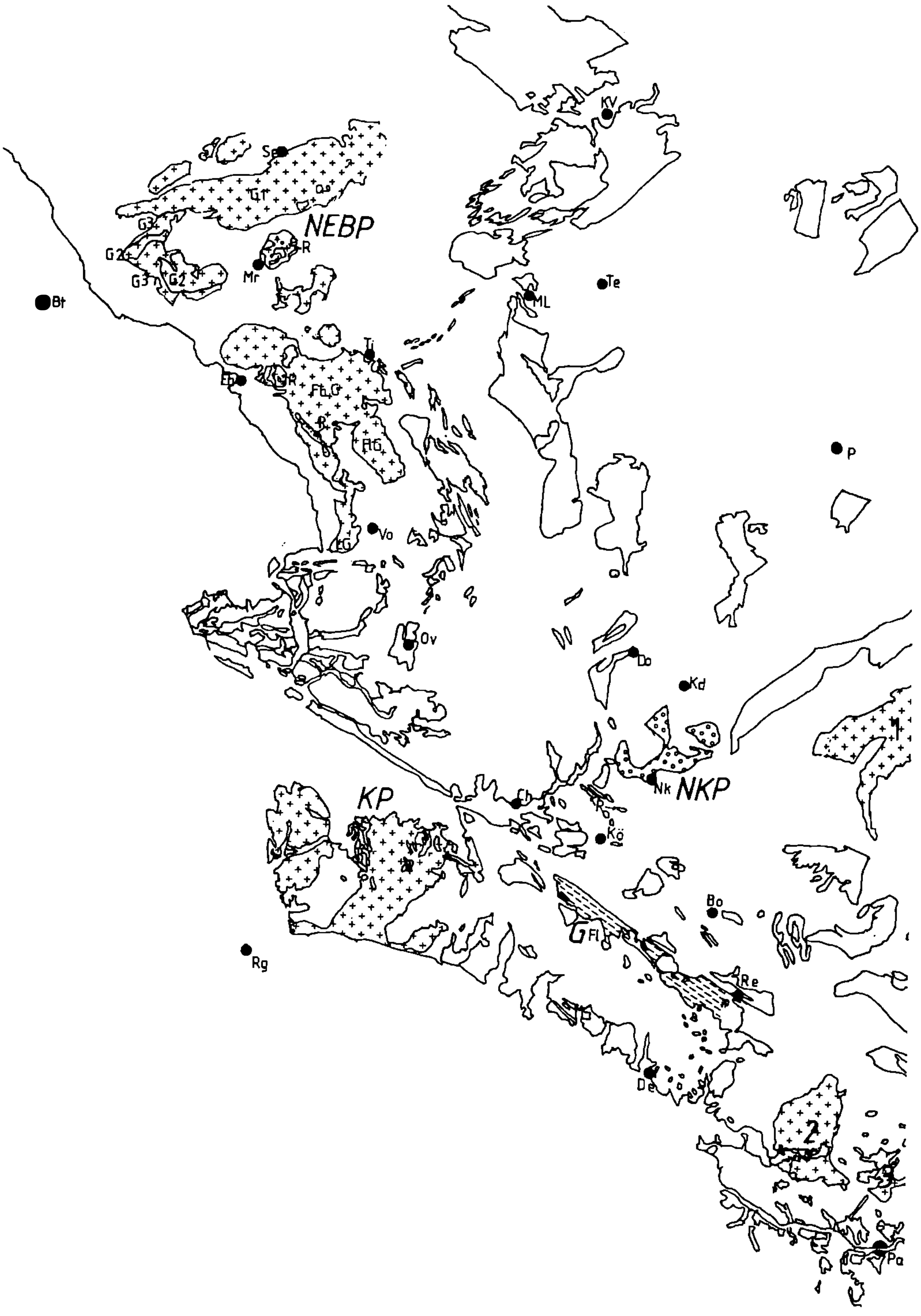
(1) the Neukirchen-Kdynè Pluton (NKP)

(2) the Kristallgranit Pluton (KP)

(3) the Oberpfalz-Fichtelgebirge-Erzgebirge-Slavkovsky les Pluton

THE NEUKIRCHEN-KDYNÉ PLUTON (Figs. 1,2), a differentiated mafic body, is included here, because it appears to be post-tectonic with respect to a pre-Variscan (Cadomian) event (see also the contribution by OKRUSCH et al.). It is situated at the southwestern edge of the Tepla'-Domazlice Crystalline Basement, which is the metamorphic equivalent of the Barrandean U. Proterozoic. The intrusion age of the NKP is bracketed by the stratigraphic age of the metamorphic wallrocks, which is supposed to be U.Proterozoic, and a K/Ar age of the cross-cutting Stod granite (approx. 450 Ma). Direct evidence comes from U/Pb zircon data (530 Ma, GEBAUER & GRÜNENFELDER 1982).

The Bavarian portion of the NKP was investigated by G. FISCHER (1929), the Czech portion by VEJNAR (1986). The pluton is divided into 3 parts: lower, middle and upper zone. It is well differentiated into basic, intermediate and acidic members in sub-conformable position with the wallrocks (micaschists, gneisses and amphibolites), producing contact-aureoles up to the pyroxene-hornfels facies.



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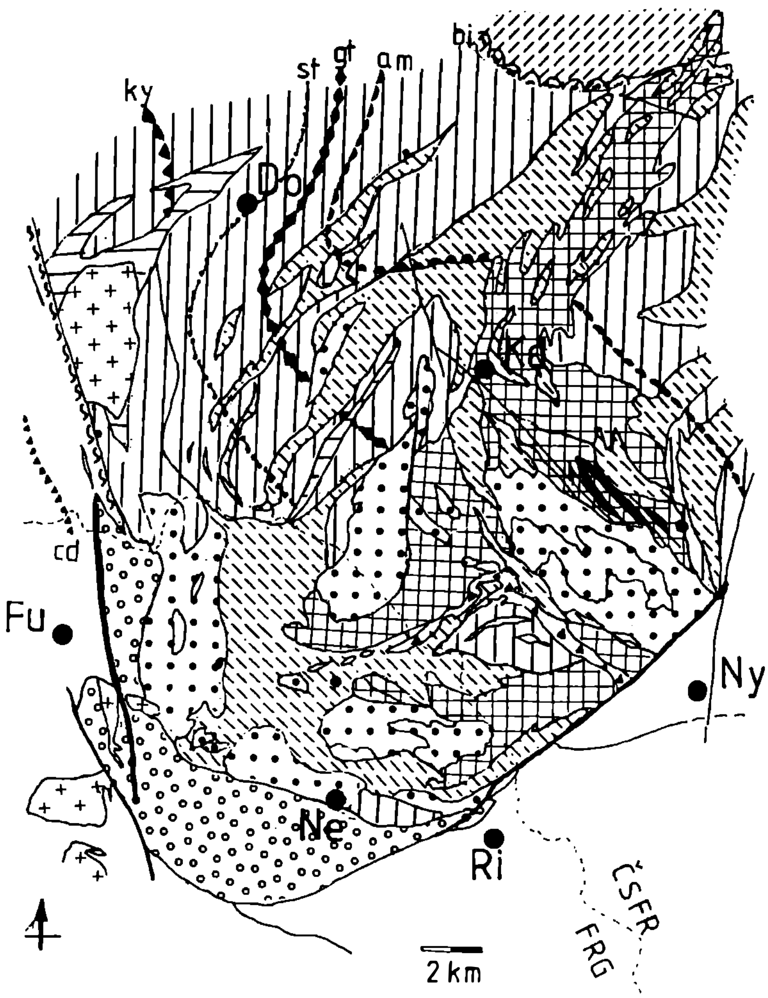


Fig.: 2 : Southwestern edge of the Zone of Teplá-Domazliče (ZTT) with the Neukirchen-Kdyně Pluton. Do Domazliče, Fu Furth i. W., Kd Kdyně, Ny Nýrsko, Ne Neukirchen, Ri Rittsteig

Domazlice cristalline region

- ZTT metasediments, phyllites (Algonkian)
- ZTT metasediments, mica schists, plg-paragneisses, bi-plg paragneisses & migmatites
- splitic greenschists (Algonkian) & associated fine grained amphibolites
- granite (includes Moldaunubian rocks)

Neukirchen-Kdyně basic complex

- gabbroamphibolites, ultrabasic rocks (serpentinite)
- gabbros, uralitized gabbros, gabbronorites & 2px-ferrodiorites
- diorite, diorite with metabasite-xenoliths quarzdiorite
- hbl-bi-tonalite & bi-trondjemite

bi / am / gt / st / ky // cd : "Isograds" of Assyntian (c. 620 Ma, bi=biotite, am=amphibole, gt=garnet, st=staurolite, ky=Kyanite) and of Variscan (cd=cordierite) regional metamorphim.

Central Bohemian Lineament, "Böhmischer Pfahl"

However, uralitization is widespread and (?) mylonitic deformation producing a NE-dipping foliation is locally observed. In the southwestern (Bavarian) portion of the pluton, olivine gabbro, "uralite" gabbro and diorite occur, the contact relations with the wall rocks being buried below thick quarternary deposits.

Medium-grained olivine-gabbro contains euhedral plagioclase (An 58-64), anhedral olivine (X^{Mg}= 0.68-0.72), poikilitic augit (X^{Mg}= 0.75-0.88; Al_2O_3= 2.58-3.66 wt.%) enclosing plagioclase, furthermore dark-brown hornblende, ilmenite and pyrrhotite. Olivine may be rimmed by bronzite or augite (inner corona) and by brown amphibole (outer corona).

Gabbronorite contains olivine (X^{Mg}= 0.37-0.57), orthopyroxene (X^{Mg}= 0.63-0.71; Al_2O_3= 0.73-1.56 wt%), augite (X^{Mg}= 0.70-0.75; Al_2O_3= 2.36-2.62 wt%), plagioclase, brown amphibole, ilmenite, pyrrhotite and apatite. Olivine is rimmed by hyperstene and amphibole.
Anorthositic schlieren (thickness: several cm to dm) are rimmed by seams of olivine+pyroxene+ilmenite+apatite. Single ultramafic layers rich in olivine (X^{Mg}= 0.38-0.40) and ilmenite (up to 15 vol.%) were mined for iron and investigated as potential Ti ore.

Fine-grained massive diorites comprise varieties with pyroxene, pyroxene+amphibole or pyroxene+amphibole+biotite as mafic phase(s) with or without quartz, pyroxene being represented by augite ± hypersthene. Among them ferro-diorite contains olivine (X^{Mg}=0.02 - 0.22) + orthopyroxene + clinopyroxene + andesine + ilmenite + apatite.

The most acidic members comprise granodiorite, tonalite and trondhjemite the latter two being observed in an intrusive position with the basic parts of the pluton.

The NKP displays a primary zonality with gabbro toward SW and gabbrodiorite plus quartzdiorite toward NE, which resulted from differentiation within one single intrusive phase. This vertical magmatic polarity coincides with the direction of decreasing regional metamorphism in the wallrocks., which has been dated at about 380 Ma by K/Ar on hornblendes (SCHÜSSLER et al. 1989). These features indicate strong NE-ward tilting of the Variscan metamorphic zonation and the older intrusive body.

Two differentiation trends seem to seperate out of the gabbro-gabbrodiorite-diorite sequence, a calcalkali trend via tonalite and granodiorite to trondhjemite and a Skaergaard-like trend toward ferrodiorite. It may well be that the acidic units form a genetically independent intrusion.

Besides the NKP, the KRISTALLGRANIT (G.KRAUS 1962; G.FISCHER 1965, Fig.1) is the oldest postmetamorphic pluton in the Moldanubian of Bavaria. It is situated in several antiforms within anatectic paragneiss of the western Bavarian Forest and may have either diffuse contacts blurred by the growth of K-feldspar or discordant contacts, both suggesting a near in-situ position of the pluton. Kristallgranit I, the main mass of the pluton, is characterized by K-feldspar phenocrysts (average diameter: ca. 3 cm) set in a groundmass of grano- to quartzdioritic composition. The K-feldspar phenocrysts are arranged in a subparallel way to the paragneiss contact of the granite and even seem to trace the geometric b of the youngest deformation in the paragneiss (KRAUS 1962).
The modal composition is: kf 34%, plag (An 19-28) 28%, qu 27%, bi (±cord) 9%, accessories 2%. In the Streckeisen plot it extends at kf/(kf+plag) values of 15-60 and at qu values of 20-45. Kristallgranit I is cut by fine-grained diorite, which in turn is "corroded" by dikes of Kristallgranit II compositionally similar with Kristallgranit I. The average chemical composition is (wt%): SiO_2: 68.3, TiO_2: 0.63, Al_2O_3: 15.0, FeO: 3.3, MnO: 0.05, MgO:1.1, CaO: 2.0, Na_2O: 3.0, K_2O: 5.0, P_2O_5: 0.28, Al_2O_3/Na_2O+K_20+CaO = 1,5; K_2O/Na_2O 1.7; (PROPACH 1977).

Eleven whole rock samples from different localities of the Kristallgranit I define a Rb/Sr isochrone age of 349 ± 11 MA, which is interpreted as the intrusion age. The Rb/Sr- age of biotite is 326 ± MA. The low $^{87}Sr/^{86}Sr$ ratio of 0.7076 (± 0.0005) - lower than that of the wallrock (0.715) - is interpreted to result from a lower crust protolith (KÖHLER & MÜLLER-SOHNIUS 1986; KÖHLER, unpub. data). Another genetic interpretation is put forward by PROPACH (1989). Accordingly Kristallgranit I was derived from the anatectic wallrocks plus a component of ca. 10% melt of basaltic composition.

In the northwestern part of the Bohemian Massif, a pronounced gravity minimum (< 100 mgal) is measured, which extends through the southern Saxothuringian turning southwards into the northern Moldanubian of West Bohemia and NE-Bavaria (Behr et al. 1989). Here several posttectonic granitoid complexes occur, among others the intrusive complexes of the Erzgebirge - an older complex with biotite monzogranite to leucogranite, and younger complex with Li-F granites containing the famous Saxonian tin mineralization; (TISCHENDORF et al. 1987)- and the NE-Bavarian Pluton (Fig. 1) comprising basic and intermediate members (termed "Redwitzit") and several generations of granites (MADEL 1975; RICHTER & STETTNER 1979).

Fig.: 3a : Chemical composition of redwitzite varieties (gabbrioc, dioritic and granodioritic) in the Fichtelgebirge area (wt. %) :

	gabbro	diorite	granodiorite
SiO_2	49.41	54.54	63.84
TiO_2	0.85	1.30	0.78
Al_2O_3	11.73	16.66	15.94
Fe_2O_3	2.17	1.55	0.45
FeO	6.98	5.30	3.95
Mno	0.14	0.12	0.08
Mgo	16.23	3.68	3.23
CaO	6.59	7.29	4.21
Na_2O	1.71	3.00	2.97
K_2O	1.80	2.52	3.28
P_2O_5	0.33	0.55	0.30
H_2O	2.06	1.49	0.70

Fig.: 3b: Modal composition ofredwitzite varieties (gabbroic, dioritic and granodioritic) in the Fichtelgebirge area (wt. %) :

	gabbro	diorite	granodiorite
Px (mainly hypersthene)	3.5	---	---
Hb	50.7	19.8	1.2
Pl	24.4	39.2	42.7
Bio	18.1	18.9	24.2
Kf	---	6.2	8.9
Q	1.3	13.4	22.0
accessories	2.0	2.5	1.0
An content	65 37	50 30	43 28

Fig.: 3c : Streckeisen plot of redwitzites and granites from the NE-Bavarian Pluton:

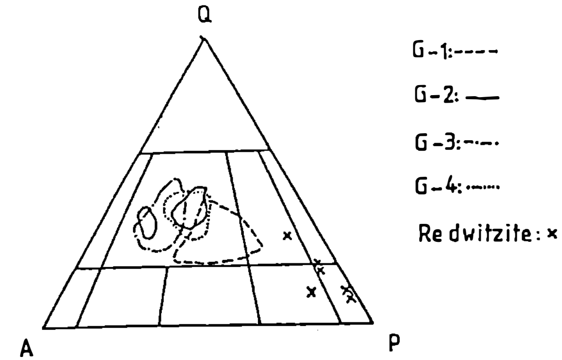
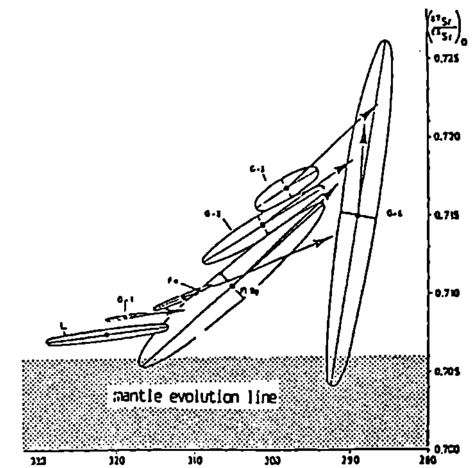


Fig.: 3d : $^{87}Sr/^{86}Sr$ evolution diagram for granites of the NE Bavarian Pluton (NEBP)



Another member of the NEBP is the "REDWITZIT" (NE Marktredwitz), a differentiated pluton (ca. 20 km^2) comprising the range between gabbro and granite (TROLL 1967). Chemical and modal composition as well as Streckeisen plot are shown in Figs. 3a-c.

The redwitzites are characterized by their petrographic inhomogeneity, the richness in magmatic xenoliths with diffuse borders against the hostrock, and in particular by the replacement of augite and hornblende by large blades of biotite. Main-oxide variation diagrams display distribution patterns compatible with magmatic differentiation. However textures and isotope data (Sr, Nd, O_2) point to magma mixing (during emplacement) of a differentiating basaltic magma with an intruding granitic melt. Mixing is also indicated by a Rb/Sr "isochrone" age which exceeds by far that of the metasedimentary wallrocks (468 MA; KÖHLER, PROPACH & TROLL 1989).

The granites of the NEBP (G1,G2,G3,G4) are mainly porphyric and chemically characterized as per-aluminous (muscovite, cordierite, andalusite or/and sillimanite). Pelitic contact aureoles contain cordierite + andalusite (or/and sillimanite) + muscovite (or k-feldspar) (locally even: cordierite + garnet + sillimanite + biotite + k-feldspar, OKRUSCH 1971). Geochemical criteria like the $^{87}Sr/^{86}Sr$- age plot (Fig. 4), the correlation Li-Rb, Sr-Ba and TiO_2-Zr seem to indicate a comagmatic origin (RICHTER & STETTNER 1979; WENDT et al. 1986).
The sequence of NEBP intrusion is as follows (WENDT et al.):

G1 (Weißenstadt-Marktleuthen, Reut, Selb, Leuchtenberg): 319 ± (3)MA
Falkenberg granite : 315-308MA
Flossenbürg granite : 306-303MA
G2 (Randgranit), G3 (Kerngranit), G4 (Zinngranit) : 301-295MA

G1 has probably the geometry of a southward dipping plate the dip being indicated by xenolithes, pegmatites and aplites near the southern edge. It intrudes the Fichtelgebirge anticline (B: WSW-ENE) and cooled rapidly (nearly concordant mica ages). Conversly the younger granites are spread toward south of the G1 independently of the WSW-ENE fold structure and form small stocks with a thin contact-aureole. Among them G2 may be compared with the older, and G3 and G4 with the younger intrusive complex of the Erzgebirge. G3 locally may contain restitic "xenoliths" with garnet, cordierite, andalusite/sillimanite and green spinel. G4 was rich in volatiles as indicated by miaroles containing topaz, tourmaline, zinnwaldite and cassiterite as well as by greisen with tungsten. The Oberpfalz part of NEBP protrudes toward south into the Moldanubian in two fingerlike massivs. Among them the Flossenbürg granite seems to dip gently toward SE below its wallrocks, since here pegmatite bodies (e.g. the wellknown Hagendorf pegmatite) and hydrothermal alteration is widespread. The other finger-like body is the Leuchtenberg granite of a steeply E-dipping plate-like geometry (MADEL 1975). Flow fabrics with kf-phenocrysts resembling convection cells (width ca. 4m) are known from the Falkenberg granite (FISCHER 1967). Geochemical surface trend analysis of the Oberpfalz granites revealed their genetic correspondence as well as locally differing directions of magmatic fractionation (ACKERMANN, unpub. DFG reports, MADEL 1975).

Variscan magmatism terminates with the crystallisation of pegmatites (Plößberg-Hagendorf area: phosphates, beryll and columbite; similar mineralization in Bodenmais area), of rhyolite dikes (locally with cordierite) and of hornblende porphyry (cutting late mylonites).

Recent geochemical studies of the central-European posttectonic plutonism (HENES-KLAIBER 1989; LIEW et al. 1989; LIEW & HOFMANN 1988) reveal the existence of:

(1) I-type (and minor S-type) plutons in the Odenwald (part of the Saxothuringian)

(2) S-type (and some I-type) plutons in the Schwarzwald (part of the Moldanubian)

(3) I-, "transitional"- and S-type plutons in the southern Bohemian Massiv (part of the Moldanubian)

From this LIEW & HOFMANN (1988) and LIEW et al. (1989) deduce a paired pattern (from N toward S) of continental margin I-type with inner continent S-type plutons, and, hence, subduction towards south from the Rhenohercynian Zone. This concept is thought to be at variance with the model of ZIEGLER (1986), who suggested accretion of continental fragments to the southern margin of Europe in a regime with northward subduction. These considerations disregard the fact, that the Variscan Belt of Europe is a collage of at least three separate subduction zones with a bilateral symmetry, the Rhenohercynian and Saxothuringian Belt on the flank of the orogen displaying tectonic polarity directed northwards (i.e., southward subduction), and a Moldanubian front driving southeastwards (northwestward subduction; see the introductory contribution by FRANKE). In fact, FINGER & STEYRER (1988) have reported I-type plutons from the Eastern Alps, which they relate with northward subduction. Any more conclusive discussion of the Variscan plutons requires a complete study of all plutonic rocks, and especially more precise age-dating.

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METALLIC AND NON-METALLIC ORE MINERALIZATION IN NORTHEASTERN BAVARIA

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ABSTRACT

The ore formation in northeastern Bavaria is described in terms of the geological history. Upper Proterozoic sulfide mineralizations in the Saxothuringian Zone might be interpreted in favour of a submarine-exhalative ore formation due to an arc volcanism. Sulfide deposits in the Moldanubian Zone are possibly temporally and genetically similar. There is no evidence for Early Palaeozoic ore deposits in the Bavarian part of the Moldanubian Zone. On the contrary, different types of ore deposits have been formed during the Early Palaeozoic time in sedimentary and volcano-sedimentary lithologies in the Saxothuringian Zone, in part obviously due to rifting. Late-Variscan, granite-related ore formation (greizen, vein-type and skarn-type) include tin, tungsten and uranium occurrences and deposits. They are presumably a heritage from older (Proterozoic and Early Palaeozoic) preconcentrations. The post-Variscan ore formation in northeastern Bavaria is due to a platform evolution, either as vein-type along faults (e.g. fluorite-barite and (Cu-)(Ag-)Pb-Zn) or as ore-bearing platform sediments (iron, kaolinite-feldspar-quartz, coal and clays).

INTRODUCTION

The Mid-European Variscides are subdivided into the Rhenohercynian, Saxothuringian and Moldanubian Zones. The Rhenohercynian Zone in the NW is separated by the Mid-German Crystalline Rise from the Saxothuringian Zone, which in turn is connected by the Erbendorf Line with the Moldanubian Zone in the SE. The latter includes the Erbendorf-Vohenstrauss Zone (ZEV) with the Continental Deep Drilling (KTB) site. The Moldanubian Zone is composed largely of polymetamorphic gneisses and mica schists, and minor amphibolites of probably Proterozoic age. Metasediments of Early Palaeozoic (Silurian) age, however, have been recently identified in the Moldanubian Zone by palynological data (PFLUG & REITZ, 1987; REITZ & HÖLL, 1988). Preferably Palaeozoic rocks form the Saxothuringian Zone. The existence of Upper Proterozoic (Lower Vendian) strata in the Saxothuringian Zone has been assured by palynological results (REITZ & HÖLL, 1988).

mineralization (KNAUER & MATTHES, 1970; DILL, 1988). Pyrrhotite, pyrite and chalcopyrite are disseminated in amphibolites of the Randamphibolit (DILL, 1985a, 1988). Small gold occurrences are also known within the Münchberg gneiss mass.

UPPER PROTEROZOIC

In the Moldanubian Zone rocks of probably Upper Proterozoic age are abundant. They are host to some sulfide deposits in an area from the Mt. Osser in the NW to the Mt. Rachel in the SE: Johanneszeche and Fürstenzeche near Lam, Silberberg near Bodenmais, Roter Koth near Zwiesel (HEGEMANN & MAUCHER, 1935; SCHRÖCKE, 1955; DILL, 1985a; TROLL et al., 1987). These deposits have many features in common: The major deposit Silberberg has been summarized by TROLL et al., 1987: Banded cordierite-gneisses and cordierite-garnet-sillimanite-bearing metatexites are associated with calcsilicate-gneisses, quartzites, silicic gneisses, sillimanite-bearing rocks and granitic rocks. Intercalated are the predominantly iron sulfide ores of the Silberberg Mine, biotite-monazite-rich layers in close contact with sulfide lenses and bands, and both anthophyllite-bearing rocks and magnetite-rich layers at the base of the ore horizon. The sulfide mineralization and most of the lithologies suggest an initial sedimentary regime characterized by variation in space and time. Rocks of this sequence might contain a substantial volcanic component, and the ore itself might be of volcanic, submarine-hydrothermal origin. There is also evidence for a possibly widespread, low-grade scheelite mineralization in metabasites of presumably Upper Proterozoic age (JUNG & HÖLL, 1982, 1989; DILL, 1985a). The graphite mine Kropfmühl near Passau is the only active graphite mine in the European Community and a major graphite producer. The strongly tectonized graphite beds and lenses of biogenic origin in a metamorphic, probably Upper Proterozoic volcano-sedimentary rock series contain some 30 % C on the average (WEINELT, 1987).

In the Saxothuringian Zone recent palynological data indicate an Upper Proterozoic (Lower Vendian) age for the Prasinit-Phyllit-Serie at the southern rim of the Münchberg gneiss mass (REITZ & HÖLL, 1988). This series was formerly considered being of Ordovician age (STETTNER, 1964; FRANKE, 1984; DILL, 1985a, 1988). It is composed mainly of phyllites and metavolcanics (calcalkali basalts) (OPPERMANN, 1985).These metavolcanics represent an arc volcanism and are host to stratiform sulfide occurrences (near Sparneck) with pyrite, pyrrhotite, chalcopyrite and sphalerite.

These occurrences are interpreted as submarine-exhalative ore mineralization (HEGEMANN, 1937; WURM, 1961). DILL (1988) assumes that the lack of galena and a barite fringe, the absence of alteration zones and the calcalkaline host rock lithology might be indicative for a tentative classification of these volcanic-hosted sulfide occurrences as Besshi-type rather than Kuroko-type. However, no outcrops or underground exposures exist any more for further studies.

Fig. 1. Metallic and non-metallic ore deposits in Northeastern Bavaria.

The Palaeozoic record in the Saxothuringian Zone is characterised by two distinct lithological groups, called "Thuringian Facies Group" and "Bavarian Facies Group". Both groups differ from the Cambrian to the Lower Carboniferous, albeit gradual changes. The Bavarian Facies Group rims the Münchberg gneiss mass. The Thuringian Facies Group is widespread elsewhere. During late-Variscan times, granitoids have been emplaced in wide areas (e.g. in the Fichtelgebirge and Oberpfälzer Wald). After the Sudetian (Lower/Upper Carboniferous) tectonism, the Bohemian Massif, including its

Bavarian realm, was uplifted and rimmed by platform-type Permian and Mesozoic-Cenozoic rocks in the southwest and north.

Mining of mostly small metallic and some partly large non-metallic ore deposits is reported since ancient times. Mining of non-metallic ore deposits is still of great economic importance. Many papers on ore deposits and occurrences in northeastern Bavaria have been published (e.g. WURM, 1924, 1961; TEUSCHNER & WEINELT, 1972; SCHMID & WEINELT, 1978; SCHWERD & WEINELT, 1987). Compilations of the metallogenetic evolution in geodynamic models from the Cambrian to the Mesozoic have been presented by DILL (1985a, 1988).

The record on the ore formation in the Saxothuringian Zone covers the long interval from the Upper Proterozoic to the post-Variscan time. In the Bavarian part of the Moldanubian Zone, ore formation obviously occurred in probably Upper Proterozoic as well as in Variscan and post-Variscan times. There is no clear evidence, however, for Early Palaeozoic ore deposits in this part of the Moldanubian Zone.

MÜNCHBERG GNEISS MASS

The Münchberg gneiss mass in northeastern Bavaria forms a block of medium- to high-grade metamorphic rocks amidst Palaeozoic rocks of the Saxothuringian Zone. Interpretations as a nappe system (e.g. BEHR et al., 1984; FRANKE, 1984; WEBER & VOLLBRECHT, 1986) are still questioned (e.g. GANDL et al, 1986; BAYER & HOCHSIEDER, 1989; SCHREIBER, 1989). The Münchberg gneiss mass is composed of an Upper Series ("Hangendserie") (predominantly metabasites, including widespread amphibolites and minor eclogites) and a Lower Series ("Liegendserie") (mainly gneisses) (STETTNER, 1960). It is surrounded by amphibolites ("Randamphibolit") and a prasinite-phyllite series ("Prasinit-Phyllit-Serie"). SÖLLNER et al. (1981a, 1981b) proposed an Upper Proterozoic/Cambrian age for metasediments (paragneisses) of the Liegendserie and an Early Palaeozoic (probably Cambrian/Ordovician) age for metasediments of the Hangendserie. The eclogites and amphibolites in the Hangendserie are interpreted being of oceanic tholeiite and Al-gabbroic origin (MATTHES et al., 1975; DILL, 1988) with a supposedly Early Palaeozoic protolith age (GEBAUER & GRÜNENFELDER, 1979). The medium- to high-grade metamorphism occurred presumably between 400 and 380 my (SCHÜSSLER & et al., 1986).

The amphibolites and eclogites of the Münchberg gneiss mass together with the metabasites of the Randamphibolit and possibly also some serpentinite wedges in the Prasinit-Phyllit-Serie probably represent an (incomplete) ophiolite sequence, and might be interpreted as remnants of an oceanic crust due to an advanced stage of rifting of possibly Cambrian-Ordovician age. In the Münchberg gneiss mass no lithologies have been found that might be attributed to the Silurian or any younger formation. Some of the metabasites of the Hangendserie host a very scarce magmatic Ni-Fe-Cu-Ti mineralization (KNAUER & MATTHES, 1970; DILL, 1988). Pyrrhotite, pyrite and chalcopyrite are disseminated in amphibolites of the Randamphibolit (DILL, 1985a, 1988). Small gold occurrences are also known within the Münchberg gneiss mass.

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WEINHOLD (1977) and BAUMANN (1979) have described widespread, stratabound ore mineralizations, including many ore occurrences within the Upper Proterozoic Pressnitz series (Pressnitz-Serie) in the Erzgebirge (German Democratic Republic and Czechoslovakia). These ore mineralizations comprise Fe oxides in carbonate-volcanogenic lithologies, sulfide ores (Fe, Cu, Zn, Pb) and Fe silicates in pelitic-volcanogenic sequences, and most interestingly stratiform cassiterite-sulfide ores in a pelitic-volcanogenic-siliceous rock sequence (Felsithorizont, i.e. "felsic bed" e.g. of the Halsbrücke ore deposit near Freiberg, GDR). This metamorphic cassiterite-sulfide ore mineralization is interpreted in terms of a syngenetic-submarine ore formation due to hydrothermal fluids from intrusive magmas (WEINHOLD, 1977; BAUMANN, 1979). The Pressnitz series is considered to be an equivalent of the spilitic and post-spilitic, Upper Proterozoic series of Bohemia. The author suggests that it might also be coeval with the Prasinit-Phyllit-Serie and possibly represent an Upper Proterozoic active continental margin evolution. Furthermore, a close temporal relationship is also indicated to the Upper Proterozoic Habach Group within the Tauern window/Eastern Alps due to fossil evidence (REITZ & HÖLL, 1988). The Habach Group represents a volcanic-sedimentary rock sequence from an active continental margin, and includes the large stratabound scheelite deposit Felbertal (HÖLL, 1975; HÖLL & SCHENK, 1988). There is also evidence for a pre-Variscan, possibly also Upper Proterozoic scheelite mineralization in northeastern Bavaria (JUNG & HÖLL, 1982, 1989; DILL, 1985a). Supposedly pre-Variscan tin and tungsten mineralizations have been remobilised in Variscan time, when granite-related tin and tungsten deposits formed.

CAMBRIAN

The Pressnitz series of the Erzgebirge has presumably been partly eroded still in Precambrian time. It is overlain by transgressive metasediments of the supposedly Lower Cambrian Keilberg series (WEINHOLD, 1977). In Thuringia, no unconformity is indicated between the Upper Proterozoic Katzhütter Schichten and the Lower Cambrian Goldisthaler Schichten (Thomas Heuse, Bergakademie Freiberg, personal communication).

Widespread sulfide (Fe-Cu-Zn-Pb) and above all magnetite ore occurrences are closely related to amphibolite (metatuffs) and carbonate beds in the Keilberg series (e.g. near Hammerunterwiesenthal) and in the possibly Middle and Upper Cambrian Joachimsthal series, where cassiterite is locally an accessory mineral.

These ore beds are interpreted in terms of an originally submarine-exhalative ore formation by WEINHOLD (1977) and BAUMANN (1979).

In northeastern Bavaria, no fossils have been found in possibly Lower Cambrian sediments. The Middle Cambrian of the Bavarian Facies Group in the Saxothuringian Zone is assured by fossil evidence at some restricted areas. Its sediments display a clastic deposition. An intra-basinal volcanism, mostly as volcaniclastics, might be attributed to progressive rifting. Minor phosphorites are regarded as indicative of coastal upwelling (DILL, 1988). Ore deposits are unknown.

In the Thuringian Facies Group, metasediments of greenschist- to amphibolite-facies metamorphism, mainly in the east and southeast of the Saxothuringian Zone are supposedly of Cambrian age. Predominantly pelitic and psammitic metasediments and minor marble beds are interpreted due to sedimentation in a continental rift basin possibly near the shelf. At Bayerland near Waldsassen, lenticular beds with pyrrhotite, pyrite, chalcopyrite, sphalerite and galena have been mined (MAUCHER, 1939; SPROSS, 1954; PFEUFER, 1960; WOLF,1971; DILL, 1985a, 1988). Their host rocks are sericite-chlorite schists, mica schists, and quartzites of presumably Cambrian age. This stratiform ore deposit is "sediment-hosted" sensu LARGE (1980) or of "Sullivan-type" sensu SAWKINS (1976). Magmatic activity is indicated by tuffaceous beds.

ORDOVICIAN

The Bavarian Facies Group includes small occurrences of Tremadocian Leimitz slates and more widespread Randschiefer series surrounding the Münchberg gneiss mass. A volcanism in the Randschiefer series is indicated by alkali basalts and keratophyres (WIRTH, 1978). The red staining of mudstones in this series has been attributed to hydrothermal brines with Fe oxide precipitation in oxygenated sites (DILL, 1985a, 1988).

The Thuringian Facies Group is characterized by clastic sequences (Frauenbach schists, Phycode schists) of Lower Ordovician age. During Middle and Upper Ordovician times preferably fine-grained sediments have been deposited presumably on a passive continental margin. Oolitic Fe ores with substantial amounts of Fe phyllosilicates (thuringite, chamosite) together with magnetite and siderite have been formed in two seams (lower and upper Fe seam), possibly within a lagoonal environment, e.g. near Lauenstein-Schwarzenberg. These iron ores have been mined in the past. DILL (1988) claimed that these near-shore iron ores laterally change into stratiform iron ores of hydrothermal origin.

Stratabound base metal sulfide occurrences in phyllites and marble beds and minor basaltic tuffs of Lower Ordovician age in the Erzgebirge (e.g. near Johanngeorgenstadt-Kraslice, Plaue and Hermsdorf) have been interpreted in favour of a submarine-hydrothermal ore formation by WEINHOLD (1977) and LEGLER (1985).

However, there is no evidence for an Ordovician subduction-related ore formation in the Thuringian or Bavarian Facies Groups or further east, as supposed by DILL (1988). The Prasinit-Phyllit-Serie with an arc volcanism and volcanic-hosted sulfide occurrences is not of Ordovician, but Lower Vendian age (REITZ & HÖLL, 1988). The Kupferberg sulfide deposit is not hosted by Ordovician, but obviously by Lower Devonian (early Emsian) metasediments (HAMMANN et al., 1989).

SILURIAN

The Silurian period comprises similar lithologies in the Thuringian and Bavarian Facies Groups, apparently with only minor volcanic activity. Fine-grained sediments of the graptolite shale facies or limestones have been preferably deposited, depending on water depth. The graptolite shale facies is composed of chert, alum shales and phosphorites. Its setting is interpreted as a starved basin (DILL, 1988). These shales might be considered as large tonnage, very low-grade deposits with enrichments in Cu, Zn, Pb, Au, V, Mo, U etc. (SCHMID, 1980; DILL, 1986, 1988). In the alum shales pyrite is a common sulfide mineral, together with minor chalcopyrite, galena, sphalerite and tetrahedrite. This sulfide mineralization obviously formed during diagenesis, and was subsequently remobilized (DILL, 1988).

DEVONIAN

The Devonian period is of special interest for sulfide and hematite ore deposits. The Kupferberg-Wirsberg sulfide deposits have long been considered of Ordovician age (URBAN & VACHE, 1972; DILL, 1985a, 1988). Palynological data, however, indicate a Lower Devonian age for the host rocks (shales, basaltic metatuffs) at least for the Kupferberg ore deposit (HAMMANN et al., 1989). This stratiform ore deposit is interpreted as a submarine-exhalative ore mineralization (mainly pyrite, minor chalcopyrite, sphalerite, galena, pyrrhotite, magnetite, traces of silver and gold), followed by a superficial bornite-chalcosite-chalcopyrite enrichment (URBAN & VACHE, 1972).

During the Upper Devonian basaltic volcanics (pillow basalts, tuffs) have been erupted. The age of the volcanism is of lower Adorf stage due to fossil evidence (GANDL, 1989). Lahn-Dill type iron ores occur are well exposed in the active hard-rock quarry HEISS, about 1 km east of Stadtsteinach. A quartz-hematite ore mineralization is disseminated, irregularly dispersed or concentrated in veinlets within pillow basalts, pillow breccias and tuffs. Stratiform quartz-hematite enrichments ("Roteisen-Grenzlager") with minor magnetite and sulfides (pyrite, chalcopyrite, sphalerite) on top of these submarine volcanic rocks are overlain by dark slates. On a regional scale, unconformities and stratigraphic gaps supposedly reflect a basin-and-swell topography (DILL, 1988). These oxide iron ore occurrences in northeastern Bavaria are small analogues to the bigger and previously economically important Lahn-Dill type deposits in the Rhenohercynian Zone east of the Rhine River (Lahn and Dill areas, Ostsauerland and Balve areas, Elbingerode Complex and Oberharzer Diabaszug/Harz Mountains) (BOTTKE, 1965). These ore deposits in the Rhenohercynian Zone have supposedly formed on a relatively thin crust at volcanic seamounts, preferably along NE-SW and less important NNW-SSE volcanotectonic fracture zones (WERNER, 1989, 1990). The biggest iron ore deposits (hematite, minor magnetite and siderite) have been deposited at the Givetian-Frasnian boundary ("Grenzlager") (BOTTKE, 1965). They are overlain by shales or cephalopod-limestone beds. Given this age for the Grenzlager and new fossil evidence by GANDL (1989) for the hematite-quartz occurrences in northeastern Bavaria, a slightly younger ore formation in northeastern Bavaria is indicated, otherwise a very close genetical relationship is inferred. Two groups of genetic models for the Lahn-Dill type Fe-rich exhalites have been reported (WERNER, 1990): In the first model the iron and silica are derived from cooling basaltic magmas (LEHMANN, 1972; QUADE, 1976). The second model involves leaching of Fe, Mn, Si and Ca from the underlying volcanic rocks by circulating seawater (HENTSCHEL, 1960; WEDEPOHL et al., 1983), whereby a submarine, syndiagenetic low-temperature alteration has been concluded by FLICK & NESBOR (1988).

LOWER CARBONIFEROUS

In the Lower Carboniferous, flysch facies rocks (slates and greywackes) are dominant both in the Bavarian and Thuringian Facies Groups. Minor occurrences with Hg, Sb, As and Au are interpreted by DILL (1985b, 1988) to be fault-controlled. The age of this ore formation, however, is questionable.

UPPER CARBONIFEROUS AND LOWER PERMIAN

The Variscan orogeny with the Sudetian tectonism at the Lower/Upper Carboniferous boundary terminated the sedimentation (flysch facies) of both the Bavarian and Thuringian Facies Groups. After the collision of the Saxothuringian and the Moldanubian realms post-tectonic granitoids intruded in the Fichtelgebirge-Erzgebirge anticline as well as further south both in the Saxothuringian and Moldanubian Zones. These plutonic rocks have been dated at 325 - 280 my (KÖHLER et al., 1974; KÖHLER & MÜLLER-SOHNIUS, 1976; BESANG et al., 1976; CARL et al., 1985; SCHÜSSLER et al., 1986). Four stages of granitoid emplacement in the Fichtelgebirge have been concluded (STETTNER, 1958, 1960, 1964; RICHTER & STETTNER, 1979, 1987). These granitoids display an increasing differentiation from the oldest (G 1)(310+/-14 my) to the youngest (G2 - G4)(291+/-7 my to 285+/-6 my) (BESANG et al., 1976).
A minor scheelite mineralization in a vesuvianite-garnet skarn at the contact of the Wunsiedel marble (dolomite) to the Weissenstadt-Marktleuthener granite within the active talcum (soapstone) mine Göpfersgrün near Wunsiedel (JAKOB, 1979) is genetically related to hydrothermal fluids after the emplacement of this oldest granite (G 1) (JUNG & HÖLL, 1982, 1989). The formation of the talcum (soapstone) preferably within the Wunsiedel marble (dolomite) by a Mg metasomatism has followed

the scheelite deposition at lower temperatures. STETTNER (1959), however, concluded a genetical relationship between the talcum formation and fluids after the emplacement of a Lower Permian rhyolite. Younger granites (e.g. Kerngranit (G 3) of the Epprechtstein area) also display some increased tungsten and tin content. The youngest and highly differentiated granitoids (Zinngranit, i.e. tin granites) are the most productive ore-forming granites in the Fichtelgebirge. These ore types include cassiterite and cassiterite-wolframite greizen and vein-type occurrences (e.g. near Schönlind and Seehaus), locally with a minor uranium (pitchblende, coffinite, brannerite) and sulfide (pyrite, arsenopyrite, chalcopyrite, bismuthinite) mineralization (e.g. at Rudolfstein and Fuchsbau).

Hematite-quartz veins with a very minor tungsten grade, e.g. at Gleissinger Fels near Fichtelberg, represent the end of the granite-related tungsten mineralization (MORTEANI & FRIEDRICHSEN, 1978).

These Fichtelgebirge ore occurrences are genetically, temporally and spatially closely associated with some major tin and tungsten deposits of the neighbouring Erzgebirge further east. However, cassiterite mining in the Fichtelgebirge from underground and placer deposits (e.g. near Weissenstadt) has never been so important as in the Erzgebirge. Tungsten has been recovered as a very minor by-product only during the Second World War. BAUMANN (1979) concluded a metallogenetic relationship between pre-Variscan, stratabound tin mineralizations of Upper Proterozoic age (Pressnitz series) and Cambrian age (Joachimsthal series) and the Variscan, granite-related tin deposits of the Erzgebirge due to a Variscan remobilization. This heritage might also be true for the tin (and tungsten) in the Fichtelgebirge.

Small wolframite-quartz veinlets are exposed and have been drilled in possibly Upper Cambrian metasediments at the location Sibyllenbad near the village Neualbenreuth. They are undeformed and of post-tectonic, Variscan age (DILL, 1985a; JUNG & HÖLL, 1989). A vein-type deposit with (wolframite-)cassiterite and lense-shaped scheelite enrichments near Gottsmannsgrün represents an isolated ore mineralization close to the border to the German Democratic Republic (DILL, 1985a).

A great number of scheelite occurrences is known in the Moldanubian Zone, especially in the area Weiden-Pleystein-Oberviechtach (JAKOB, 1976, 1979; JUNG & HÖLL, 1982, 1989; RICHTER, 1984). Most of them are skarn-type occurrences, and spatially and genetically related to differentiated, post-tectonic Variscan granitoids. A scheelite occurrence of this type is well exposed in the hard-rock quarry Oberbaumühle near Windischeschenbach, only some 3 km ESE from the KTB site. This quarry displays the intrusive contact of the S-type Falkenberg granite to contact-metamorphic amphibolites as host rocks of a fracture-, veinlet- and shear zone-type scheelite mineralization. However, some scheelite occurrences in northeastern Bavaria are presumably unrelated to Variscan granitoids and possibly older. These occurrences are commonly stratabound in calcsilicate and/or amphibolite layers of supposedly Upper Proterozoic age (JUNG & HÖLL, 1982, 1989; DILL, 1985).

Variscan uranium occurrences and deposits are known in the Fichtelgebirge (e.g. at Großschloppen) and in northernmost areas of the Moldanubian Zone between Tirschenreuth and Mähring (Höhenstein and Wäldel) (GUDDEN et al., 1974; BÜLTEMANN, 1979; STETTNER, 1979; ZIEHR, 1980; RICHTER & STETTNER, 1983; DILL, 1985a). The Großschloppen uranium deposit is structurally controlled by shear zones at the contact of the Weissenstadt-Marktleuthener granite (with a granodioritic-dioritic-redwitzitic composition near the contact) and metasediments (mica schists and quartzites). The primary ore mineralization (pitchblende) in strongly altered shear zones has presumably formed due to late Variscan hydrothermal activity by leaching of uranium from organic-rich, supposedly Upper Proterozoic metasediments (DILL, 1985a). Further stages of remobilization and redeposition with the formation of predominantly uranophane have been described by DILL & KOLB (1986). The uranium deposit Höhenstein near Poppenreuth with pitchblende and a variety of accessory ore minerals lies in a rock assemblage of mica schists and gneisses and small Variscan granitoids. The ore-bearing shear zones are intensely altered and desilicified (DILL, 1982). The ore mineralization is interpreted as granite-related, followed by younger remobilization (BÜLTEMANN, 1979; CARL & DILL, 1985). The Wäldel uranium deposit near Mähring consists of late Variscan quartz veins with uranium oxides, uranium-bearing sphene, pyrite, marcasite and molybdenite within altered gneisses (DILL, 1983). RICHTER & STETTNER (1979, 1983) presented geochemical data from different granites with evidence for a widespread uranium preconcentration.

Gold is known from several sites in the Saxothuringian Zone, including the sulfide deposits Sparneck and Kupferberg (WURM, 1924, 1961; DILL, 1985a). Old gold mining is reported from an area around Neualbenreuth and above all at Brandholz-Goldkronach. The abandoned gold occurrences Schachten and Güldenstern near Neualbenreuth are interpreted in favour of late-Variscan granite-related veins by DILL (1985a). At Brandholz-Goldkronach the last underground studies have been performed by BUSCHENDORF (1930). He describes quartz veins in Early Palaeozoic host rocks. DILL (1985a) concludes a close genetical link of the gold-quartz veins to the late-Variscan, granite-related metallogenesis. A (scheelite-)gold-stibnite ore mineralization in supposedly Upper Devonian metavolcanics at the former Silberne Rose Mine is included in this model, whereas JUNG & HÖLL (1982) also discussed a possible genetical relationship to these volcanics.

Pegmatites and pegmatoids obviously of different age and including late-Variscan types, are known from different areas of the Moldanubian Zone (e.g. large, exhausted pegmatites near Hagendorf and several occurrences near Püllersreuth-Windischeschenbach), in the Münchberg gneis mass and in the Fichtelgebirge.

POST-VARISCAN ORE DEPOSITS

The post-Variscan (Permian to Quarternary) ore formation in northeastern Bavaria is due to a platform evolution either as vein-type along faults or as ore-bearing platform sediments.

Some vein-type (Cu-)(Ag-)Pb-Zn occurrences, e.g. at Dürrenweid/Nordhalben, Wallenfels and Erbendorf, have been mined on a small scale. They have been summarized by DILL (1985a) and considered of late-Variscan to post-Variscan origin. Vein-type fluorite deposits have been mined in three areas of northeastern Bavaria: in the Frankenwald (at Issigau-Lichtenberg-Kemlas), in the Nabburg-Wölsendorf region and near Sulzbach/Donaustauf. The fluorite deposits near Nabburg-Wölsendorf with some 50 ore veins in an area of 20 km by 8 km have been a major fluorite source in the past (SCHMID & WEINELT, 1978; WEISS, 1979). Barite is a common mineral besides fluorite. Accessory minerals are pitchblende, coffinite, brannerite, galena, sphalerite, chalcopyrite, pyrite. Ag-bearing galena has been mined on a small scale. HORN et al. (1986) inferred a much younger age for the vein formation (254 +/- 6 my) than for hosting granites (Neunburger granite about 320 my, Flossenbürg granite 293 +/- 11 my), but concluded a genetic relationship to the 140 km long, NW-SE striking quartz lode of the Bavarian Pfahl within a huge shear zone. This still actively mined quartz lode formed during the Permian period due to geological evidence (HOFMANN, 1962), and radiometric data (HORN et al., 1986).

Basins in NNE-SSW direction formed in Permian-Triassic time due to a Variscan basement subsidence. The troughs (e.g. at Stockheim, Erbendorf and Weiden) filled with reddish and grey clastic sediments. They contain minor coal seams. Triassic arkoses in an elongated basin at Hirschau-Schnaittenbach and at Kaltenbrunn-Weiherhammer have been altered to large kaolinite deposits of major economic importance for kaolinite, feldspar and quartz. Kaolinized marginal parts of the late-Variscan Falkenberger granite are actively mined near Tirschenreuth. Besides kaolinite also large quantities of feldspar and quartz are recovered. The genesis of the kaolinite, either due to hydrothermal activity after the emplacement of this intrusion, or by much later weathering processes is still under debate (STROBEL, 1969; HAMMERL, 1989). In the Jurassic fine-grained, high-quality quartz sands are actively mined near Hirschau. In the Jurassic and Cretaceous stratabound iron ores have been formed. The latter, within ore-bearing karstic troughs, have been of major economic importance, and hosted the iron ore deposit at Auerbach, which has been the last iron ore mine in West Germany until 1988. Tertiary clays are widespread in northeastern Bavaria. High-quality clays, presently mined in open pits, together with exhausted brown coal seams, cover a large area between Regensburg and Schwandorf. They formed in a palaeo-Naab valley under a much warmer Miocene climate.

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METAMORPHISM ALONG THE SW MARGIN OF THE BOHEMIAN MASSIF - AN OVERVIEW

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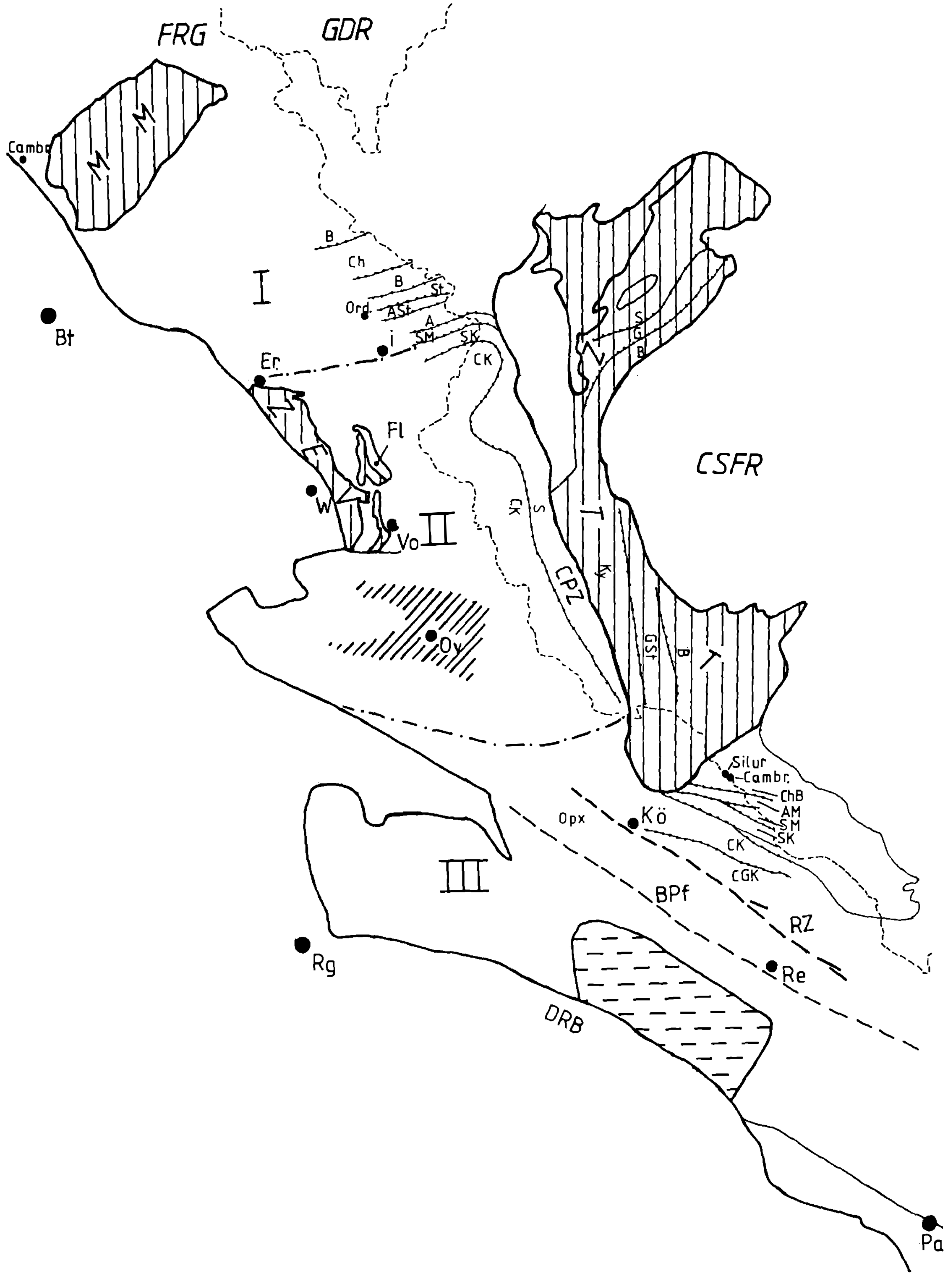
Mountain belts have undergone a complex and long-lived (ca. 100 MA and more) tectono-thermal evolution which ends with the uplift, thrusting and piling of portions of the synorogenic upper and lower crust. Tectonic boundaries cut across older primary rock associations which equilibrated at metamorphic geotherms of different PT ratio (and of variable thermal spread) corresponding to different baric types of metamorphism. Thus medium-pressure metamorphism is attributed to a normal geotherm (ca. 25^{o}C/km, THOMPSON & ENGLAND 1984). Anomalous metamorphic geotherms, which are due to uplift faster than thermal relaxation either produce HP rocks in subduction zones or LP rocks in zones of rapid uplift. Moreover LP metamorphism may need surplus heating by convection of magmas or hot fluids.

Metamorphic units of the area are defined by P-critical mineral assemblages (e.g. cordierite - sillimanite or andalusite, garnet - kyanite etc.) and by mica-, monazite- and hornblende ages whose closing temperatures are better known than those of zircon and of Rb/Sr whole rock isochrons. It is clear that metamorphic units will comprise rocks of contrasting provenance like "Altkristallin", metaperidotite, eclogite, granulite and syn-orogenic sediments. Metamorphic units thus defined offer the clue for the reconstruction of the synorogenic middle and lower crust and serve as markers of large-scale tectonic structures.

In the excursion area two metamorphic units are distinguished
(Blümel 1983, 1984; 1986). (Fig 1)

(1) the Low-Pressure Unit
(2) the Medium-Pressure Unit

The LOW-PRESSURE UNIT (LPU) is the main constituent of the northern Variscan basement. Ca-poor metapelites and -graywackes predominate, but some sub-areas with variegated associations containing siliceous marble, amphibolite, orthogneiss and serpentinite exist (Passauer Wald, Strakonice etc.).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Amphibolite facies is widespread and mainly defined by cordierite (+ sillimanite) + biotite + microcline + oligoclase + quartz + ilmenite + Fe-sulfides. This mineral assemblage is stable in migmatites (Bayerischer Wald/FRG, Mühlviertel/Austria) as well as in paleosome rocks (Oberpfalz/FRG). Migmatization locally culminates in the formation of orthopyroxene - garnet assemblages in both the leucosome and the melanosome (Kötzting-Cham area, Bayerischer Wald). For some localities in the cordierite - potash feldspar zone, PT-conditions of 3-4 kbar and 670^{o}-$700^{o}C$ have been determined (BLÜMEL 1986, BLÜMEL & SCHREYER 1977). The wide extension of this mineral zone is due to the broad thermal stability of the critical assemblage as well as to the subparallel position of the isogradic surface with the recent erosion level. In rare (late) synforms, low-grade equivalents of the LPU are preserved (biotite-garnet-chlorite zone in the Künische Glimmerschiefer-Synform; BLÜMEL 1972, VEJNAR 1963; chlorite zone in the Waldsassen-Synform, WAGENER-LOHSE & BLÜMEL 1984).

The structure of the LPU is complex. As regards to the most simple element, the main schistosity, 3 domains are recognized: (1) the Paleozoic Saxothuringian with sf^{SW-NE}, (2) the Moldanubian of the Oberpfalz with sf^{SW-NE} turning into sf^{N-S} and (3) the Moldanubian of the Bayerischer Wald with $sf^{WNW-ESE}$.

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Fig.1: Metamorphic units, isograds and mylonites at the western margin of the Bohemian Massif. Wide ruling, MPU klippen (ZEV Zone of Erbendorf Vohenstrauß, ZTT Zone of Teplá-Domazlice, MM Münchberg Massif); narrow ruling, meta-ultrabasite-eclogite-granulite paragneiss association near Oberviechtach. I, II and III are structural domains (defined simply by the orientation of main schistosity; with dash-dotted boundaries). Filled circles, microfossils. Broken ruling, Perlgneiss area.

Mineral zones of the LPU: Ch chlorite, B biotite, ChB chlorite-biotite, St staurolite, ASt andalusite-staurolite, A andalusite, SM sillimanite-muskovite, SK sillimanite-potash feldspar, CK cordierite-potash feldspar, CGK cordierite-garnet-potash feldspar, Opx orthopyroxene. Mineral zones of the MPU (for ZTT only): B biotite, G garnet, GSt garnet-staurolite, Ky kyanite.
Shear-zones: CPZ Czech Pfahl Zone, RZ Runding Zone, BPf Bavarian Pfahl Zone, DRB Donaurandbruch-Aicha-Hals Zone.
Bt Bayreuth, Er Erbendorf, Fl Floß (part of thrust zone at the base of the MPU), Kö Kötzting, Ov Oberviechtach, Pa Passau, Rg Regensburg, Re Regen, Vo Vohenstrauß, W Weiden.

In the Saxothuringian, the first 3 deformations are coaxial; D2 and D3 are related with the thermal climax producing open megafolds and D4 and D5 increasingly become brittle and change the direction of compression (STEIN 1988). The structural grain of domain (2) may be linked to the thrusting of the MPU (see below). While there is sufficient evidence for the structural transition from the Saxothuringian into the Moldanubian of the Oberpfalz (STEIN 1988) the domains (2) and (3) within the Bavarian Moldanubian seem to be seperated by strike - slip faulting.

The structural evolution of domain (3) is (BLÜMEL 1972): D1 with $B^{SW\text{-}NE}$, D2 with $B^{WNW\text{-}ESE}$ (facing SSW) and D3 with steeply dipping open folds. D2 (and D3) is related with the climax of LP metamorphism and with D3 mylonitization begins ("Perlgneise" and other mylonites). The schistosity of D2 and D3 seem to be coplanar. Medium-T and low-T mylonites define narrow shear zones which truncate en-échelon the Bohemian Massiv toward SW.

Within the LPU, local relics of older metamorphic stages are found, which are documented either by mineral inclusions in paragneiss (kyanite ± garnet within feldspars or cordierite Tirschenreuth-Mähring, Moosbach, Kötzting, Regen, Bayerisch-Eisenstein) or by rock lenses of eclogite, amphibolite etc.. Most spectacular is the Oberviechtach area (to be visited), where narrowly associated and variably retrogressed eclogites, meta-ultrabasites (garnet-pyroxenite and olivine + orthopyroxene + tremolite + spinel meta-peridotite) and kyanite-granulite are intercalated into cordierite - sillimanite gneiss. In the mafic and felsic members, a multistage uplift history (symplectitic coronae) is analyzed passing from amphibolite facies through eclogite (P 15kbar / T= 710^{o}C), HP granulite(P= 12kbar / T= 800^{o}C) and MP granulite (P= 9 - 7kbar / T= 700^{o}) back into amphibolite facies (O'BRIEN 1989). These intercalations are dated with ca. 1250 MA for protolith formation (zircon age), 427 ± 5 and 423 ± 8 MA for the HP stage (Sm/Nd mineral isochron) and with 320 MA for retrogressed granulite monazite age (v.QUADT & GEBAUER, 1988). The provenance of this particular rock association (Winklarner Serie, G.FISCHER) is under discussion. Based on the island-arc like composition of the metabasites, (v.QUADT & GEBAUER) have argued for an allochthonous position of the HP members. It is intriguing to include this association as a further tectonic klippe among the MPU. However in absence of a seperating shearzone their incorporation into the LPU - during an older event - seems to be more realistic.

The stratigraphic age of the Moldanubian metasediments generally is estimated as Precambrian (e.g. CHALOUPSKY 1989). However the merging of Paleozoic anchizonal sediments (Arzberger Serie) into the Moldanubian in the Tirschenreuth area already lead earlier authors to consider a similar age at least for part of the Moldanubian (e.g. SCHREYER 1966). Meanwhile in Moldanubian micaschists further toward S microfossils were detected to which a Paleozoic age is ascribed (PFLUG & REITZ 1987). However, this age is not unanimously accepted. On the other hand, isotope geochronology did not succeed in detecting a Cadomian basement. Thus it appears to be wise to consider a wide spread of protolith ages.

LP metamorphism has been dated at 335 - 320 MA (monazite ages: GRAUERT et al. 1990; v.QUADT & GEBAUER 1988; TEUFEL 1988) both in the Oberpfalz and in the Bayerische Wald portion of the Moldanubian. Rb/Sr whole rock isochron ages ranging from Ordovician to Carboniferous so far are out of geologic interpretation. The cooling ages of the LPU are 320 MA for hornblende (K/Ar, KREUZER et al. 1989) and 310 - 290 MA for biotite (TEUFEL 1988; GRAUERT et al. 1974).

It should be noted that part of the Saxothuringian, i.e. the Paleozoic sediments in NE-Bavaria, are integrated into the LPU as the low-grade equivalent. This is clearly justified by petrologic as well as structural evidence (WAGNER-LOHSE & BLÜMEL 1984; STEIN 1988). Interestingly this portion of the Saxothuringian seems to lack an earlier HP or MP event (instead: andalusite transforming into sillimanite). Other portions of the southern Saxothuringikum, e.g., the eastern Erzgebirge, are attributed on petrological grounds to the Medium-Pressure Unit, reliable cooling ages being absent (BLÜMEL 1986).

The MEDIUM-PRESSURE UNIT (MPU,Fig.1) consists of several klippen which survived erosion in tectonically favourable positions. MPU klippen in the western Bohemian Massiv are: (1) the Zone von Erbendorf-Vohenstrauß (ZEV), (2) the Zone von Teplá-Domazlice (ZTT in W-Bohemia, VEJNAR 1982; with a southern edge protruding in the northern Bavarian Forest known here as the Neukirchen Gabbro Amphibolit Masse) and (3) the Münchberg Massif (MM). Tentatively added are (BLÜMEL 1986) the Osterzgebirge basement in Saxonia/DDR (WIENHOLZ et al. 1979) and the Gföhl Unit of the Waldviertel/Austria (FUCHS & SCHARBERT 1981; PETRAKAKKIS 1986).

The lithology of the MPU comprises metapelites and -psammites (generally poor in CaO), few marble, orthogneisses, metabasites (eclogiteamphibolites, metagabbro and various amphibolites) and metaultrabasites (serpentinite with relics of orthopyroxene and green spinel; pyroxenite). The age of the educts ranges from U.Proterozoic (in the ZTT) to Lower Devonian (ZEV: KTB drill core, PFLUG & PRÖSSL 1989).

In the MPU amphibolite facies prevails, a prograde MP isogradic sequence being evidenced only for the ZTT (sericite schists to kyanite - sillimanite zone; VEJNAR 1982). PT-conditions are determined with 6-8 kbar / 610 - 720 ^{O}C for metapelites with garnet - kyanite (sillimanite) - biotite - muscovite - plagioclase - quartz - rutile - ilmenite in the ZEV and part of the MM (BLÜMEL 1986; KLEEMANN, manuscript; REINHARDT 1990), 9 -11 kbar / 700 - (800 ^{O}C for pelitic and basic granulites at the southern periphery of the ZEV (BLÜMEL, unpublished; KLEEMANN, manuscript) and 7 -9 kbar / 72o - 770 ^{O}C for Gföhlgneis (PETRAKAKKJS 1986). Regional metamorphism in the ZEV, MM and the ZTT merges into retrograde mylonitization either within the stability field of kyanite or straddling the kyanite/sillimanite boundary eventually to give cordierite augenmylonite (VOLL 1960; rediscovered by KLEEMANN, manuscript).

Events prior to MP regional metamorphism are recorded in eclogite (amphibolite) and in metagabbros. Eclogites occur in the upper part of the Müncherg nappe pile (e.g., Weißenstein), occur locally in the ZEV and gain considerable extension at the northern edge of the ZTT (Marianske Lazne area). In the Weißenstein eclogite P 13 - 15 kbar and T 620 ^{O}C are analyzed for the HP stage and P= 12 - 8.5 kbar for the symplectite stage (FRANZ et al. 1986). Different metagabbros of the KTB drill cores preserve: (1) a HP stage by mineral inclusions of omphacite Jd_{30} within metamorphic garnet (RÖHR, pers. comm.), (2) a granulite stage by garnet coronae between magmatic clinopyroxene and plagioclase, (3) a decompression stage by hornblende - plagioclase coronae rimming garnet (OKRUSCH et al. 1990). Garnet rims on biotite in MM metagabro equilibrated at ca. 610 ^{O}C (Steinhügel, Liegendserie; BLÜMEL; unpubl. data).

Geochemical contrasts between the metabasites (SCHÜSSLER, manuscript) and the absence of a HP event in paragneiss (REINHARDT 1990) point to the ZEV being an old (pre-MP metamorphic) tectonic composite.

The age of MP regional metamorphism is approximated by hornblende K/Ar ages from various amphibolites of the ZEV, MM and ZTT, which give an average value of ca. 380 MA (KREUZER et al. 1989; KREUZER et al.1990). This is corroborated by a paragneiss monazite age of 380 MA (ZEV; TEUFEL 1988). Biotite cooling ages are 371-364 MA for the ZEV (Rb/Sr; TEUFEL 1988) and 378/361 MA for the MM (Liegendserie and Hangendserie respective Rb/Sr and K/Ar; MÜLLER-SOHNIUS et al. 1987). HP metamorphism sofar is dated only in the Weißenstein eclogite, which gave differing ages of 380 MA (zircons; GEBAUER & GRÜNENFELDER 1979), 435 MA (composite of Sm/Nd on eclogite and Rb/Sr on paragneiss MÜLLER-SOHNIUS et al. 1987) and 395 MA (Sm/Nd mineral-whole rock isochron; STOSCH & LUGMAIR

1986). Further ages predating MP metamorphism are from the ZEV: 494 MA (metagabbro, KTB drill core, zircon, upper intercept; v.QUADT 1990), 520 MA (amphibolite, Rb/Sr whole rock, TEUFEL 1988) and 457 MA (granitic augengneiss, zircon, lower intercept; TEUFEL 1988) and 489/436 MA (paragneiss, Liegendserie/Hangendserie; both Rb/Sr whole rocks, MÜLLER-SOHNIUS et al. 1987). Except for the latter they all probably give intrusion/effusion age into wallrocks of unspecified state (rift zone or/in Altkristallin?).

GEOMETRIC RELATIONS BETWEEN THE MEDIUM-PRESSURE UNIT AND THE LOW-PRESSURE UNIT

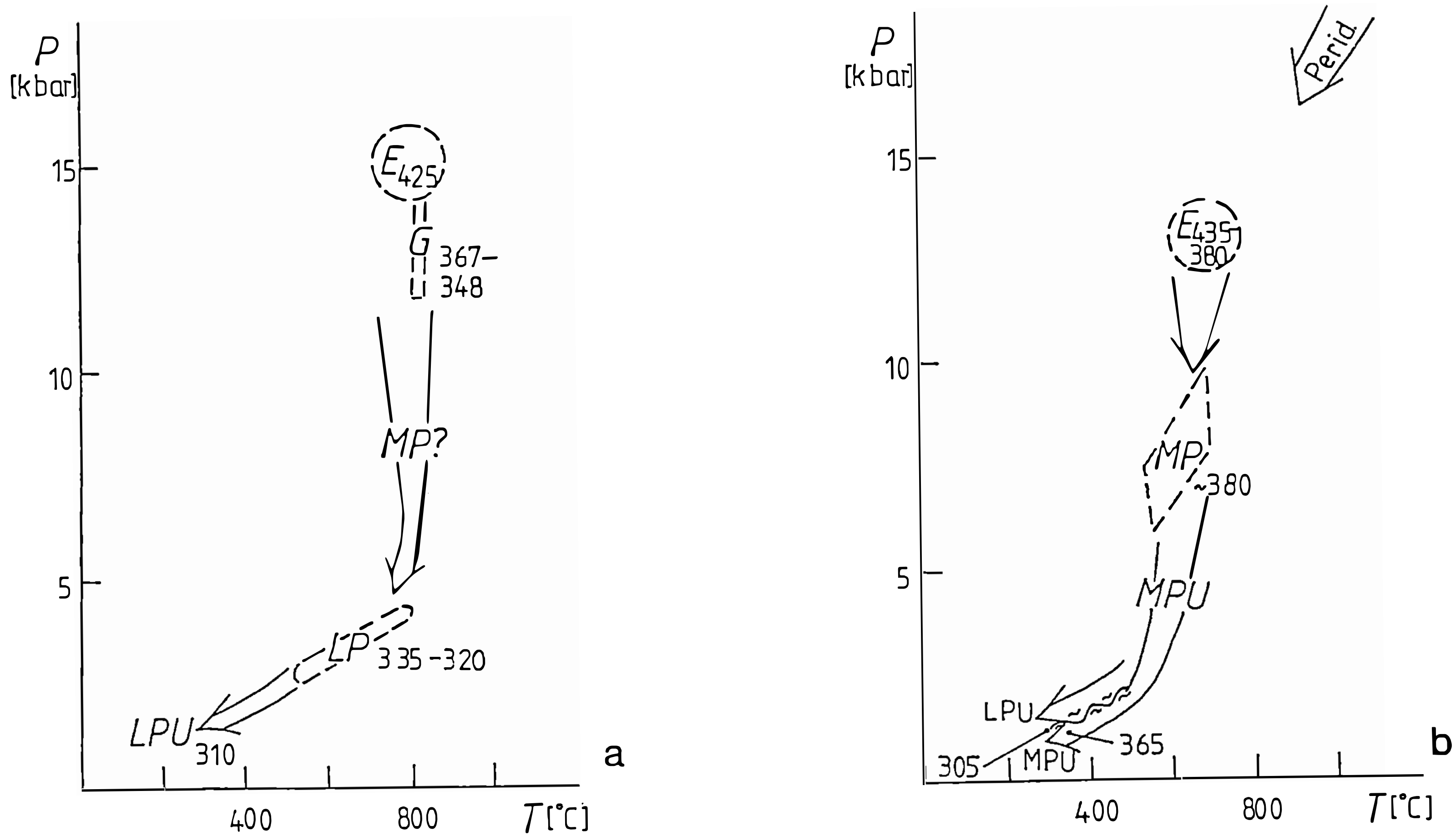
First of all the medium-pressure rocks of amphibolite facies with old cooling age must rest with tectonic contacts on top of low-pressure rocks of similar grade but young cooling ages. Next we look at the contacts. Primary transitions between both units seem to be absent. Conversely, both units are seperated by (locally exposed) shearzones of originally subhorizontal position. These shearzones cut into the LPU at the sillimanite zone level (eastern edge of ZEV and western edge of ZTT). It is trivial that the distance of horizontal transport cannot be evaluated directly. However in view of the considerable difference in the cooling age of both units, which amounts 50 - 60 MA, the nappe character of the MPU appears to be well founded.

AGE AND DIRECTION OF THRUSTING

The MPU was emplaced subsequently to the climax of LP metamorphism. This could be dated in a temporary outcrop within the LPU near the eastern edge of the ZEV, which exposed a subhorizontal mylonite zone (KLEEMANN et al. 1989). The age of the paragneiss mylonite is 305 ± 9 MA (GRAUERT B. et al. 1990). Shear-sense indicators give a SW direction of tectonic transport (KLEEMANN et al. 1989) which clearly deviates from the direction of earlier ductile compression being NW-SE (STEIN 1988). The geologic interpretation of the 305 MA age being true nappe-thrusting must have occured during the onset of the period of intense acidic plutonism in the area (NE-Bavarian Pluton, see A4). Indeed the oldest intrusive, the Leuchtenberg granite in the ZEV of 321 MA is locally sheared as already recognized by VOLL (1960) whereas the neighboring granite in the LPU, the Flossenbürg granite of 311 MA, is undeformed. Obviously the melt did not intrude into the thrustzone, which may indicate that it was close to the solidus temperature.

METAMORPHIC EVOLUTION AT THE WESTERN MARGIN OF THE BOHEMIAN MASSIV

Following first attempts in constructing PT loops for the area (BLÜMEL 1986) the present state of knowledge is condensed in Fig.2.



E_{425} = eclogite in LPU with age of 425 Ma; $G_{367-348}$ = granulite in LPU with age of 367-348 Ma; $LP_{335-320}$ = LP-metamorphism at 335-320 Ma; LPU_{310} = Low Pressure Unit cooling at ca. 310 Ma. Data sources see text.

$E_{435-380}$ = eclogite in MPU with age of 435-380 Ma; MP_{380} = MP-metamorphism at ca. 380 Ma; MPU_{365} = Medium Pressure Unit cooling at about 365 Ma; 305 refers to the age of tectonic emplacement of the MPU. Data sources see text.

Fig.2: Pt-conditions and age of metamorphic stages in the western Bohemian Massiv

2a) LPU (Low Pressure Unit) 2b) MPU (Medium Pressure Unit)

As can be seen, a nearly isothermal uplift pattern results in the case of an in-situ interpretation of HP (and MP) metamorphism in both units. A problem arises as to the former unity/non-unity of both metamorphic associations. Two variants exist. Variant 1, favoured by BLÜMEL (1986), derives LPU and MPU from different subduction units on account of a supposed high tectonic mobility within the synorogenic lower crust as well as the large difference in the cooling ages (365 versus 310 MA). Variant 2, the THOMPSON & ENGLAND (1984) model as put forward by STÖCKHERT (1989), derives both units as lately detached members from one coherently uplifting former "HPU".

Also shown in Fig.2 is the incorporation of the "cold" Paleozoic Saxothuringian via andalusite to sillimanite into the "hot" polyphase Moldanubian (to give the LPU) and the tectonic emplacement of the MPU onto the LPU. The simple PTt pattern of Fig.2 certainly will complicate, if loop "incisions" as suggested by magmatic activity are considered and further thermobarometric data become available.

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AN OUTLINE OF THE GEOLOGICAL HISTORY OF THE SE-AND NW-BOHEMIAN MASSIF BASED ON GEOCHRONOLOGICAL DATA

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A compilation of the geochronological data published so far allow the following schematic model for the geological evolution of the SE-and NW-Bohemian Massif (see Fig. 1 and 2).

SE-BOHEMIAN MASSIF (AUSTRIA)

Moravian

- First records of detrital material in the Keprnik paragneisses on zircons of about 1450 Ma. This upper intercept may reflect a mixture of Svecokarelian (c.1900 - 1850 Ma and Sveconorwegian (Grenvillian)(c.1050 - 1000 Ma) events. This is much younger than the 2600 Ma - 2400 Ma found in the NW-Bohemian Massif.
- Magmatic and metamorphic events around 580 Ma (Cadomian).
- Signs of a possible Caledonian metamorphic overprint by Rb-Sr whole rock ages of about 480 Ma. According to present knowledge an interpretation of these data as being significant for a metamorphic event (Caledonian) is not consistent with other available data.
- Regional cooling down at about 325 Ma after a HT/LP Hercynian metamorphic event, the peak of which is not yet proved but may have been time equivalent with the granulite facies metamorphism in the Moldanubian.

Moldanubian

- First records of detrital material in the Gföhl gneiss on zircons with a poorly defined upper intercept age of about 1800 Ma which might be attributed to the Svecokarelian event.
- Magmatic and possibly metamorphic events around 580 Ma (Cadomian).
- Same difficulties than in the Moravian to prove a Caledonian magmatic or metamorphic event around 480 Ma by Rb-Sr whole rock data.
- Few informations on zircons and Sm-Nd measurements on relict high pressure ultramafic rock assemblages suggest an early HP Hercynian metamorphism in the range of 400 Ma to 370 Ma.

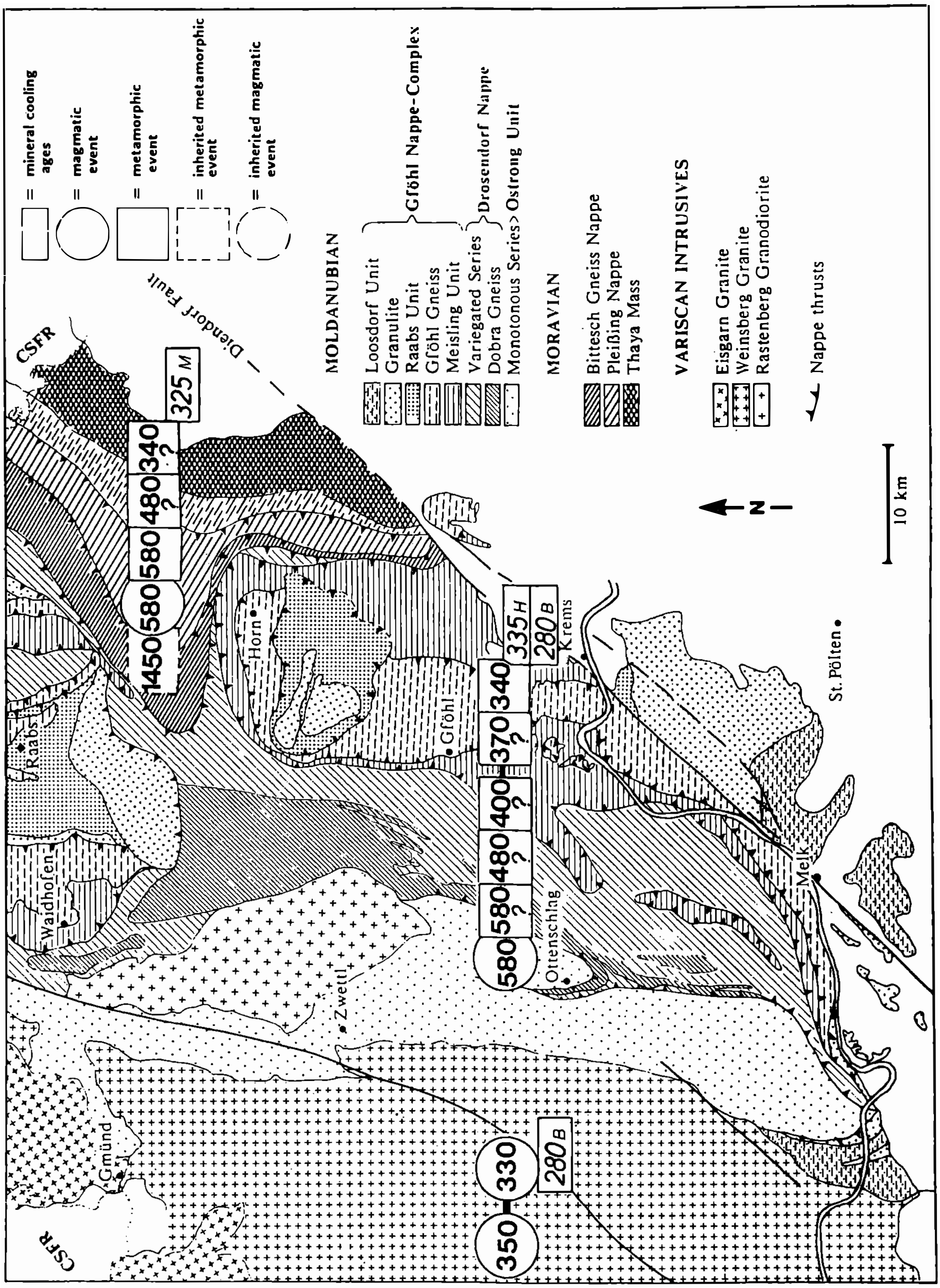

Fig. 1: Schematic compilation of geochronological data of the SE- Bohemian Massif (Austria)

- Granulite facies metamorphism around 340 Ma, proved by nearly concordant zircon and concordant monazite data.
- Emplacement of late to post-tectonic granitic intrusions between 350 Ma and 330 Ma.
- Final record of regional cooling down on biotites below 300°C around 280 Ma.

NW-BOHEMIAN MASSIF

Moldanubian

- First records of detrital material in paragneisses on zircons of about 2600 Ma - 2400 Ma.
- Meagre indications for a Caledonian overprinting in the time span between 480 Ma and 460 Ma.
- Indistinct signs for a possible medium pressure metamorphic event around 380 Ma.
- Final strong metamorphic overprinting under HT/LP conditions at about 320 Ma.
- During this time starting of late to post-tectonic granitic intrusions which came to an end at about 290 Ma.
- Regional cooling down and passing through the 300°C isotherm is reflected by biotite ages of about 3oo Ma.

Saxothuringian

- First records of detrital material in paragneisses on zircons of about 2300 Ma.
- Records of a "Pan African" metamorphic event around 620 Ma on detrital muscovites in Cambrian sandstones.
- Minimum age of 560 Ma for a metamorphic event in the source area,inherited in metasediments.
- Volcanic activity around 450 Ma.
- Peak of the last metamorphic overprinting around 320 Ma in the south with decreasing tendency in age and intensity to the northwest.
- Similar record of granitic intrusions than in the Moldanubian between 320 Ma and 290 Ma
- regional cooling down below 300°C at about 300 Ma in the southern parts and at about 280 Ma in the northwestern parts.

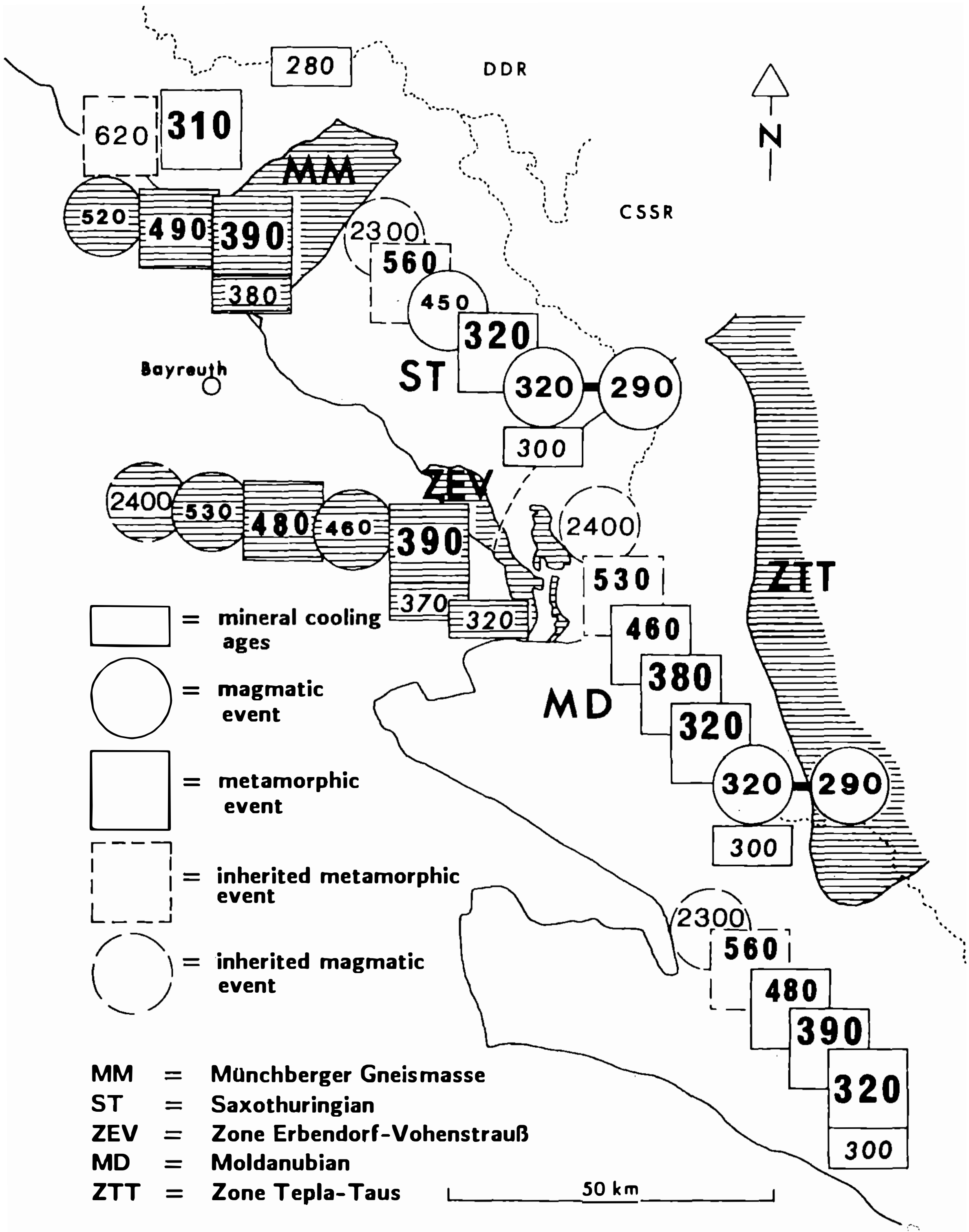

Fig. 2: Schematic compilation of geochronological data of the NW-Bohemian Massif (from Hansen et al., 1989)

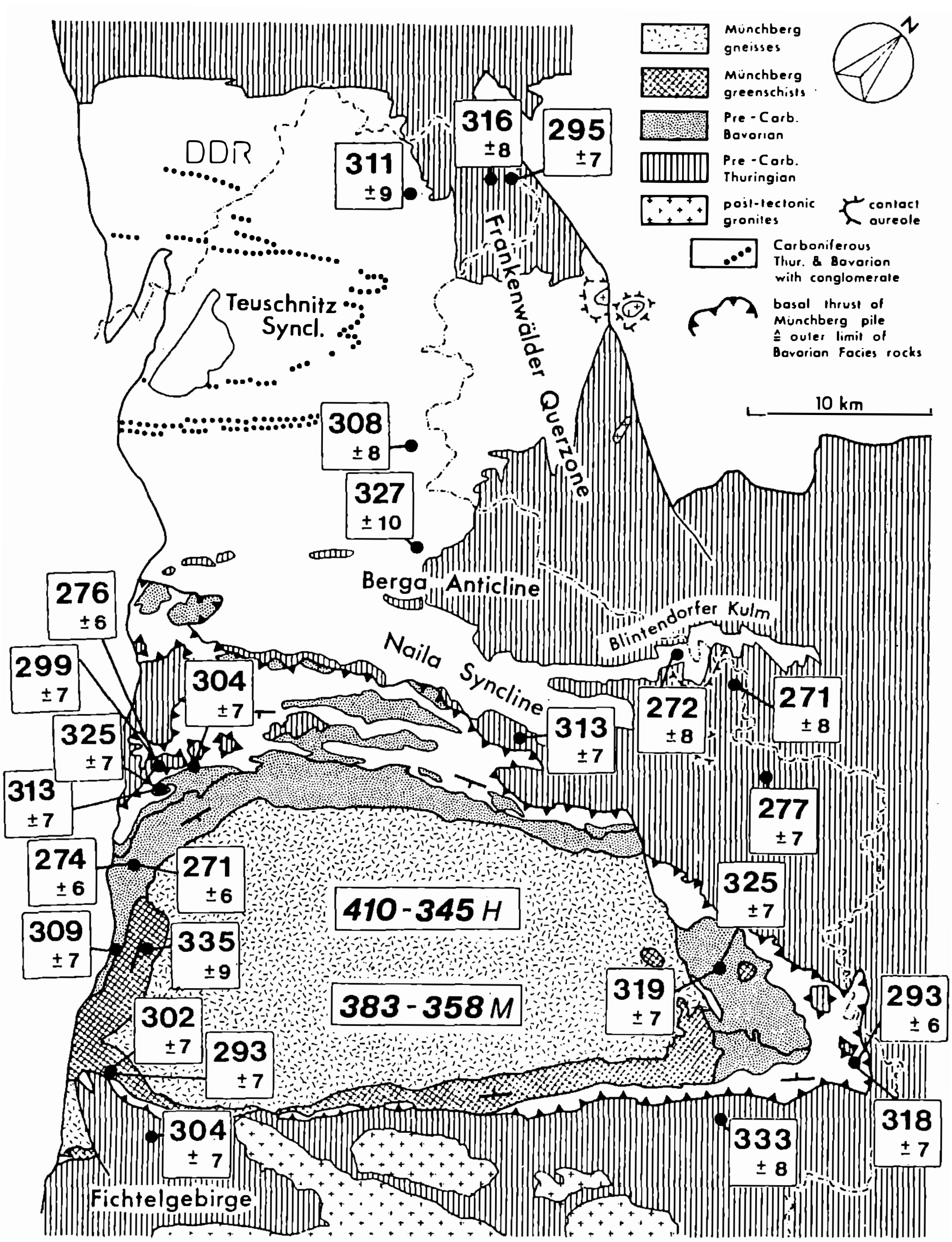

Fig. 3: Mineral cooling ages in the crystalline rocks of the Münchberg Massif (data from Kreuzer et al., 1989) and K-Ar ages of fine mineral fractions (< 2μm) in the very low to low grade metamorphic rocks of the nappe pile and the surrounding area (from Ahrendt et al., in prep.)

NAPPE UNITS

ZEV (Zone of Erbendorf-Vohenstrauß)

- First records of detrital material in paragneisses on zircons of about 2500 Ma - 2400 Ma.
- Magmatic events between 530 Ma and 460 Ma.
- A poorly defined metamorphic event around 480 Ma.
- Main metamorphic overprinting under medium pressure conditions around 390 Ma.
- Subsequent regional cooling below 300°C until 360 Ma.
- Final emplacement of the ZEV nappe complex between 360 Ma and the intrusion of the late to post-tectonic granites.
- Late to post-tectonic granitic intrusions around 320 Ma.which may have led to a mild reheating in a smaller regional scale
- causing an influence and a partly reset of mineral cooling ages in the south-eastern parts of the ZEV.

Münchberger Gneismasse

- Magmatic and metamorphic events between 530 Ma and 470 Ma.
- High pressure metamorphism around 390 Ma.
- Rapid cooling until 380 Ma.
- Youngest records of cooling ages in the crystalline rocks of the nappe pile for the K-Ar-system on white micas with 358 Ma and on amphiboles with 345 Ma.
- Taking the stratigraphic age of the overthrust sediment into account,the final emplacement of the Münchberger Gneismasse took place after the Lower Carboniferous.

A more detailed distribution of K-Ar measurements on white micas and fine mineral fractions representing the cooling history of the nappe pile itself and the surrounding area is given in Fig.3. K-Ar data in the range of 410 Ma - 345 Ma for amphiboles (H) and in the range of 383 Ma - 358 Ma for white micas (M) of crystalline rocks from the nappe pile give information about the early cooling history of the high grade metamorphic parts of the nappe complex. The K-Ar data on fine mineral fractions of the very low to low grade metamorphic rocks represent the peak of a late regional metamorphic event caused by the superposition of nappes in this area. An exception must be made for the youngest data.

West of the Münchberg gneisses the data are partly rejuvenated by hydrothermal activities along the Franconian Line, while in the north- western part the data represent cooling ages because of the higher degree of metamorphism caused by an abnormal high heat flow in the Frankenwälder Querzone.

According to the available data the ZEV and the Münchberger Gneismasse must be regarded as different parts of the same nappe unit.

The geochronological data obtained so far in the SE- and NW- Bohemian Massif do not prove, that orogenic events of Caledonian age play an important role in the developement of these crustal segments.

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$^{40}Ar/^{39}Ar$ MINERAL AGE CONTROLS ON THE CHRONOLOGY OF LATE PALEO- ZOIC TECTONOTHERMAL ACTIVITY IN THE SOUTHEASTERN BOHEMIAN MASSIF, AUSTRIA (MOLDANUBIAN AND MORAVO-SILESIAN ZONES)

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INTRODUCTION

$^{40}Ar/^{39}Ar$ incremental-release age analyses have been carried out on hornblende and muscovite concentrates from several exposures within the Moldanubian and Moravian Zones which will be examined during this excursion. These results provide important chronologic constraints for the late Paleozoic tectonothermal evolution of the southeastern Bohemian Massif, and are briefly discussed in this report.

GEOLOGIC SETTING

Detailed descriptions of geologic relations within the Southern Bohemian Massif are presented elsewhere in this volume and will not be duplicated here. The locations of the samples analyzed are indicated in Figure 1.

ANALYTIC METHODS

The mineral concentrates were wrapped in aluminium-foil packets, encapsulated in sealed quartz vials, and irradiated for 80 hr in the Central thimble position of the TRIGA Reactor at the U.S. Geological Survey, Denver. Variations in the flux of neutrons along the length of the irradiation assembly were monitored with several mineral standards, including MMhb-1 (ALEXANDER et al. 1978). The samples were incrementally heated until fusion in a double-vacuum, resistance heated furnace. Temperatures were monitored with a direct-contact thermocouple and are controlled to ± 1°C between increments and are accurate to ± 5°C. Measured isotopic ratios were corrected for total blanks and the effects of mass discrimination. Interfering isotopes produced during irradiation were corrected using the factors reported by DALRYMPLE et al. (1981) for the TRIGA Reactor. Apparent $^{40}Ar/^{39}Ar$ ages were calculated from corrected isotopic ratios using the decay constants and isotopic abundance ratios listed by STEIGER & JÄGER (1977) following the methods described in DALLMEYER & KEPPIE (1987).

Two categories of uncertainties are encountered in $^{40}Ar/^{39}Ar$ incremental release dating. One group involves intralaboratory uncertainties related to measurement of the isotopic ratios used in the age equation. The other group considers interlaboratory

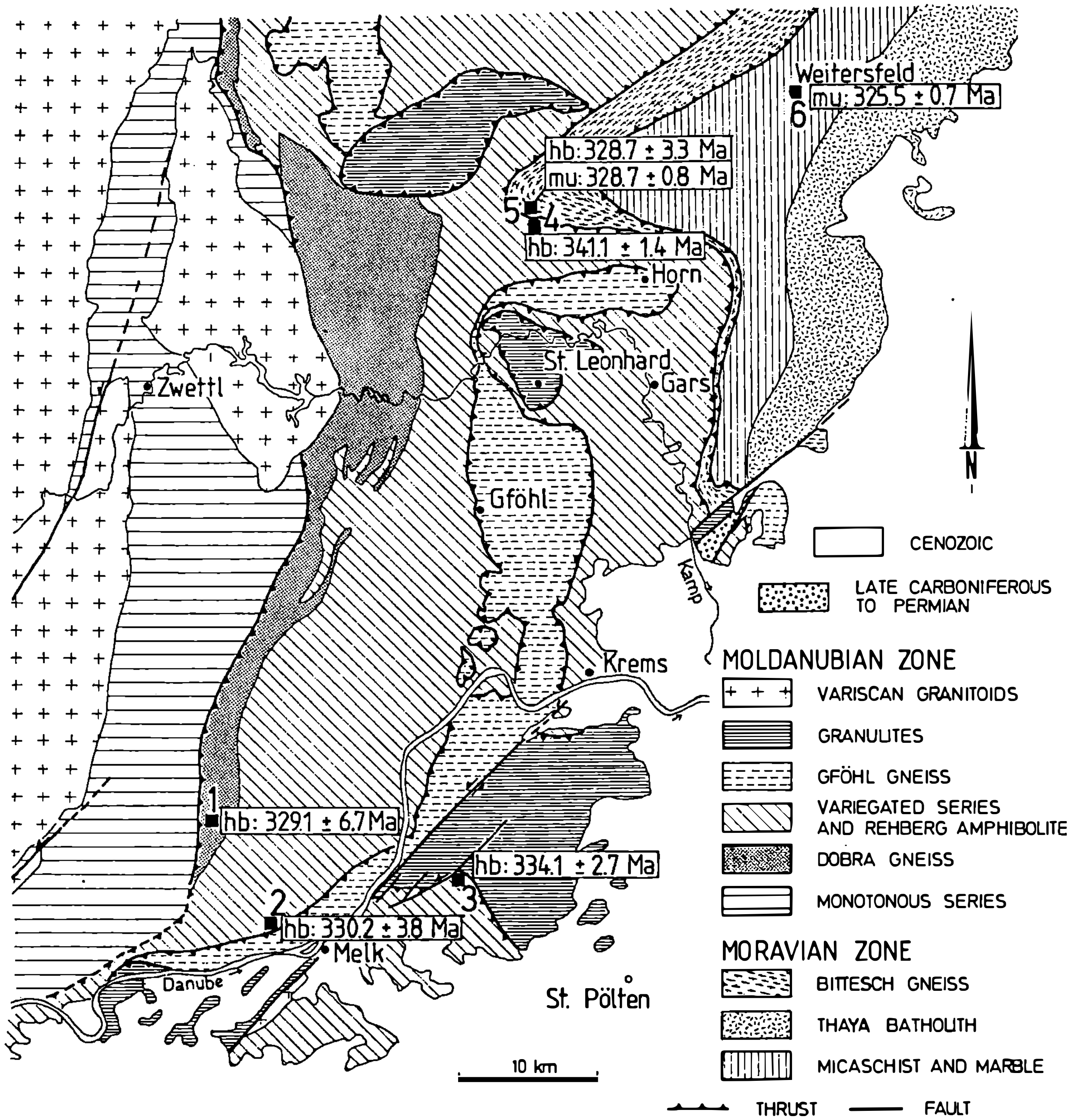

Fig. 1: Generalized geologic map of southern sectors of the Bohemian Massif indicating locations sampled for $^{40}Ar/^{39}Ar$ mineral dating; isotope correlation ages are listed (hb = hornblende, mu = muscovite).

uncertainties in the other parameters used in the age equation (monitor age, J-value determination, etc.), and are the same for each gas increment evolved from a particular sample. Therefore, to evaluate the significance of potential incremental age variations within a sample, only intralaboratory uncertainties should be considered. These are reported here, and have been calculated by statistical propagation of uncertainties associated with measurement of each isotopic ratio (at two standard deviations of the mean) through the age equation. Interlaboratory uncertainties are c. ± 1.25 - 1.5% of the quoted age. Total-gas ages have been computed for each sample by appropriate weighting of the age and percent ^{39}Ar released within each temperature increment. A "plateau" is considered to be defined if the ages recorded by two
or more contiguous gas fractions each representing > 4% of the total ^{39}Ar evolved (and together constituting > 50% of the total quantity of ^{39}Ar evolved) are mutually similar within a ± 1% intralaboratory uncertainty. Analysis of the MMhb-1 monitor indicates that apparent K/Ca ratios may be calculated through the relationship 0.518 (± 0.005 x $^{39}Ar/^{37}Ar$) corrected.

Plateau portions of the analyses have been plotted on $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlation diagrams (RODDICK et al. 1980, RADICATI DE BROCOLO et al. 1981). Regression techniques followed the methods of YORK (1969). A mean square of the weighted deviates (MSWD) is the statistical parameter which has been used to evaluate isotopic correlations. RODDICK (1978) suggests that an MSWD > c. 2.5 indicates scatter about a correlation line greater than that which can be explained only be experimental errors.

RESULTS

Five hornblende and two muscovite concentrates have been prepared from samples collected within the southeastern Bohemian Massif. Sample locations are shown in Figure 1.

Hornblende

Hornblende from amphibolite within several units of the Moldanubian Zone have been examined. These include the Dobra Gneiss (1), the Rehberg Amphibolite (2), the Loosdorf Complex (3) and the Micaschist Zone (4). An additional Hornblende concentrate has also been prepared from the Bittesch Gneiss (5) within the Moravian zone. Some of these localities will be visited during this excusion. Apparent $^{40}Ar/^{39}Ar$ age and apparent K/Ca spectra are shown in Figures 2 and 3. Low-temperature gas fractions display considerable variation in apparent ages. These are matched by intrasample fluctuations in apparent K/Ca ratios which

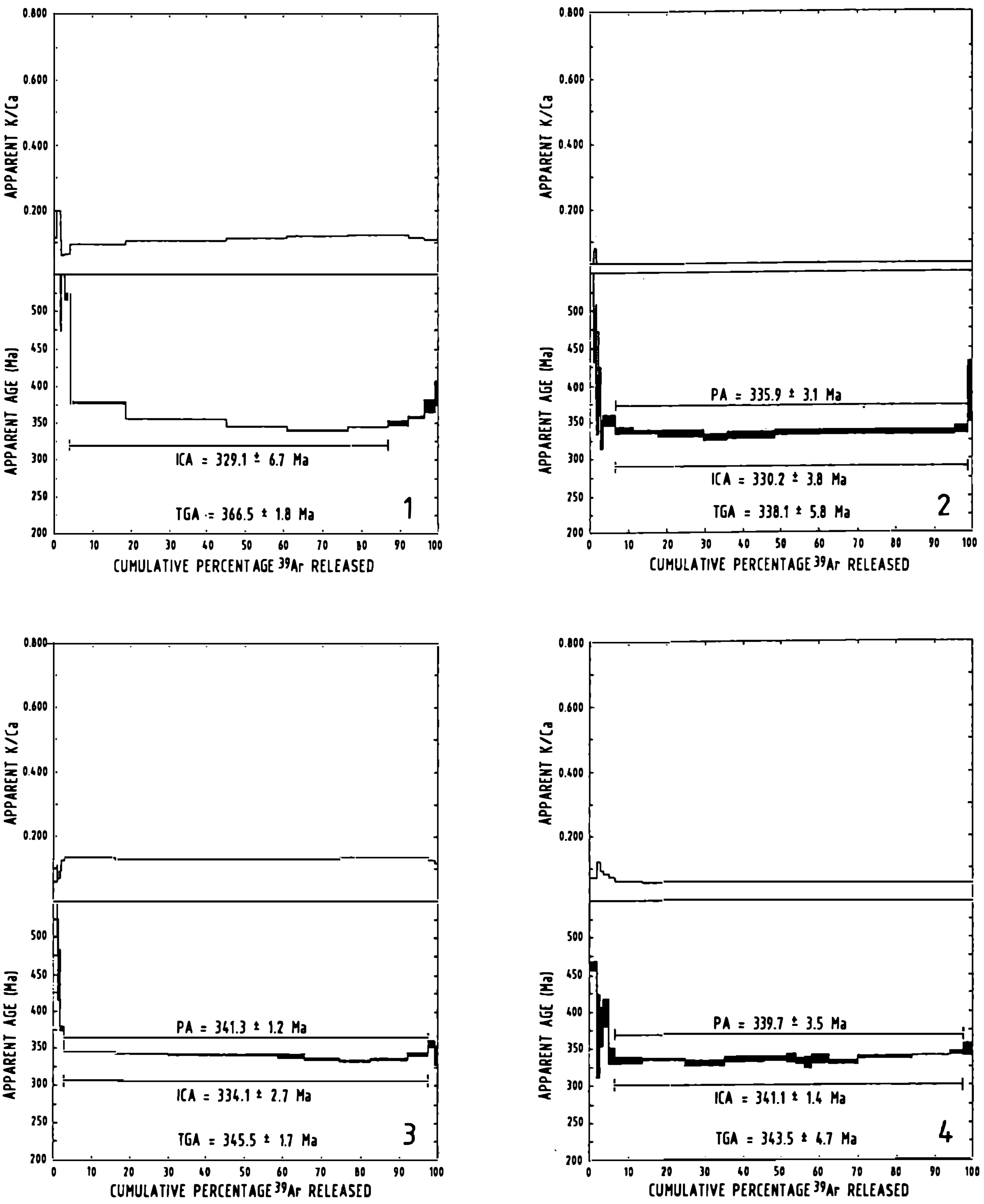

Fig. 2: $^{40}Ar/^{39}Ar$ incremental-release age and apparent K/Ca spectra for hornblende concentrates from the Moldanubian nappe complex, southeastern Bohemian massif, Austria. Analytical uncertainties (2 , intralaboratory) shown by vertical width of bars. Total-gas age (TGA), plateau age (PA), and/or isotope correlation age (ICA) are listed on each spectrum. Experimental temperatures increase from left to right.

suggests experimental evolution of argon from compositionally distinct, relatively non-retentive phases. These could be represented by very minor, optically undetectable mineralogic contaminants in the hornblende concentrates and/or petrographically unresolvable exsolution of compositional zonation within constituent amphibole grains. In general, most gas fractions evolved from the Moldanubian hornblende concentrates at intermediate and high experimental temperatures are characterized by similar intrasample apparent K/Ca ratios, indicating evolution of gas occured from compositionally uniform amphibole phases. However, markedly different apparent age relationship are observed in these portions of the five experiments.

The intermediate- and high-temperature increments evolved from samples 2, 3, 4, and 5 generally record mutually similar intrasample apparent ages which correspond to plateaux ranging between 332.6 ± 2.3 Ma (sample 4) and 341.3 ± 1.2 Ma (sample 3). The plateau date yield well-defined $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlations (MSWD < 2.0) which define inverse ordinate intercepts ($^{40}Ar/^{36}Ar$ ratios) which are generally largely than that which characterizes the present-day atmosphere. This suggests variable extraneous ("excess") argon is present within constituent hornblende grains. Using the inverse abscissa intercepts ($^{40}Ar/^{39}Ar$ ratios) in the age equation yields plateau isotope correlation ages (Figs. 2 and 3) which range between 328.7 ± 3.3 Ma (sample 4) and 341.1 ± 1.4 Ma (sample 6). Because calculation of these ages does not depend upon assumption of a modern-day $^{40}Ar/^{36}Ar$ ratio they are considered more reliable than the plateau ages directly calculated from the analytical data. The ages are interpreted to date the last cooling through those temperatures required for intracrystalline retention of argon within constituent hornblende grains. HARRISON (1981) indicated that closure temperatures for argon systems within igneous hornblende are not significantly affected by compositional variations. He suggested that values of 500 ± 25°C are appropriate in the range of cooling rates likely to be encountered in most geologic settings.

Hornblende from sample 1 displays a markedly discordant apparent age spectra in which apparent ages systematically decrease throughout low- and intermediate-temperature portions of the analysis. Apparent ages increase in the four high-temperature increments. Similar types of "saddle-shaped" discordance in hornblende $^{40}Ar/^{39}Ar$ age spectra have been interpreted by DALLMEYER (1975), HARRISON & McDOUGALL (1981), DALLMEYER & RIVERS (1983), and DALLMEYER et al. (1985) to reflect experimental liberation of gas with large and variable components of extraneous ^{40}Ar relative to intracrystalline radiogenic ^{40}Ar. The 990 - 1045°C increments comprise c. 67% of the total ^{39}Ar evolved from the sample. These analytical data yield a well-defined isotope correlation (MWSD = 1.6) which corresponds to an inverse ordinate intercept of 3080 ± 117.6 and an isotope correlation age of 329.1 ± 6.7 Ma. This is considered geologically viable, and is interpreted to date post-metamorphic cooling through appropriate intracrystalline argon closure temperatures.

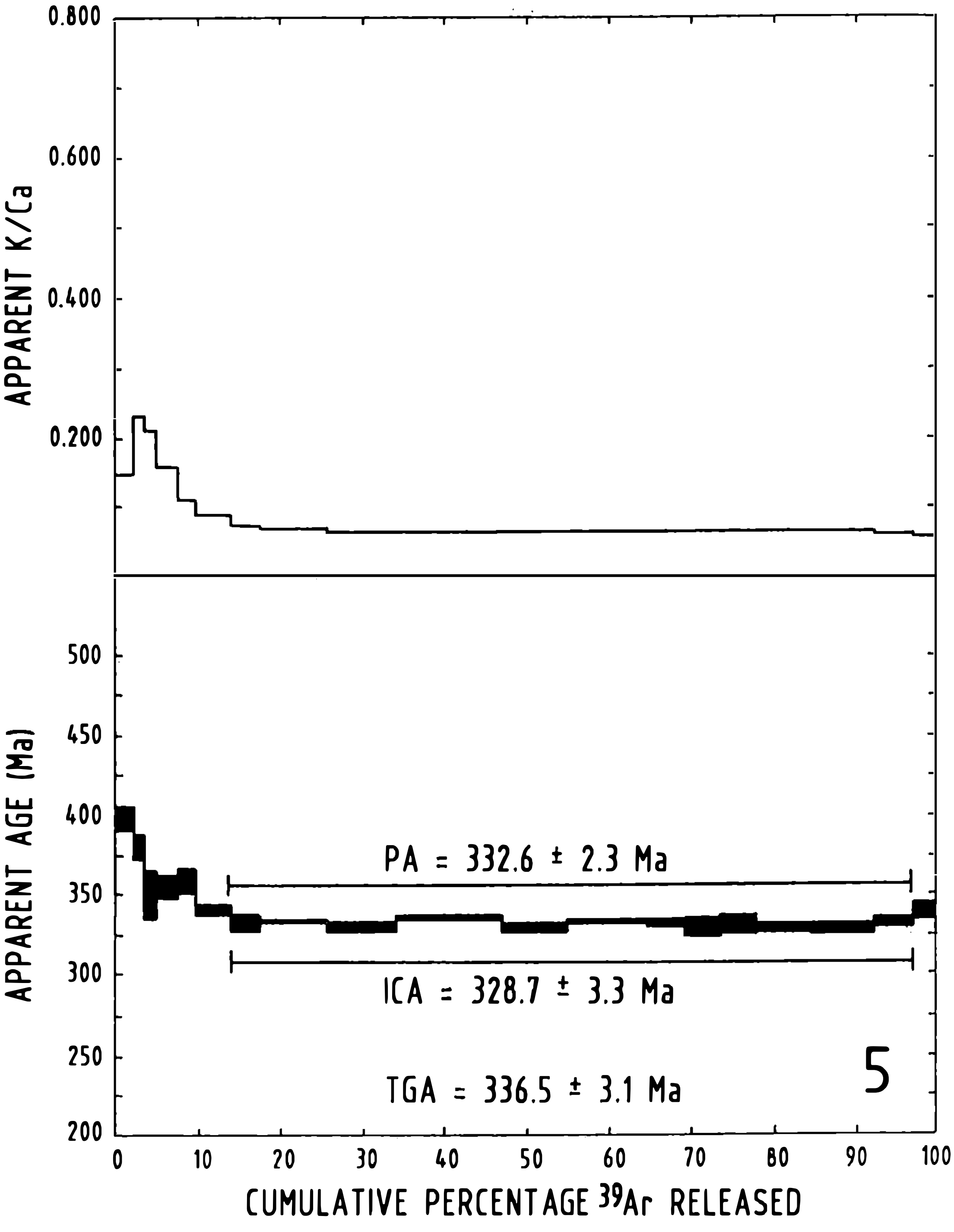

Fig. 3: $^{40}Ar/^{39}Ar$ incremental-release age and apparent K/Ca spectra for hornblende concentrates from the Moravo-Silesian zone, SE-Bohemian massif, Austria. Data plotted as in Fig.2.

Muscovite

Muscovite concentrates have been prepared from samples collected at two locations within the Moravian Zone. These include the Bittesch Gneiss (5) and the Weitersfeld Gneiss (6). Incremental age spectra are presented for the two samples in Figure 4. Apparent K/Ca ratios are very large and show no significant or systematic variations throughout the mica analyses. Therefore they are not included in Figure 5.

Internally concordant age spectra are recorded by the two muscovite concentrates. These correspond to plateau ages of 327.8 ± 0.6 Ma (sample 5) and 328.3 ± 0.6 Ma (sample 6). Generally similar isotope correlation ages are defined by the plateau analytical data. These are interpreted to date the last cooling through temperature required for intracrystalline retention of argon in constituent muscovite grains. Although not fully calibrated experimentally, using the preliminary data of Robbins (1972) in the diffusion equations of Dodson (1973) indicates muscovite closure of temperatures of c. 375 - 400°C. This is similar to those suggested for muscovite on the basis of empirical comparisons with other mineral isotopic systems (e.g. WAGNER et al. 1977; JÄGER 1979). The $^{40}Ar/^{39}Ar$ results are similar to 325 ± 7 Ma and 326 ± 7 Ma Rb-Sr model ages reported for biotite and muscovite from locality 5 by Morauf and Jäger (1982).

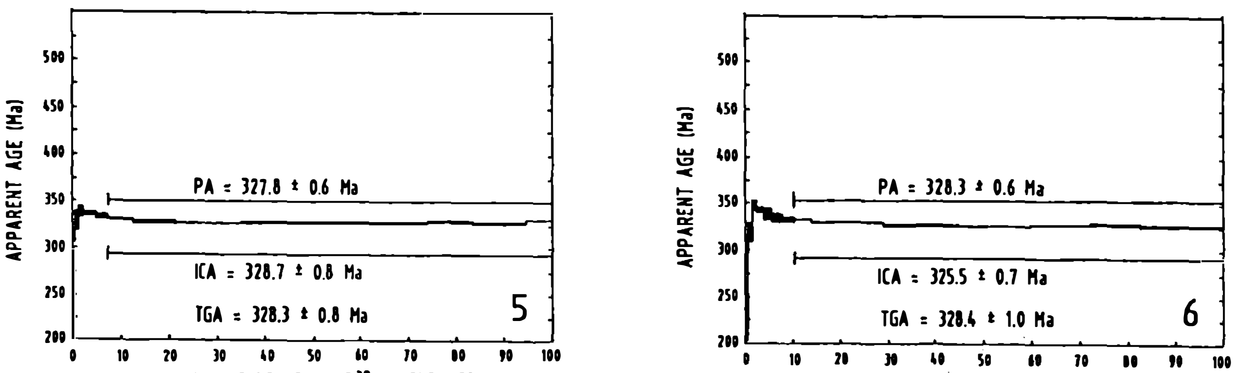

Fig. 4: $^{40}Ar/^{39}Ar$ incremental release age spectra of muscovite concentrates from the Moravo-Silesian zone, SE-Bohemian massif, Austria. Data plotted as in Figure 2.

GEOLOGIC SIGNIFICANCE

The hornblende and muscovite ages are interpreted to date post-Variscan metamorphic cooling through the appropriate closure temperatures. No record of a pre-Variscan thermal event is preserved in either the hornblende or muscovite argon systems; however, the widespread occurrence of extraneous argon components point toward a pre-Variscan stage of tectonothermal development. The near concordancy of ages recorded by intracrystalline Rb-Sr and K-Ar isotopic systems in hornblende, muscovite, and biotite suggest relatively rapid cooling through the contrasting closure temperatures. This indicates that relatively high crustal level must have been attained prior to the Early Carboniferous. The rapid cooling may have occurred during crustal extension accomodated by southeast-directed, low-angle ductile normal faulting (e.g. NEUBAUER, in press). PETRAKAKIS (1986a,b) and HÖGELSBERGER (1989) have described local retrogression of highgrade amphibolite facies assemblages to lowgrade amphibolite and geenschist facies assemblages proximal to some of the extensional faults. The hornblende cooling ages may closely date this retrogression and consequently, the ductile fault movements.

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ITINERARY

Tuesday, August 28
Drive Göttingen - Austria (will take the whole day)
Overnight: A-3642 Aggsbachdorf/Niederösterreich
Gasthof Lechner
(Tel. 0043 2753 8243)

Wednesday, August 29
Moldanubian Zone of the Waldviertel
Overnight: Gasthof Lechner

Thursday, August 30
Moravo-Silesian Zone of the Waldviertel
Overnight: Gasthof Lechner

Friday, August 31
Drive into Bavaria, Moldanubian of the Arber Region and boundary with the Tepla-Barrandian
Overnight: D-3490 Cham
Kolpinghaus
Schützenstr. 14
(Tel. 09971 4500)

Saturday, September 1
Drive towards NW; Zone of Erbendorf/Vohenstrauß (ZEV) and adjacent parts of the Moldanubian s.str.
Overnight: D-8650 Kulmbach
Hotel Purucker
Melkendorferstr. 4
(Tel. 09221 7757)

Sunday, September 2
"Vertical terrane sequence" of the Münchberg nappe pile
Overnight: Kulmbach, Hotel Purucker

Monday, September 3

Drilling Site and field-laboratory of the German Continental Deep Drilling Program (KTB) near Windisch-Eschenbach, and optional outcrops near-by.
Early afternoon: drive to Göttingen via Frankfurt a.Main railway station and international airport.

MOLDANUBIAN ZONE OF THE WALDVIERTEL, LOWER AUSTRIA

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REGIONAL GEOLOGY

INTRODUCTION

The southern Bohemian Massif comprises the "Bavarikum" (FUCHS 1976, the Moldanubian rocks along the SW margin of the Bohemian Massif), the southern part of the Moldanubian s.str., and the Moravian part of the Moravo-Silesian Zone (see also the contribution by FRANKE). The "Bavarikum" is characterized by NW-trending SW-facing structures, which overprint an older, NE- trending structural grain. To the E of the "Bavarikum", there follows a vast, NE-trending antiformal structure with the S-Bohemian Pluton in its core. The Waldviertel ("forested quarter") to the E of the pluton consists of rocks of high metamorphic grade belonging to the Moldanubian Zone, which overly, with a tectonic contact, the lowergrade Moravian units to the E. These structural relationships between the "Moldanubische Scholle" and the "Moravische Scholle" have already been identified by F.E.SUESS (1897); the "Moldanubian micaschists" along the border were interpreted, by SUESS, as a diaphtoritic shear-zone.

Between 1920 and 1940, geologists and petrographers like WALDMANN, KÖHLER, LIMBROCK, MARCHET, KÖLBEL a.o. have studied the area. They essentially followed SUESS concept, in which the Moldanubian structures are governed by the granite pluton (Intrusions-Tektonik), whereas the Moravian Zone and its contact with the Moldanubian is characterized by thrust tectonics ("Wandertektonik").

KOBER (1938) developed an alternative model, in which all of the Waldviertel is characterized by alpinotype thrust tectonics. He subdivided the Moldanubian into an upper ("Gföhl") nappe with granulites and Gföhl gneisses, and a lower "Schiefergneis" nappe. The allochthonous position of the Gföhl unit has meanwhile been confirmed by detailed mapping of FUCHS, MATURA and THIELE. Apart from this basic tectonic concepts, there are extremely diverging views of the protolith ages, metamorphic ages, and structural development.

LITHOLOGY

In the Moldanubian part of the Waldviertel, it is possible to discern, in order from bottom to top, three main tectonic units (Fig.1a, b). The Ostrong and the Drosendorf unit are often summarized, in a larger sense, under the term of Drosendorf Unit (see TOLLMANN 1982 and the contribution by FRANKE).

Ostrong Unit

(named after its main outcrops in the Ostrong Hills, to the SE of the S-Bohemian Pluton). The OU is rather monotonous and consists of paragneisses with garnet-sillimanite-biotite plus cordierite and K-feldspar, which are partly migmatic. Muscovite is subordinate and probably of retrograde origin. There are some intercalations of calc-silicates, leucocratic orthogneisses, and rare amphibolites.

Drosendorf Unit

The base of the DU is occupied by the Dobra Gneiss, a platy orthogneiss derived from granites and granodiorites. Concordant and (partly) discordant intercalations of amphibolite and biotite-amphibolite contain inclusions of Dobra Gneis and are, therefore, younger than the latter. The biotite-amphibolites may be transitional into amphibolite schists. The belt of outcrop of the Dobra Gneiss in the northern Waldviertel attains more than 10 km width; towards the S, it is gradually reduced, until it pinches out to the N of Artstetten. The granodiorite-gneiss of Spitz, in the southeastern Waldviertel, is probably an equivalent of the Dobra Gneiss. A further equivalent might be seen in the less metamorphosed Bites Orthogneiss (FUCHS & MATURA 1976, see also the contribution by FRASL et al.), which occurs only a few km further E, in the W part of the Moravian Zone.

The Dobra Gneiss is overlain, probably with a sedimentary contact (FUCHS & MATURA 1980), by a "Variegated Sequence". It consists of bt-plag-paragneisses, amphibolites, marbles, calcsilicates, metaquartzites and -arkoses, as well as graphite-bearing marbles, schists and gneisses. Minor intrusions of granitoids, aplites and pegmatites occur mainly in the upper part. The variegated sequence has evolved from an epicontinental association of clastics and carbonates with intercalations of mafic volcanic rocks.

The paragneisses contain garnet and sillimanite +/- muscovite (retrograde?), and oligoclase-andesine.

The amphibolites are often migmatic, with leucosomes rich in plagioclase (oliogoclase-andesine). Biotite and garnet occur but locally.

The marbles are banded and medium- to coarse-grained. They consist of calcite, diopside, tremolite, phlogopite, quartz, feldspar, skapolite and graphite. They are transitional into calcsilicates with diopside, andesine, quartz, garnet and (locally) amphibole, K-feldspar and skapolite.

The metaquartzites show transitions into quartzitic gneisses and meta-arkoses, and contain accessory biotite, sillimanite, garnet and graphite. After FUCHS & MATURA (1980), they occur mainly in the lower part of the variegated sequence.

Graphite-schists and -gneisses are mostly connected with marbles, and locally form graphite deposits of economic significance.

Gföhl Unit

The GU is characterized by two conspicuous rock types: **granulites** and **Gföhl Gneiss.** These are accompanied by a **variegated sequence** which comprises paragneisses, amphibolites with garnet and pyroxene, serpentinites, and subordinate carbonates, which habe been termed "**Begleitserien**" (rocks accompanying the granulites). The stratigraphic and structural position of these "**Begleitserien**" is essentially unknown, and, therefore, subject to a confusing number of contrasting interpretations:

After FUCHS (1986), the "Begleitserie" of Raabs (Fig. 1) underlies the Blumau granulites, and is different from the "Begleitserie" underlying the Gföhl Gneisses, which, in its turn, occurs structurally above and below the Gföhl Gneiss of St.Leonhard (SW of Horn, Fig 1). THIELE (1984), in following TOLLMANN (1982), summarizes these different "Begleitserien" under the term of "Raabs-Meisling Unit". As a consequence, the Gföhl Gneiss S of the Horn Synform (also termed "Horn Gneiss") would become part of the Raabs-Meisling "Begleitserie" - an interpretation strictly rejected by FUCHS (1986).

Detailed mapping by WEBER et al. (in prep.) in the area of Gars - St.Leonhard has revealed, that the "Begleitserie" underlying the St.Leonhard granulite is not identical with that underlying the Gföhl Gneiss, but correlates, instead, with a higher part of the Gföhl Nappe, which is again overlain by granulites. This higher tectonic unit has been thrust, S of Horn, over the "Begleitserie" underlying the Gföhl Gneiss (which is cut out by the thrust and therefore does not appear S of Horn; Fig. 1).

It has to be concluded, that two lithologically similar "Begleitserien" exist in the Gföhl nappe of the Kamptal.In order to avoid new local names, WEBER et al. (in prep.) have proposed to designate the "Begleitserie" underlying the Gföhl Gneiss as "Meisling-Unit", and the one underlying the granulites as "Raabs- Unit". The combination of these two as a "Raabs-Meisling-Unit" (TOLLMANN 1982, 1985, THIELE 1984) is considered incorrect.

The "Meisling-Unit" (sensu WEBER et al.) is characterized by amphibolites ("Rehberg A." or "Buschandlwand A."), a HT-mylonitic alternation of amphibolites, gabbro-amphibolites, orthogneisses and metasediments with serpentinites and eclogites.

The "Raabs-Unit" (sensu WEBER et al.) is composed, after THIELE (1976), of para- and orthogneisses, amphibolites and graphite- quartzites. The Raabs-type "Begleitserie" underlying the granulites of St.Leonhard consists of garnet- and pyroxene- bearing amphibolites alternating with leucocratic gneisses and migmatic paragneisses and meta-carbonates, accompanied by alkali- syenite and alkalifeldspar-quartz-syenite. These syenitic rocks have been intruded at a late stage of tectonic deformation, and therefore show a relatively weak gneissic texture.

Another variegated sequence is known as the "Loosdorf Complex", which overlies the SW margin of the Dunkelstein Forest. It consists mainly of migmatic paragneisses, amphibolites, garnet- amphibolites, marbles and calcsilicates. The border towards the underlying Dunkelstein granulites is marked by pyroxene- amphibolites and serpentinites. The Loosdorf complex is correlated, by MATURA (1984), with the variegated sequence of the Drosendorf Unit, and, by THIELE (1984) with similar rocks in the Ysper Valley between the Weinsberg Granite to the W and the Ostrong Antiform to the E, i.e., structurally in the hanging wall of the Ostrong Unit.

A further uncertainty regards the occurrence of marbles E of the Gföhl Nappe Complex (Maria Dreieichen, map-sheet Horn). Graphite- calcite thermometry in these marbles yields 680°C. This contradicts the interpretation of FUCHS (1986) of these rocks as part of a Moravian window, because typical Moravian marbles show temperatures which are 200°C lower. It is possible that the marbles of Maria Dreieich form part of the Gföhl Nappe, though marbles from the latter generally contain more dolomite and are devoid of graphite.

In this context, it should be noted that marbles from the micaschists which overly the Bites Gneiss N of Horn, show metamorphic temperatures corresponding to those of typical Moravian marbles (WEBER et al. in prep.). They must not, therefore, be regarded as part of the "Moldanubian Micaschists", which are taken to represent - after FUCHS,THIELE and TOLLMANN, following SUESS (1908) - the shear-zone along which the Moldanubian was emplaced over the Moravian Zone. Instead, at least the marble-bearing part of the micaschists must be interpreted as part of the Moravian Zone, so that - in accordance with DUDEK (1962) - the Bites Gneiss does not form the structurally highest unit of the Moravian Zone, but is overlain by further Moravian rocks, which, in their turn, are overlain by the Moldanubian nappe pile.

The **Gföhl Gneiss** is a leucocratic granitic gneiss, with a polyphase deformation and metablastic to migmatic fabric intercalated with some paragneiss and amphibolite sheets. It consists of K-feldspar (perthitic), oligoclase (antiperthitic), biotite, sillimanite, garnet and (locally) kyanite. Muscovite occurs as a retrograde phase. The Gföhl Gneiss occurs in a metablastic variant, but may also show a fine-grained, equigranular fabric, which resembles that of the accompanying granulites, and can be interpreted, in both these cases, as resulting from a HT mylonitization. At Senftenberg, there occurs an amphibolite with amphibole/plagioclase symplectite formed from clinopyroxene. This amphibolite has been agmatically deformed by late tectonic partial melts of the Gföhl Gneiss. These relationships suggest an older HP/HT metamorphism and subsequent decompression at still elevated temperatures.

The **granulite** is a fine-grained, equigranular, leucocratic gneiss with a strong parallel banding. SCHARBERT (1963, 1964) has described the following varieties:

The most widespread type is the leucocratic granulite, or "granulite sensu stricto" in the sense of SCHARBERT 1963, which has been termed "Weißstein-Granulit" because of its light colour. It consists of quartz (often in ribbons), mesoperthitic K-feldspar (partly with myrmekite), antiperthitic plagioclase (oligoclase), biotite, garnet, sillimanite, kyanite, spinell, rutile, apatite, zircon and graphite. The banding is essentially caused by different amounts of fine-grained biotite. There are transitions between biotite-rich and -poor varieties, the biotite-rich ones also containing more plagioclase and garnet. Quartz-free varieties are rare.

Associated rock-types comprise:
Plagio-granulites with plagioclase dominating over K-feldspar;

Pyroxene-granulites and pyriclase-granulites with ortho- and subordinate clinopyroxene in addition to the normal Weißstein- assemblage, but without sillimanite and kyanite;

rare pyriclasites, which are devoid of quartz and consist of basic plagioclase, orthopyroxene, garnet and biotite.

Interspersed among the granulites of the Gföhl Nappes, there are lenses of serpentinite, partly with relict mineral assemblages of garnet-peridotites, garnet-pyroxenites (SCHARBERT & KURAT 1974) and kyanite-bearing eclogites (CARSWELL 1989).

METAMORPHISM

Ostrong Unit (Monotonous Sequences)

630-670°C/ 3-4 kb: cordierite-gneiss from the southern end of the Ostrong (Loyagraben); PT-estimate after mineral chemistry, SCHARBERT 1982.

630°C/ 3 kb: paragneisses, PT-estimate after the mineral assemblage cordierite-biotite-sillimanite-muscovite-K-feldspar- plagioclase (ZAYDAN & SCHARBERT 1983).

Drosendorf Unit (data from the Variegated Series)

670°C/ 5 kb: paragneisses, garnet-biotite thermometer, P- estimate after the mineral assemblages garnet-biotite-sillimanite-K-feldspar-quartz-plagioclase-(kyanite) and garnet-biotite-quartz-plagioclase and mineral chemistry (ZAYDAN & SCHARBERT 1983).

740-800°C/ 5 kb: amphibolite, garnet-clinopyroxene thermometer, P-estimate after the mineral assemblages named above (ZAYDAN & SCHARBERT 1983).

700-770°C/ 6-9 kb: paragneisses in the S part of the Variegated Sequence, garnet-biotite thermometer, garnet-plagioclase- sillimanite-quartz barometer (PETRAKAKIS 1986).

620-690°C: Graphite-bearing marbles, calcite-graphite isotope- thermometer, with a tendency toward lower temperatures in the upper parts of the Variegated Sequence (WEBER et al. in prep).

Gföhl Nappes

760°C/ 9-10 kb: PT-estimate in pyroxene-granulites, after mineral assemblage kyanite-mesoperthite-quartz-orthopyroxene-clinopyroxene, and partitioning coefficients of Fe, Mn and Ca (SCHARBERT & KURAT 1974).

670-750°C/6.5 kb (garnet-core); 550°C/ 4 kb (garnet-rim): St.Leonhard granulite, garnet-biotite thermometer, garnet- plagioclase-sillimanite-quartz barometer (WEBER et al. in prep.).

580°C/ 8 kb (garnet-core); 530°C/ 5 kb (garnet-rim): Meidling granulite, garnet-biotite thermometer, garnet-plagioclase- sillimanite-quartz barometer (WEBER et al. in prep.).

575°C / 5 kb (garnet-core); 520°C/ 5 kb (garnet-rim): mafic nodules in the Meidling granulite, garnet-biotite thermometer, garnet-plagioclase-sillimanite-quartz barometer (WEBER et al. in prep.).

850-920°C (centres of separated grains of garnet and clinopyroxene); 770-850°C (margins of grains of garnet and clinopyroxene in contact) / 8-9 kb (measurements at grain contacts): garnet-pyroxene-amphibolite from the Raabs- "Begleitserie" below the St.Leonhard granulite; garnet- clinopyroxene thermometer; garnet-plagioclase-sillimanite-quartz barometer (WEBER et al. in prep.).

750-810°C (centres of grains of garnet and clinopyroxene in contact); 630-730°C (margins of grains of garnet and clinopyroxene in contact) / 8.5-9 kb (margins of grains of plagioclase and garnet in contact, minimum pressure): garnet-pyroxene-amphibolite, from the contact with the Ysper Valley granulite; garnet-clinopyroxene thermometer, garnet- plagioclase-sillimanite-quartz barometer (WEBER et al. in prep.).

750-800°C (biotite - core of garnet)/ 6.5-7.7 kb (plagioclase - core of garnet); 550-660°C (biotite - rim of garnet)/ 4.5-5.8 kb (palgioclase - rim of garnet): retrograded granulite, Ysper Valley (WEBER et al. in prep.).

740-800°C (biotite - core of garnet)/ 7.3-7.5 kb (plagioclase - core of garnet); 520-660°C (biotite - rim of garnet)/ 4.5-5.3 kb (plagioclase - rim of garnet): garnet-biotite.gneiss from the Ysper Valley; garnet-biotite thermometer; garnet-plagioclase- sillimanite-quartz barometer (WEBER et al. in prep.).
710°C: graphite-bearing marble from the Loosdorf Complex; graphite-calcite-isotope-thermometer (WEBER et al in prep.).

After CARSWELL (1989), the garnet-peridotites and the kyanite- bearing eclogites in the Moldanubian of Austria have been formed at approx. 30 kb and 1050-1150°C. CARSWELL suggested, that these mantle-derived rocks were tectonically inserted during the Variscan collision into a thickened continental crust. Their tectonic incorporation started under eclogite-facies conditions (800-900°C/ 20 kb) and was continued in the granulite facies (750-800°C/ 12-15 kb).

A Variscan event is indicated by Sm/Nd data (ga-cpx-WR isochron) of 344 +/-10 Ma and 370 +/- 15 Ma of two garnet-pyroxenites. After CARSWELL (1989), the garnet-peridotites bear traces of an older,pre-HP extensional event with approx. 1200 C and 10-20 kb. This event would have been related with a bimodal magmatism, which led to the crystallization of the protoliths of the eclogites, garnet-websterites, and felsic granulites.

The retrograde PT-path of the Gföhl Nappes is well documented down to temperatures of 500-600°C and approx. 5 kb. Up to this level, the Weißstein granulites have been deformed under conditions of the dry amphibolite facies, with penetrative primary recrystallization of feldspar and intense HT- mylonitization (WEBER et al. 1990, 1990a). All rocks have passed, during their retrograde development, the HT/LP field. This is indicated by the occasional occurrence of cordierite symplectites in granulites and coronas of cordierite around garnet in the garnet-biotite-gneisses of the Ysper Valley (WEBER et al. in prep.). Strain increments acquired under lower temperatures are increasingly inhomogeneous. They are characterized, in the granulites, by the neoformation of light-brown and green biotite, epidote minerals, and chlorite, as well as by the primary recrystallization of quartz and cataclastic deformation of feldspar.

Like in the HT-mylonitic Weißstein granulites, retrograde PT paths can also be demonstrated for the gneissified granulites and intercalated metetectic ga-bt-gneisses of the Ysper Valley, and for lamellae of granulitic gneisses within the Gföhl Gneiss (Försterbach, Kamptal). From these relationships, WEBER et al. (in prep.) conclude that the differential development of tectonic fabrics was essentially controlled by the availability of fluid phases. A common amphibolite-facies development (under 800°C) is probable for all rocks within the Gföhl Nappes. Higher temperatures and pressures have only been detected in the eclogites/websterites and garnet-peridotites, which probably represent tectonic inserts.

RADIOMETRIC AGES

The relevant data may be taken from table 1. Critical data are referred to in the text.

			Age [Ma]	System	Interpretation	Author
MORAVIAN	Bittescher Gneiss		796±49	Rb/Sr -whole rock	Magmatic age	6
			570±42	Rb/Sr -whole rock	Magmatic age	5
			480±50	Rb/Sr -whole rock	Metamorphic age	3
	Brünner Pluton		584± 5	U/Pb Zirkon	Magmatic age	3
			555± ?	K/Ar Biotite	Magmatic age	4
	Thaya-Batholite		551± 6	Rb/Sr -whole rock	Magmatic age	7
MOLDANUBIAN	GFÖHL UNIT	Gföhl - Gneiss	570±60	Rb/Sr -whole rock	Magmatic age	3
			474±23	Rb/Sr -whole rock	Magmatic age	2
			341± 4	U/Pb Zirkon	Deformation age	3
			337± 3	U/Pb Monazite	Amphibolite Facies Overprint	3
		Granulite	469±11	Rb/Sr -whole rock	Metamorphic age	1
			431±35	Rb/Sr thin slab isochron	Metamorphic age	1
			345± ?	U/Pb Zirkon	Metamorphic age	10
			345± 5	U/Pb Zirkon	Metamorphic age	3
			339± 2	U/Pb Monazite	Amphibolite Facies Overprint	3
			295±12	Rb/Sr Biotite	Cooling age	1
			277±11	Rb/Sr Biotite	Cooling age	1
	VS	Marble	465±28	Fissiontrack Titanite	Metamorphic age	9
		Amphibolite	420±21	Fissiontrack Apatite	Metamorphic age	8
	CBP	Pluton	331± 4	Rb/Sr -whole rock	Magmatic age	3
		Pegmatite	331± 5	Rb/Sr Muscovite	Deformation age	3
	SBP	Weins - berg Granite	280± 4	K/Ar and Rb/Sr Biotite	Cooling-age	8
			300± 1			8
			349± 4			11

Authors:
1: ARNOLD & SCHARBERT (1973), 2: ARNOLD in FUCHS & MATURA (1980), 3: v.BREEMEN et.al.(19
4: DUDEK & SMEJKAL (1968), 5: MORAUF & JÄGER (1982), 6: SCHARBERT,S. (1977),
7: SCHARBERT et.al. (1980), 8: THIELE (1969), 9: VARTANIAN (1975), 10: AFTALION et al. (1989),
11: SCHARBERT, S. (in Press).

STRUCTURAL DEVELOPMENT

Since the studies of KOBER (1938), FUCHS (1971,1976,1986), MATURA (1976,1984) and THIELE (1976, 1984), the existence of alpinotype nappes in the Waldviertel is generally accepted. However, the age of deformation, the subdivision and the direction of transport are much debated. FUCHS and MATURA suggest a Caledonian deformation with W-directed transport, and an E-directed Variscan refolding (FUCHS). THIELE and MATTE (1986) have argued for E-directed Variscan thrusting. According to Rajlich (1987) and FRITZ & STEYRER (1990), NE-trending lineations with shear criteria indicate NE-directed early Variscan thrusting of the Moldanubian nappes over the Moravian units. MATURA, like FUCHS (1986), suggests only one nappe (the Gföhl gneisses and granulites), emplaced over a Moldanubian/Moravian foreland. THIELE (1984) doubts the existence of of a nappe thrust at the boundary between the Ostrong and Drosendorf Units (and, hence, the existence of a separate Drosendorf nappe), while FUCHS distinguishes between the Drosendorf and the Gföhl Nappes, and regards the occurrence of granulite slices between the Ostrong and Drosendorf Units (FUCHS & SCHARBERT 1979) as indication of a further nappe thrust. In fact, these granulite lenses and associated amphibolite-mylonites are HT-mylonites of the same type as similar rocks associated with important thrusts in the area (DUYSTER in prep., PETRAKAKIS 1986, WEBER et al. 1990). Thermobarometry reveals the same retrograde PT path. Their HT mylonitization indicates a shear-zone active under amphibolite facies conditions. Against the suggestion of FUCHS & SCHARBERT (1979), the granulite slices between the Ostrong and Drosendorf Nappes are not derived from either of these units, but represent tectonic inserts along a nappe thrust. Among these tectonic lenses, there are also garnet-pyroxenites, which also occur, further W, on top of the Monotonous Sequence.

Within the Gföhl Nappe Complex, it is possible to distinguish several thrust sheets, which cannot be traced, however, over all the area. As already laid out in the chapter lithology, there is some uncertainty regarding the number and correlation of the variegated "Begleitserien".

Within the Moldanubian rocks, it is possible to discern at least four "phases" of tectonic deformation, all of which belong to a Variscan collisional event (WEBER et al. in prep.).

D1 is related to E-directed nappe thrusts. The monotonous rocks of the Ostrong Unit are overthrust by the Drosendorf Unit (Dobra Gneiss and Variegated Series). The nappe thrust is represented by the HT-mylonite at the base of the Dobra Gneiss. This intracrustal shear-zone is not only documented by the granulite slices first described by

FUCHS & SCHARBERT (1979), but also reflected in the pervasive HT-mylonitization of the gneisses. It should be noted, however, that the shear-zone may be annealed, in some areas, by later metablastesis. This is a general problem in HT-mylonites, which can only be formed under dry amphibolite-facies conditions. With higher P-H20, metablastic or metatectic fabrics become dominant, so that a distinct shear- zone fabric is not developed.

The base of the Gföhl Nappe Complex cuts obliquely across the Ostrong and Drosendorf Nappes, so that the variegated series of the Drosendorf Nappe pinches out in the southern Waldviertel, N of the Danube vally (Fig.1). The direction of transport of the Gföhl Nappe is toward ESE, as can be deduced from E- to ESE-facing folds in the Gföhl Gneiss and associated amphibolites, as well as from numerous subhorizontal shear-zones in the eastern part of the Gföhl Unit. Locally, it is possible to recognize several strain increments, such as refolded folds, refolded shear-zones, and folded boudins, within a progressive D1 deformation.

Shear-zones within the Gföhl Nappe suggest the existence of separate thrust sheets, e.g., at the base of the Gföhl Gneiss and at the base of the granulites. These internal shear-zones are marked by cm- to dm-scale lenses of ultramafic rocks which may be transformed into antophyllite nodules (e.g., at the base of the Gföhl gneiss at Dürrnstein). Antophyllite has only be preserved in the core of the nodules; towards the margins, it has reacted with the gneiss matrix to form actinolite and biotite.

D2 refolds the whole nappe pile with a westward vergence. The intensity of folding, accompanied by thrusting increases towards the W and can be traced up to the eastern margin of the S-Bohemian pluton. D2 is interpreted as backfolding. The Ostrong Antiform is interpreted as a large D2 structure. The presence of lenses of granulites along the contact between the Ostrong and Drosendorf Units results from backthrusting on this nappe boundary.

The steep southward plunge of the Ostrong Antiform results from a still younger overprint (D3), which originated from NS-directed shortening. D3 has also brought about the subvertical, EW- trending attitude of the Gföhl Nappe Complex between Melk and Ybbs along the Danube River as well as the S directed plunge of the Ostrong Antiform.(Fig. 2) The EW-trending D3 structures show varying dimensions and vergence. D3-structures are the S-vergent "Messen Arc", and the N-vergent Antiform of the St.Leonhard granulite. These two Antiforms are separated by the Horn Synform, which dies out toward the E (Fig 2). The attenuation of D3-folding to the E induces dextral shear along the Moldanubian/Moravian boundary for reasons of strain compatibility.

Smaller-scale D3 structures (m to 100 m wavelength) show random distribution and varying orientations, which are controlled by the attitude of the pre-existing anisotropy. In areas with a NS-trending, steeply E dipping foliation, such as along the Danube River S of the Ysper Valley, the D3 fold axes show steep easterly dips. Further typical examples of D3 folds occur around the Dobra reservoir, and in a roadside section near Rastenfeld. Locally, there are subhorizontal thrusts with transport directions both to the N and to the S.

The sinistral strike-slip Diendorf Fault relates to the same NS-directed compression. The fault was probably formed during the late stage of Variscan isostatic uplift and was active up to the cataclastic deformation regime. An Alpine reactivation is probable. Local positive flower structures indicate a transpressive regime. If the sinistral displacement of approx. 25 km (THIELE 1984) is restored, the primary connection between the granulites of the Dunkelstein Forest with those of Pöchlarn-Wieselburg becomes apparent.

The D4 structures are extensional. Subhorizontal normal faults are frequent. They have been formed in the brittle/ductile transition, partly with the formation of mylonites and ultra- mylonites. In areas with a subvertical anisotropy, there occur gravitational folds with a subhorizontal crenulation cleavage. The trend of these fold-axes is controlled by the strike of the pre-existing foliation.

The sequence of tectono-metamorphic events and the open questions can be summarized as follows. The protoliths of the Gföhl Nappe Complex are rocks of an older continental crust. They were overprinted by Variscan HP/HT metamorphism. During this Variscan metamorphism charnockitic melts formed in the lower crust. The Weißstein granulites originated from these charnockites by HT mylonitization (WEBER et al. 1990). The tectonic events recorded in these rocks are part of the Variscan orogeny, even if the protoliths are of Precambrian age.

It is completely uncertain, if the felsic granulites have followed the same PT-path as their mafic and ultramafic inclusions. The eclogite-facies relicts only occur as lenses within the granulites. Stratiform intercalations of metabasites (ga-cpx-amphibolites) show maximum PT conditions of the granulite facies, and do not contain any textural indications of derivation from eclogites, such as a former lack of plagioclase. The same is true for restitic boudins. These observations suggest, that the eclogite facies rocks and the granulites where brought together in a granulite facies level, whereby the eclogite facies rocks were retrogressed and the granulite facies rocks underwent prograde metamorphism - a relationship frequently observed in granulite facies nappes.

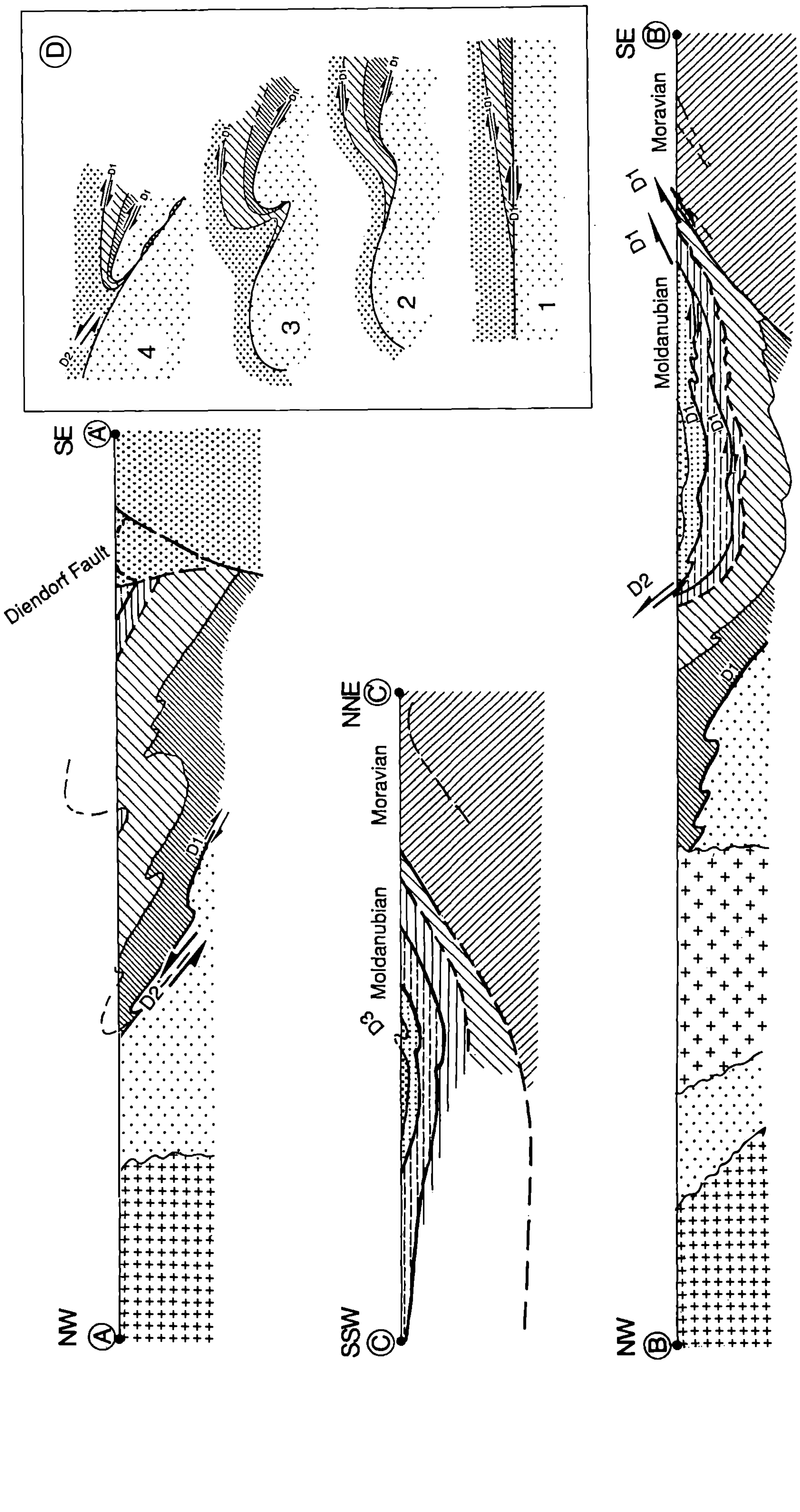
Though similar granulites are present to the NW of the S-Bohemian Pluton, there is no proof of an originally coherent granulite nappe in the SE part of the Bohemian Massif. Furthermore, a derivation of such a nappe from the Saxothuringian/Moldanubian suture (TOLLMANN 1982, 1985) appears unlikely, since Moldanubian rocks in this area have been transported to the NW (WEBER & VOLLBRECHT,1989), whereas the granulites have been transported toward the SE and E. WEBER et al. (1990) have suggested that the root zones of the two granulite nappe systems are now occupied by the large Central-Bohemian and S-Bohemian Plutons, which indicate anatexis in thickened segments of continental crust. The plutons probably rest above terrane boundaries at deeper levels. In the case of the S-Bohemian Pluton, we are probably dealing with the NW margin of the Cadomian Brunno-Vistulian (or Moravo-Silesian) terrane (Lower Plate), which has been overthrusted toward the SE by the Moldanubian (upper plate) at least as far as the present-day outcrop of the Moldanubian thrust. This is corroborated by reflection seismic profiling, which has revealed, in Czechoslovakia, NW-dipping reflectors which reach the Moho underneath the S-Bohemian Pluton (TOMEK 1989).

Fig.1b: Section A-A': W directed backfolding (D2) and backthrusting of the nappe stack. Sketch D shows our model of the tectonic development at the boundary Monotonous Series, Variegated Series.

Section B-B': SE directed (D1) nappe stacking of Moldanubian and Moravian units and (D2) backfolding and backthrusting in Moldanubian units.

Section C-C': NE directed (D3) folding.

Position of all cross sections and legend on fig.1a.


NW
A
SE
A'
Diendorf Fault
D2
D1
SSW
C
NNE
C'
D3
Moldanubian
Moravian
D
1
2
3
4
NW
B
SE
B
D1
D2

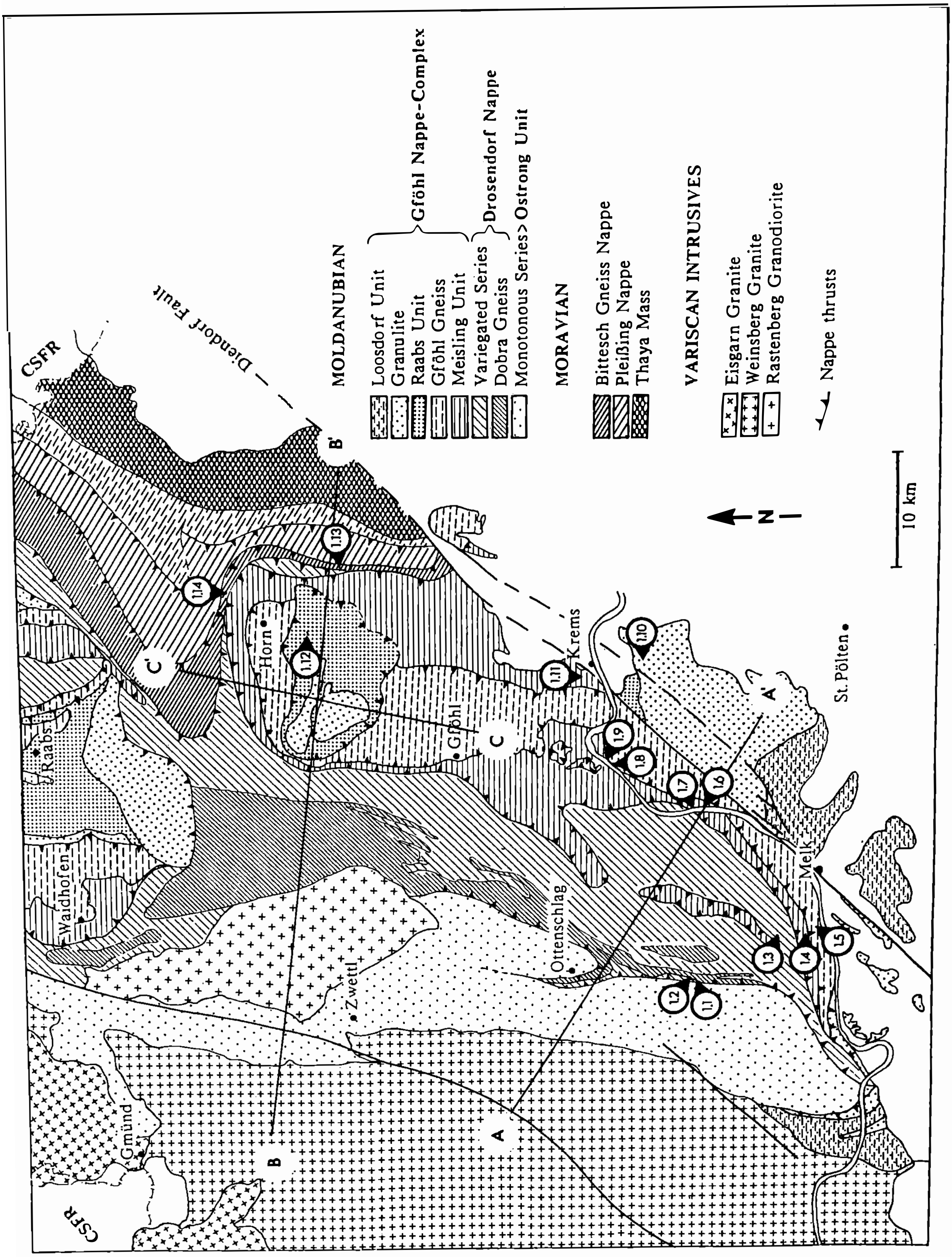


Fig.1a: Geological map of the Waldviertel, southeastern Bohemian Massif, Lower Austria with excursion stops and position of cross-sections on Fig 1b. Data from FUCHS, MATURA, THIELE and WEBER et al.

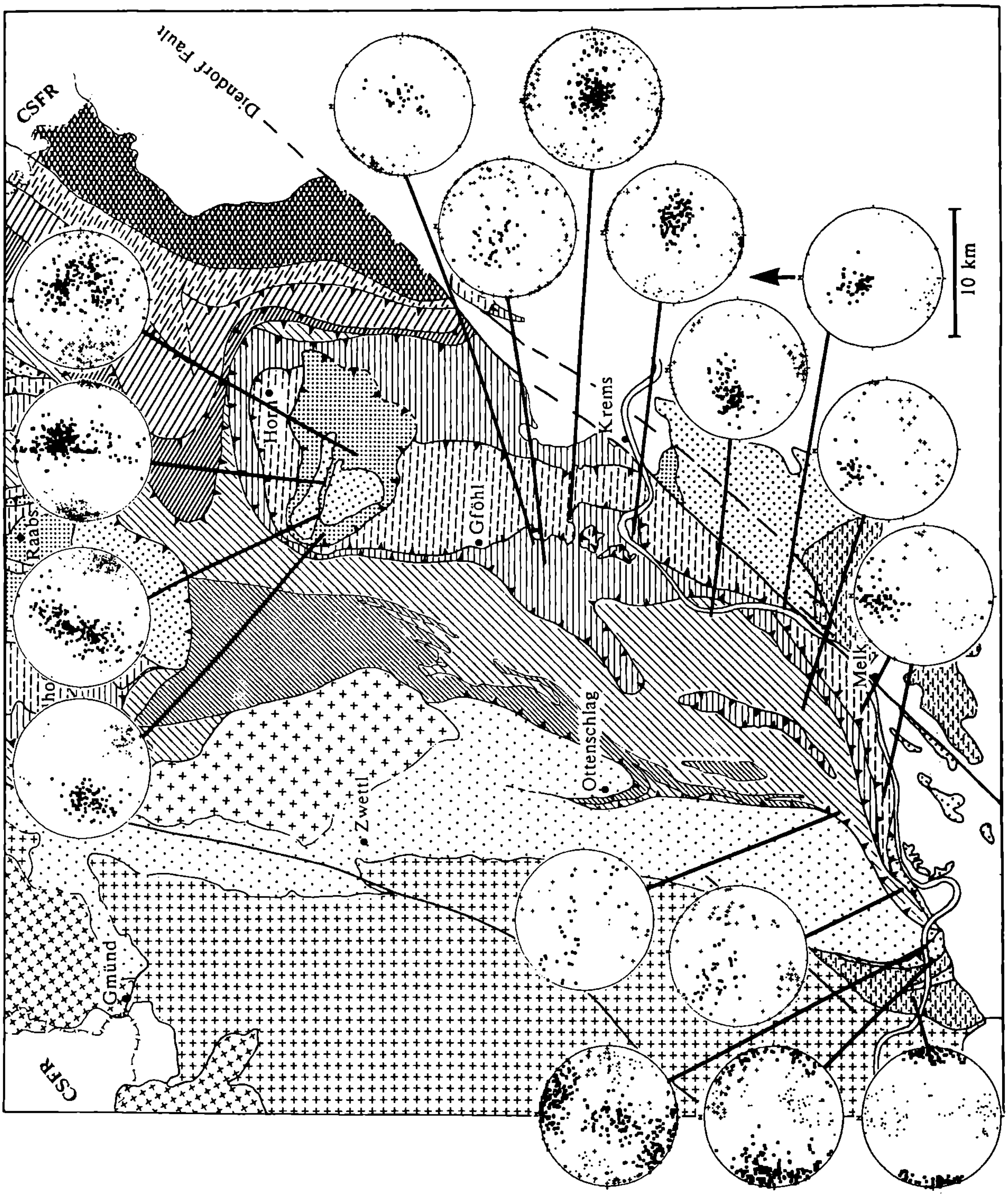


Fig.2: Structural map: Data from DUYSTER, KRIENERT, LOTTMANN (1990), MANN, OCKLENBURG, PETERS, URBAN & WÖSSNER.
Legend on fig.1a.

DESCRIPTION OF STOPS

with contributions by Franz NEUBAUER[1] and
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STOP No. 1.1 - Granulitic high-temperature mylonites at the boundary between Monotonous and Variegated Units
Hill approx. 1.2 km E of the church of Pöggstall
ÖK 50: 36 Ottenschlag (F.NEUBAUER)

Ten minutes to go approx. 300 m W of stop no.1.2; follow a path crossing the River Weitenbach on a bridge. The foot path follows the margin of the wood to the W, then within the wood to the hill. The outcrops are on the W flank of the hill at the end of the approx. horizontal path.
These outcrops expose granulitic tectonic slices at the E-dipping boundary between the Monotonous and the Variegated Units. Biotite-rich paragneiss of the Monotonous Unit at the base is overlain by m-scale felsic granulite- and amphibole slices, and mica-poor augengneiss. All these rocks are real mylonites as revealed by strong secondary grainsize reduction , and a finely laminated foliation. The foliation dips moderately to the E , whereas a lineation is poorly developed. After PETRAKAKIS (1986), the granulitic rocks were equilibrated at approx. 700-770°C and 6-9 kb.. The deformation is coaxial, as revealed by the high symmetry in quartz textures, the hazy stretching lineation , and the often random orientation of amphiboles on foliation planes. Eclogite-like rocks occur in rare lense-shaped boudins. They are composed of garnet, clinopyroxene, and amphibole, mainly.

STOP No. 1.2 - Dobra gneiss
Abandoned quarry on the road between the villages Weiten and Pöggstall, 1800 m E of the church in Pöggstall
ÖK 50: 36 Ottenschlag (F.NEUBAUER)

The quarry exposes an orthogneiss, the Dobra Gneiss, which characteristically encloses thin amphibolite layers, as it often occurs in leptynite-amphibolite associations. The Dobra Gneiss forms the structural and possibly the primary base of the Variegated Unit.

The foliation of the gneiss dips to the E and is caused by the separation of quartzofeldspathic layers from biotite layers. The stretching lineation dips gently to the S. As revealed by quartz fabrics, the deformation is largely coaxial. Some asymmetric boudins suggest late top to the ESE shear.
A hornblende concentrate yielded a 40/39-Ar isotope correlation age of 329.1 +/- 6.7 Ma (see the contribution by DALLMEYER et al.).

Stop No.1.3 - NE-directed HT deformation within the Variegated Unit
Approx. 150 m N of the northern margin of the village of Eitental, Weitenbach valley.
ÖK 50: 36 Ottenschlag (F.NEUBAUER)

The outcrop in the turn of a by-road exposes a patchy plagioclase amphibolite with a strong HT deformation fabric. The amphibolite contains a clinopyroxene-bearing amphibole matrix which encloses finegrained stretched aggregates of plagioclase. Amphibole shows a strong preferred shape orientation which forms, together with the plagioclase aggregates, a NE-SW-trending stretching lineation. Strain measurements of such aggregates yielded data in the constrictional field of the FLINN plot. All minerals are well recrystallized during peak metamorphic conditions in the Variegated Unit (700-750°C, 7-9 kb.). We interpret the structures of this outcrop as the result of NE-directed internal deformation of slices during thrusting under HT metamorphic conditions. The deformation fabrics are dominantly coaxial whereas nearby outcrops indicate top to the NNE shear.

Stop No. 1.4 - Retrogressive durctile normal faults at the top of teh Variegated Unit; HT deformation of the Rehberg Amphibolite
Grießbrücke (Grieß bridge) in the Weitenbach valley, roadcuts to the N and S
ÖK 50: 36 Ottenschlag (F.NEUBAUER)

The roadcut N of the bridge exposes garnet-bearing micaschists mainly of the Variegated Unit. The micaschist is overlain by the Rehberg Amphibolite which is exposed S of the bridge. The dominant foliation of the micaschist dips to the SE. A younger s2 foliation is more steeply inclined and encloses angles between 15-25° with s1. A SSE-dipping stretching lineation is defined by stretched garnets, pressure-shadows around garnet, and striated quartz and mica. All primary minerals show retrogressive metamorphic overprint like sericitization and sometimes chloritization of garnet. Therefore, we interpret these structures as a low-angle normal fault which has overprinted earlier thrust fabrics and has transported the hangingwall rocks to the S.

HÖGGELSBERGER (1989) reported temperatures of 390 to 530°C for this retrograde event in the Variegated Unit.
The Rehberg Amphibolite S of the bridge is a clinopyroxene-bearing plagioclase amphibolite bearing high temperature deformation fabrics. The rock is relatively fine-grained, and rather massive. Thin, transposed trondhjemite veins are common. The 40/39-Ar isotope correlation age of a hornblende concentrate from this outcrop is 330.2 +/- 3.8 Ma (see the contribution by DALLMEYER et al.) We interpret this age as cooling through 500°C, and therefore as an approximation of the age of retrogressive ductile normal faulting at the top of the Variegated Unit.

Stop No. 1.5 - Deformation and metamorphism within the Gföhl Gneiss
Weitenegg, N margin of the village, Weitenbach valley, roadcut N of the intersection with the railroad
ÖK 50: 54 Melk (F.NEUBAUER)

The eastern roadcut immediately N of the intersection with the railroad exposes the Gföhl Gneiss and enclosed granitic veins. The Gföhl Gneiss is developed here as a leucocratic orthogneiss with SE-dipping foliation and a S to SSE plunging lineation. A banding produced by changes in the quartz/feldspar ratio as well as by changes in grain-size is typical of the Gföhl Gneiss. A sheet of serpentinized ultramafic rock is concordantly included within the gneiss. PETRAKAKIS & RICHTER (pers.comm.) estimated the peak metamorphic conditions of a more mafic Gföhl Gneiss (from the railway exposure immediately E of the outcrop) at 8.5-9 kb and 750 C.
Three deformation events can be separated: (1) The formation of a migmatic foliation and banding. This event is also responsible for the elongation of biotite xenoliths. (2) The formation of S-facing isoclinal folds and an accompanying axial plane foliation.
(3) Top to the N shearing after the intrusion of dm-scale granitic veins. These subhorizontal veins may be related to the intrusion of the S-Bohemian pluton by ballooning and subsequent shearing. SCHARBERT et al. (1990) reported a Rb-Sr isochron of 330 Ma of comparable granitic veins in nearby outcrops. This indicates that the formation of the flat-lying shearzones postdates the intrusion.

STOP No 1.6 - Sinistral, SE-dipping thrust, as a part of a positive flower structure related with the Diendorf Fault
Roadcut 2.5 km N of Aggstein, E bank of the Danube River
ÖK 50: 37 Mautern

Paragneisses and amphibolites of the "Variegated Sequence" in the Drosendorf Unit, with cataclastic deformation on wrench faults. The faults dip at 30° to the ESE.

Asymmetric folds (B: 160/30) and s-c fabrics indicate top to the SW tectonic transport. The faults can be interpreted as belonging to a sinistral flower structure developed at the Diendorf fault, 2 km to the SE.

STOP No. 1.7 - Boudinage, shear veins, polyphase deformation
Roadcut at the E bank of the river, N of stop no. 1.1
ÖK 50: 37 Mautern

Following the road by the River Donau towards Arnsdorf, one observes amphibolites, calc-silicates and migmatic paragneisses of the Drosendorf Unit. Between Aggstein and Oberarnsdorf, the roadcuts expose amphibolites and calc-silicates with prominent boudinage (symmetric as well as asymmetric), and shear veins with leucocratic mobilisates. The boudinaged rocks and some early folds have partly been refolded (B: 350/07). A younger generation of asymmetric boudinage with N-dipping normal faults indicates late N-ward transports.

STOP No. 1.8 - Thrust plane at the base of the Gföhl Gneiss with ultramafic nodules.
Outcrop at the memorial "Berg Calvari", at km 22 on the E bank of the River Danube, 500 m W of St.Lorenz
ÖK 50: 37 Mautern

The outcrop is situated at the base of the Gföhl Gneiss which overlies amphibolites. Along the thrust contact, there are cm- to dm-sized, elliptical bodies of former ultrabasites. These show a retrograde zonation (rim to center): biotite, actinolite, antophyllite. Oblique orientation and sc fabrics indicate tectonic transport top to the E. The metasomatic alteration of the ultrabasites is post-tectonic. Near the thrust, the Gföhl Gneiss shows late- to post-tectonic migmatization. The fabric of the Gföhl Gneiss is largely equilibrated; only quartz shows incipient subgrain-formation. Taken altogether, the outcrop documents amphibolite-facies thrusting of the Gföhl Gneiss over amphibolites, with formation of partial melt and metasomatic alteration of ultramafic lenses by the advection of fluids at a late stage of thrusting.

STOP No. 1.9 - E-directed tectonic transports
Roadcut at St.Lorenz, Danube Valley
ÖK 50: 37 Mautern

The roadcut in the village shows recumbent folds (B: 196/05, 20/00) and eastward thrusting in migmatic amphibolites. There are two generations of feldspar mobilisates.

The older ones, concordant with the metamorphic foliation, are folded, the younger, arteritic ones post-date the folding.

STOP No. 1.10 - Weißstein-granulites (HT mylonites) and serpentinites
Quarry at Meidlingen im Tal (Dunkelsteiner Wald granulite massif)
ÖK 50: 38 Krems

The outcrop is situated at the eastern end of the Dunkelsteiner Wald granulite massif. Weißstein granulites with a subvertical foliation contain several big lenses of serpentinite, a typical associate of all granulites in the Bohemian Massif. SCHARBERT & FUCHS (1981) have described occasional intercalations of garnet- pyroxene-bearing ultrabasites.

Weißstein granulites are leucocratic granulites of granitic composition, which are derived from Al-rich lower crustal granites (charnockites). They were deformed under dry amphibolite facies conditions along intracrustal thrust zones. As opposed to previous interpretations, the well-developed planar fabric and banding is not a relic of sedimentary or volcanosedimentary fabrics, but produced by HT mylonitization. The mineral fabric is characterized by recrystallization of feldspar, and complex reactions caused by the disproportioning of ternary feldspars. Fine-grained biotite was developed from coarse-grained biotites by micro-boudinage, and equilibrated under lower amphibolite facies conditions (450-550^{o}C, 4-5 kb). SCHARBERT & FUCHS (1981) have described local occurrences of opx+ cpx-bearing granulites.

Biotite-rich layers of the Weißstein granulites may contain lensoid, zoned inclusions of metabasite, whose biotite-rich margins grade laterally into the foliation.
The **core** consists of garnet (alm 54-59, gr 17-22, Py 21-23, Sp 1.5-1.8), plagioclase (an 41-46), quartz, ilmenite, rutile, +/- sillimanite, +/- kyanite, +/- spinel, +/- clinopyroxene, +/- orthopyroxene, +/- brown hornblende (TiO_2 2.2-2.3 weight-%), +/- biotite, +/- titanite.
The **rim** is rich in biotite (TiO_2 3.7-5.8 weight-%) and depleted in garnet, pyroxene and brown hornblende. It is surrounded by an **outer margin** of granulite rich in plagioclase (an 40-60), with only few remains of K-feldspar. The biotite derives from a reaction of K-feldspar in the granulite with Fe/Mg-minerals of the inclusions. We interpret these inclusions as relics of restite transformed by boudinage, and suggest that the bt-ga- plag-rich layers in the Weißstein granulites resulted from HT mylonitization of such restites. This would be in accord with the derivation of the granulites from lower crustal partial melts.

STOP No. 1.11 - HT-mylonitic alternation amphibolite/gneiss in the Rehberg Amphibolite
Roadcut at Rehberg in the valley of River Krems
ÖK 50: 38 Krems

The "Rehberg Amphibolite" is an alternation of platy amphibolites, garnet amphibolites, ortho- and para-gneisses, calc-silicates and marbles. It can be interpreted as a HT mylonite zone at the base of a tectonic slice of the Gföhl Unit; after FUCHS (1976), it can be correlated with the "Buschandelwand Amphibolite".
At the southern margin of the outcrop, there occur bt-plag- gneisses with cataclastic deformation and a subhorizontal foliation with s-c fabrics indicating N-directed transport. Asymmetric boudinage and duplex structures in the amphibolites relate to the same phase of deformation (D3, NS-directed compression). The s3 foliation overprints an older, NS-trending mineral lineation, which is related with NS-trending D1 or D2 folds.

STOP No. 1.12 - migmatic paragneiss-amphibolite sequence with polyphase folding
Rosenburg, roadcut at the northern bank of the River Kamp at the road to castle Rosenburg
ÖK 50: 21 Horn

The outcrop is situated structurally below the granulite of St.Leonhard, in the amphibolite-rich "Begleitserie" of Raabs. An older, NNE-trending generation of folds (D1/D2) is overprinted by E-trending D3 folds. In the area between the St.Leonhard granulite and the Messen Anticline, this D3 deformation is very prominent and controls the pattern of outcrop on the geological map (Figs. 1,2). The D3 structures originated in an indentation process, during which ESE/WNW-oriented crustal shortening changed towards NS-directed compression. The Diendorf Fault was formed during the same period (Fig.1,2). D3 wanes toward the Thaya Batolith (Cadomian basement) to the E. Strain compatibility is achieved by dextral wrench faulting at the western margin of the Thaya Massif.

STOP No. 1.13 - Strike slip features at the plate boundary between Moravian acidic orthogneisses (Bittesch gneis) and Moldanubian paragneisses.
4km E Gars/Kamp, westernmost quarry in the Teichwiesenbachtal, N of the road.
ÖK 50, sheet 21 (Horn): 6916-0484-2001. (H.FRITZ, H.P.STEYRER)

The quarry is situated 100m E of the main thrust in the uppermost part of the overridden Bittesch gneis nappe. The dip orientation of the penetrative foliation is 270/25, the lineation dips 210/5.

Non-coaxial rock flow with dextral strike slip along the major shear zone is indicated by s-c fabrics, extension veins, shear bands, asymmetric strain shadows around feldspar porphyroclasts and quartz textures.

Strain geometry due to the matrix strain (centre-to-centre- technique) is plane strain. The prevailing deformation mechanism of quartz is power law creep, feldspars show beginning recrystallisation.

Both foliation and stretching lineation have later been refolded by W-verging open flexural slip folds.

We interprete these structures as motion over a lateral ramp during the general N-directed transport of the overriding Moldanubian plate.

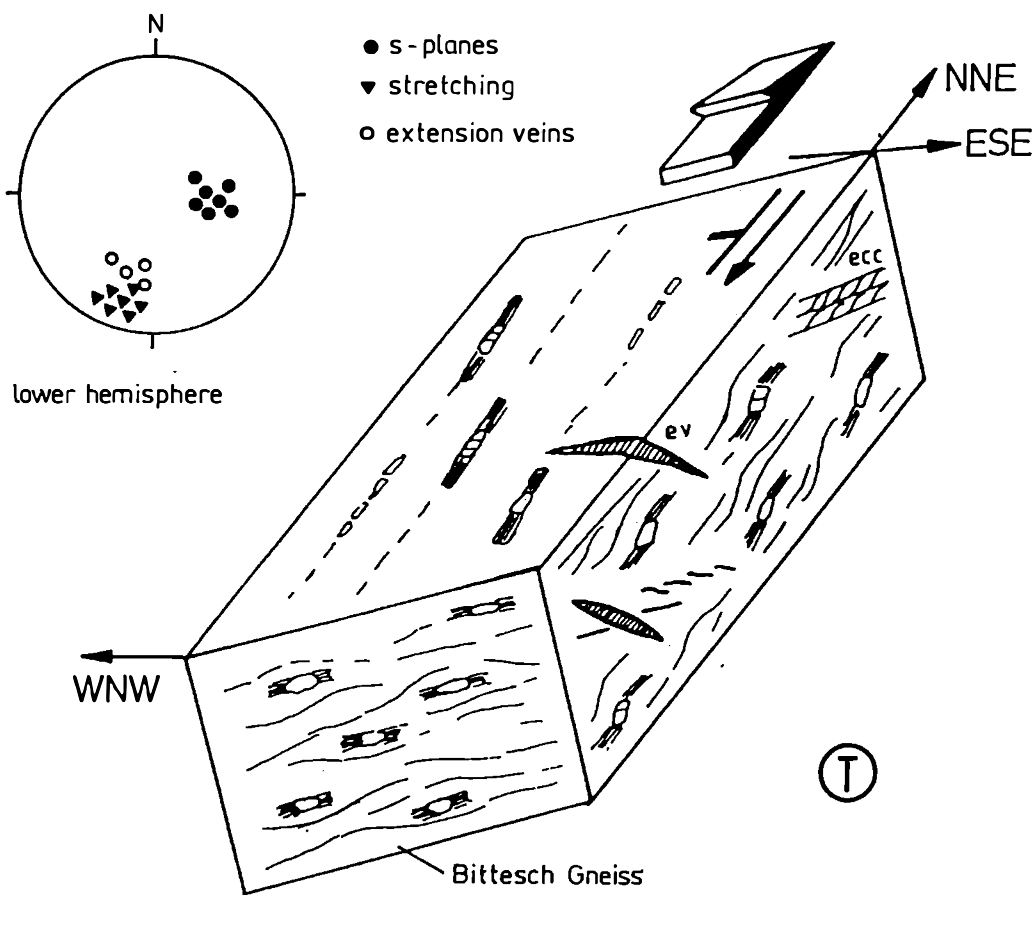

Fig.3: Sketch of the penetrative structures in the Teichwiesenbachtal.

Stop No. 1.14 - Thrusting with top to the N displacement along the major plate boundary between Moravian acidic orthogneisses (Bittesch gneis) in the footwall and Moldanubian paragneisses in the hangingwall. Dip slip geometry.
3km NE Horn: Old quarry in the Stockergraben immediately N of the railway crossing with road B 45;
ÖK 50: 21 (Horn): 6916-0249-1316 (H.FRITZ, H.P.STEYRER)

The quarry is situated within the shear zone which seperates the Moravian and the Moldanubian units. The outcrop contains the acidic Bittesch gneiss of Cadomian intrusive age and basic dikes.

The penetrative foliation (190/25) affected also the basic dikes which rotated into the shear plane. The stretching lineation is 185/25.

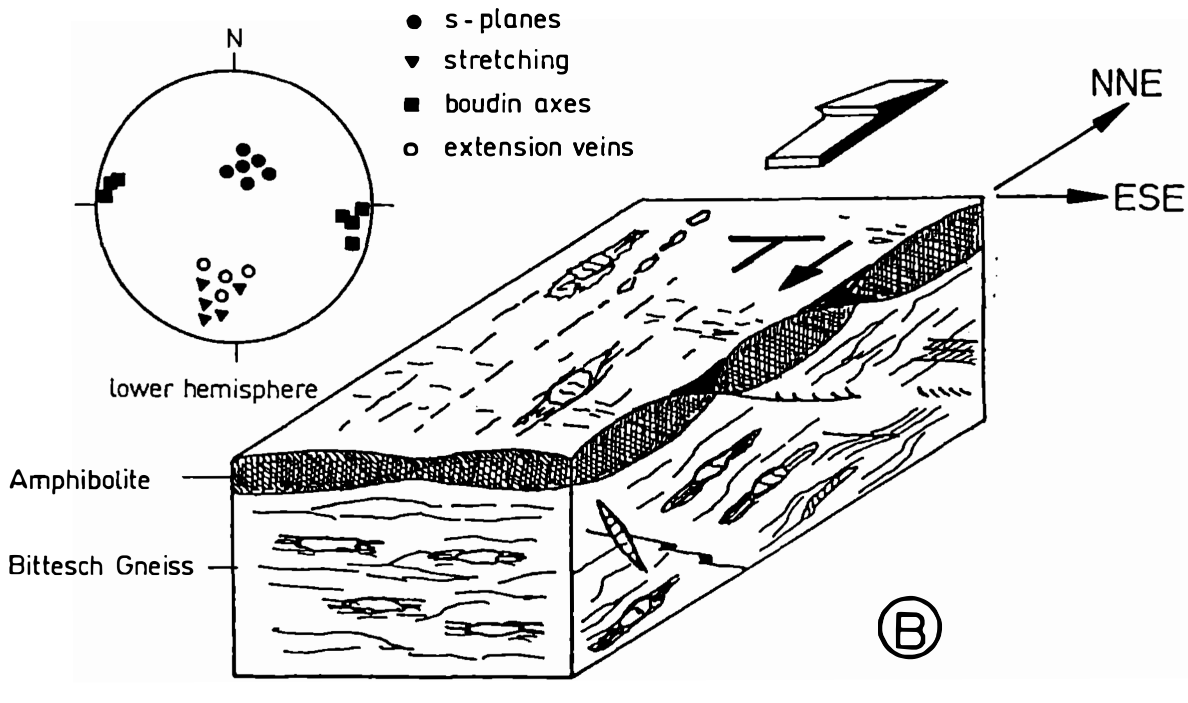

Fig.4: Sketch of the structures in the quarry NE of HORN.

Motion along the Moravian-Moldanubian plate boundary is visible by the following macroscopic shear sense indicators which indicate top- to-the-N displacement:
* Asymmetric boudins and boudin-necks in the more competent dikes;
* orientation of extension fissures and the arrangement of en-echelon veins;
* strain shadows around feldspar porphyroclasts.

Additionally microscopic structures and textures display top-to-the- N thrusting, i.e., quartz c-axes and a-axes pattern in quartz mylonites (U-stage and X-ray goniometer); s-c fabrics and ecc in finegrained amphibolite-mylonites.

Strain analyses indicate, that the dominant non-coaxial rock flow was accompanied by flattening strain, evaluated by the centre-to- centre technique. Flattening is also documented in quartz textures with cross-girdle c-axes distribution.

The deformation started under amphibolite facies conditions as indicated by the recrystallisation of feldspar and proceeded at decreasing temperatures.

We interprete the structures in this outcrop as the effect of the N- directed motion of the overriding Moldanubian unit onto the Moravian nappes, maybe on a ramp.

(with the exception of stops nos. 1.1-1.5, and 1.13-1.14: last- minute translation by W.FRANKE)

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THE MORAVIAN ZONE IN AUSTRIA

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REGIONAL GEOLOGY

INTRODUCTION (V.H.)

The general tectonic structure at the eastern border of the Bohemian Massif is known now for almost one century when F.E.SUESS 1897 discovered the overthrusting of the Moldanubian area in the west over the Moravian area in the east. This basic concept has been elaborated later on (SUESS 1903) and a larger monographic description and interpretation for the Moravian zone by F.E.SUESS appeared in 1912. In this paper the Moravian zone was divided into two windows emerging as cupolas below the higher Moldanubian nappe. The northern window has been called "Schwarzawa-Kuppel" totally situated within the border of the CSFR. The southern window was named "Thaya-Kuppel", outcropping to a large extent in Lower Austria.

Later on several workers have been employed investigating the rock types, metamorphism and structure of the Moravicum in Austria. Besides F.E.SUESS (1897, 1903, 1908, 1912) mainly WALDMANN (1922, 1930, 1951) and PRECLIK (1924, 1927, 1937) are to be mentioned. Recently FRASL (1968, 1970, 1983), HÖCK (1975, 1983), HÖCK and VETTERS (1975) HÖCK et al. (1990) and BERNROIDER (1986, 1989) were carring out a mapping project in the Moravian zone, which will be finished within the next few years. The results of these intense field and laboratory studies will be presented shortly in the following chapters (initials of the respective authors in brackets).

GEOLOGICAL SETTING OF THE MORAVIAN ZONE (G.F., F.F.)

The Moravian Zone (MZ) can be regarded as the former western marginal zone of the so-called Bruno-Vistulian block (BV), which is an old, at the latest Cadomian consolidated continental micro-plate in the eastern part of the Bohemian Massif (DUDEK 1980). Today the MZ is somewhat dissected from the BV block by post-Variscan sinistral strike slip movements along the Diendorf-Boskovice wrench-fault system, which amounted at least 25 km (SCHERMANN 1965).

The about triangle-shaped BV block consists in its SW part predominantly of Cadomian granitoids, while the northeastern two thirds are made up mainly of presumably pre-granitic, partly migmatized paragneisses (DUDEK 1980). Most of this BV-basement is covered by thick platform sediments (Cambrian ?; Old Red to Neogene) and can only be studied in boreholes (DUDEK 1980). Drillings and geophysical data also show, that on its SE side the BV-block has been regionally overthrusted in the Tertiary by outer nappes of the Carpathian Orogen.

In pre-Variscan times, the BV-block might have been a prong of the Fennosarmatian megacontinent (SUK et al,. 1984, FINGER et al. 1989) or, alternatively, an Africa-derived microplate as e.g. the Tepla-Barrandian unit.

During the Variscan orogeny, the western marginal parts of the BV-block were overthusted by a hot nappe pile of the Moldanubian mobile belt. Thrusting occurred in connection with a strong dextral transpression between the Moldanubicum and the western flank of the BV-block. This transpression is responsible for the very characteristic NS-trending elongation of the westernmost Moravian lithological units (e.g. the Bittesch gneiss - see fig.2) and demonstrates the strong indentation that occurred within the Variscan continent-collision zone of Central Europe. The transpressional movements were followed by local updoming (Thaya Dome, Schwarzawa Window fig.1a). All these Variscan events together are responsible for the distinct metamorphic and structural style of the MZ of the Thaya Dome: a high degree of deformation and medium grade metamorphism on top, and a continous decreasing of those effects towards the east and towards the northern and southern ends of the Thaya dome.

Fig.1: (a) Assumed extent of the mostly covered pre-Variscan Bruno-Vistulian Block, mainly according to DUDEK (1980). The Thaya Dome and the Schwarzawa Window are representative for the "Moravian Zone" (sensu SUESS 1904), which is a western marginal zone of the Bruno-Vistulian Block, mobilized during the Variscan orogenesis. B = Boskovice Furrow, D = Diendorf Fault, O = Odra Lineament, P = Pribyslav Zone, V = Vitis Fault.

(b) Location of the Bruno-Vistulian Block with the Thaya Dome at its western margin (Moravicum). The figure also features some of the main tectonic units of Central Europe according to POZARYSKI et al. (1981). 1 = Bruno-Vistulian Block according to DUDEK (1980), a Cadomian massif. - 2 = areas subjected to folding, metamorphism and volcanic activity by the Early Baikalian (Cadomian) and Dalslandian evolutions or to foldings and weak metamorphism during the Swietokrzyska (Late Baikalian) phase. - 3 = northern and eastern front of the Variscan orogenic belt. - 4 = deep crustal fractures.

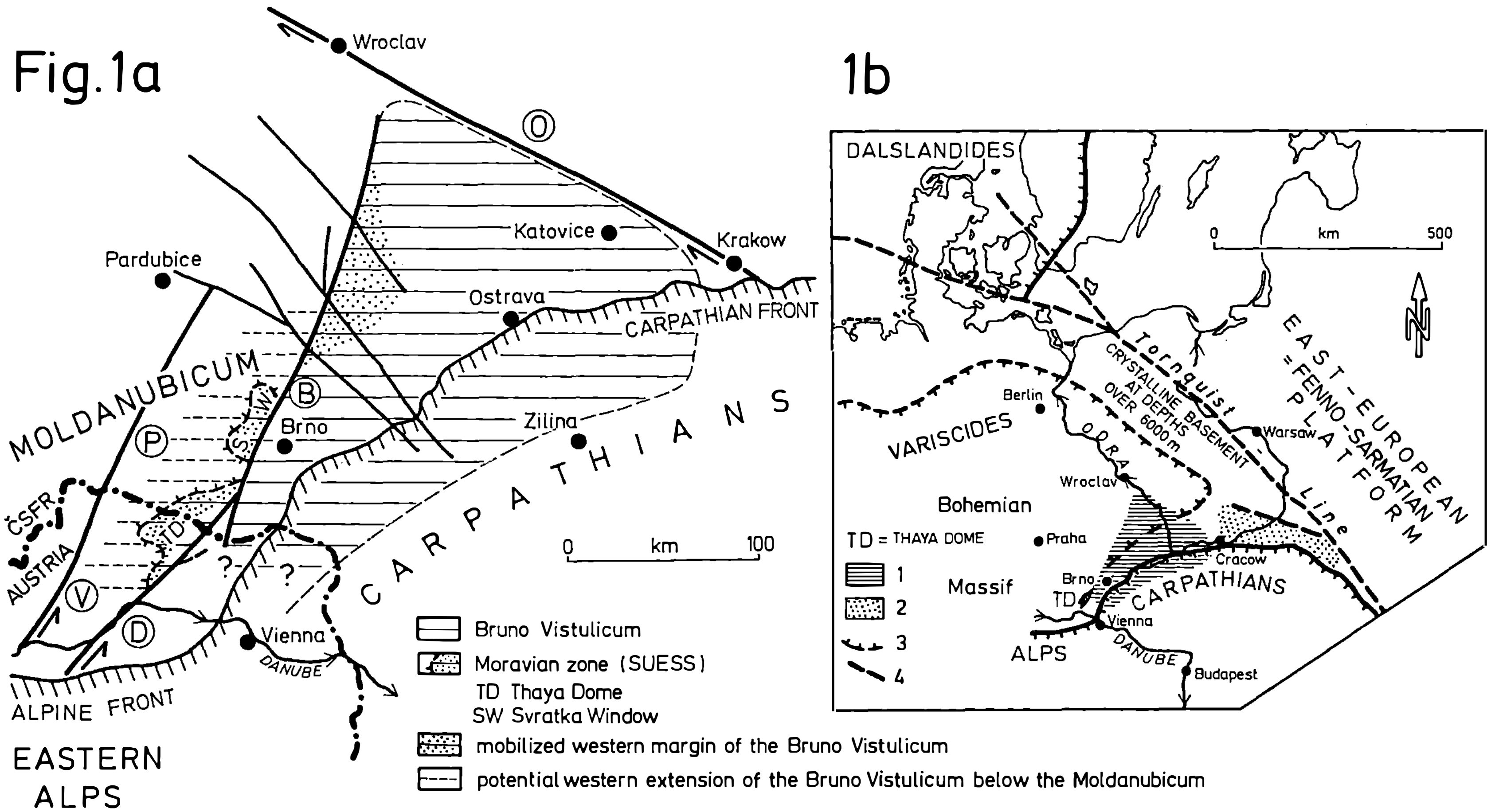
Fig.1a
Wroclav
O
Katovice
Krakow
Pardubice
Ostrava
CARPATHIAN FRONT
MOLDANUBICUM
B
Brno
P
S.W.
Zilina
CARPATHIANS
ČSFR
AUSTRIA
TD
V
D
Vienna
DANUBE
ALPINE FRONT
EASTERN ALPS
0 km 100
Bruno Vistulicum
Moravian zone (SUESS)
TD Thaya Dome
SW Svratka Window
mobilized western margin of the Bruno Vistulicum
potential western extension of the Bruno Vistulicum below the Moldanubicum
1b
DALSLANDIDES
0 km 500
Tornquist Line
CRYSTALLINE BASEMENT AT DEPTHS OVER 6000 m
EAST - EUROPEAN "FENNO-SARMATIAN" PLATFORM
Berlin
Warsaw
VARISCIDES
ODRA
Wroclav
Bohemian Massif
TD = THAYA DOME
Praha
Brno
TD
Cracow
CARPATHIANS
Vienna
ALPS
DANUBE
Budapest
1
2
3
4

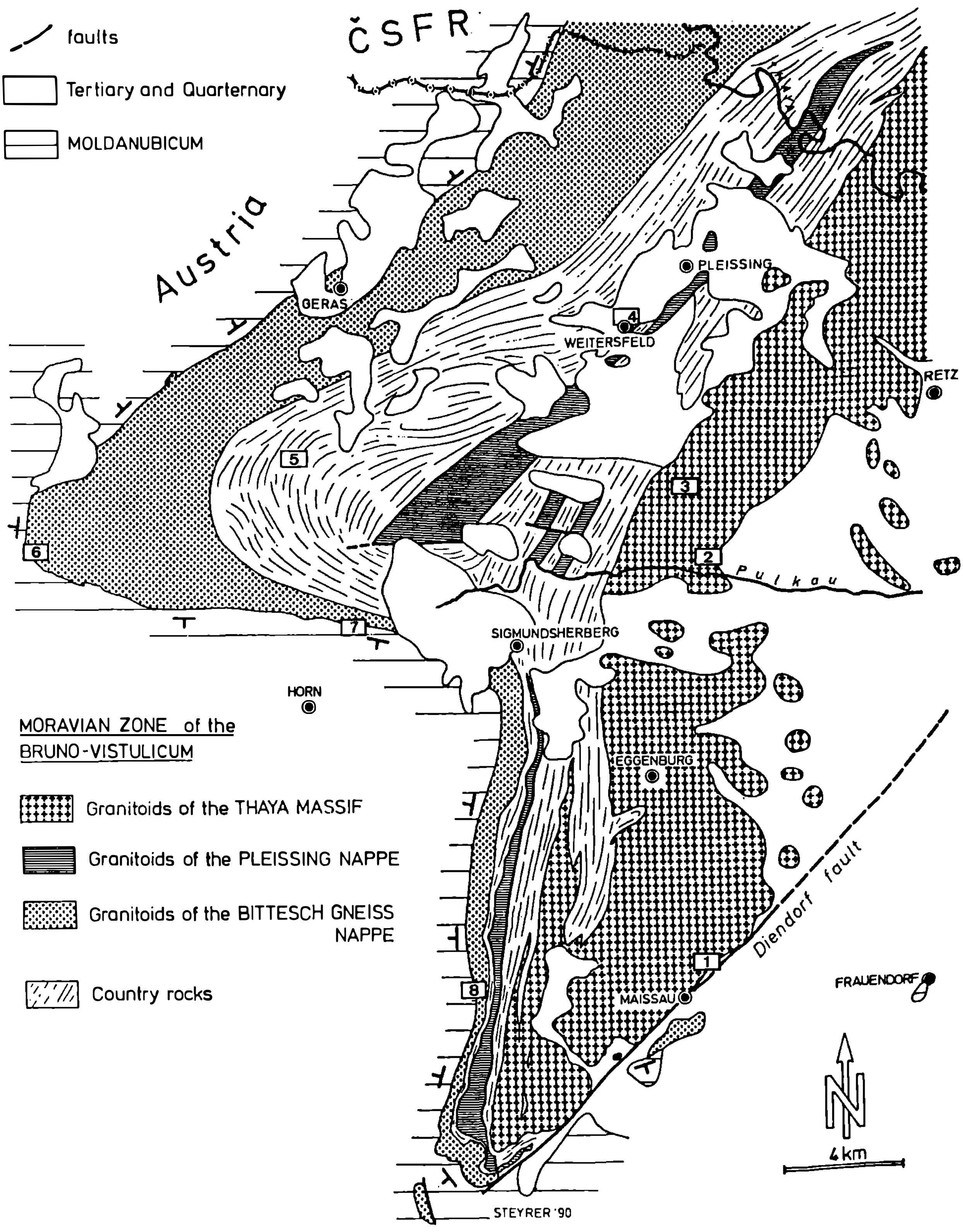

Fig. 2: Geological sketch map according to FINGER et al. (1989) showing mainly the granitoids in the Austrian part of the Thaya Dome. The described stops are: 1 = Limberg, 2 = Pulkau, 3 = Passendorf, 4 = Weitersfeld, 5 = Pernegg, 6 = Messern. (Nos. 7 and 8 are described as nos. 1.14 resp. 1.13 in the contribution by WEBER & DUYSTER).

THE MAJOR LITHOLOGICAL UNITS OF THE MZ IN THE THAYA-DOME (FROM E TO W)

The Thaya-batholith (G.F., F.F.)

This deepest structural unit of the MZ is a weakly metamorphosed and deformed granitoid complex (SUESS, WALDMANN, PRECLIK) of Cadomian age (Rb-Sr isochrone ca. 550 m.y.; SCHARBERT,S. and BATIK 1980).
Limits and contacts: Only in the west the batholith is overlain by its primary roof, in the east it is cut by the Diendorf fault and now partly covered by Tertiary sediments. The former continuation of the Thaya-batholith is exposed east of the Diendorf/Boskovice wrench-fault system in the area of Brno (Brno Massif, see STELCL and WEISS 1986). In the south the Thaya-batholith is overlain by a thin transgressive, but lowgrade metamorphic quartzite cover of probably early Paleozoic age (Olbersdorf formation - FRASL 1974), whereas nearly the whole eastern side of the Thaya-batholith is covered by Neogene sediments. Only locally in Czechoslovakia, E of Znojmo transgressive Devonian clastics crop out (DUDEK 1960), and NE of Znojmo even overlaying Devonian dolomites with evaporites are preserved (borehole Zerotice, BATIK et al. 1981).

LITHOLOGY: Based on a field mapping and chemical work, four major lithologies could be distinguished within the Thaya batholith (FINGER et al. 1989).

1. The "Hauptgranit" type (main granite type) comprises medium-grained light granites and granodiorites with low biotite contents (4-5 %). Such rocks and their gneissic variants occupy more than two thirds of the surface of the batholith (cf. also PRECLIK 1937). Recent geochemical work suggests that the "Hauptgranit" type can be further subdivided in a predominantly granitic low-Sr series, which occurs mainly south of the Pulkau valley and a northern similar felsic, but often granodioritic high-Sr series (see description of stops 1 and 2).

2. The "Gumping-type" defines more or less gneissic biotite-rich granodiorites and quartz-monzodiorites with blocky K-feldspar phenocrysts and amphibole altered to biotite. The Gumping-type is older than the adjoining "Hauptgranit" type and restricted to the SW part of the batholith, where it formes a NNE-SSW striking body, which is approximately 12 km long and 2 km wide.

3. The "Passendorf" type comprises essentially fine- to medium-grained tonalites and meta-tonalites or their gneisses (biotite: 10 - 40 %; amphibole contents are usually low).

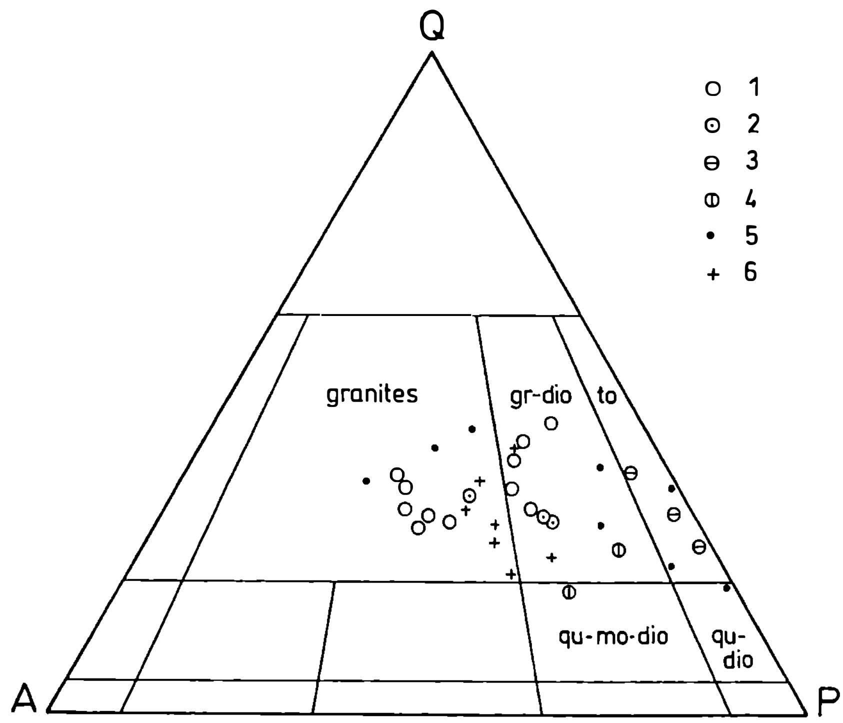

Fig. 3: STRECKEISEN-diagram with plots of Moravian granitoids according to FINGER et al. (1989). 1 = "Hauptgranite" type; 2 = "Gauderndorf" type; 3 = "Passendorf" type; 4 = "Gumping" type (all in the Thaya batholith); 5 = granitoids of the Pleissing Nappe; 6 = granitoids of the Bittesch Gneiss Nappe.

Such rocks occur mainly at the NW side of the batholith. They are older than the "Hauptgranit" type of this area.

4. The "Gauderndorf" type is a fine grained granitic to granodioritic rock with somewhat higher biotite contents than the "Hauptgranit" type. The main body is ca. 14 km long with the type loc. ca. 3 km north of Eggenburg. Dikes of this type locally cross-cut the "Hauptgranit" type.

In regard to their petrographical and geochemical characteristics the granitoids of the Thaya-batholith broadly fit the classic definition of I-type granitoids (CHAPPELL & WHITE 1974, PITCHER 1983) FINGER et al. 1989 argue that the whole batholith could have formed in connection with subduction of oceanic lithosphere beneath the former southwestern margin of the Fennosarmatian continent.

Dikes: Aplites and pegmatites are only of local importance (e.g. Manhartsberg) and show approximately the same Variscan deformation and metamorphic state as their plutonic country rocks. There are also some granodiorite- and aporphyritic dikes few post-Variscan lamprophyres (stops 1,2). Ore concentrations are absent, but white banded amethysts have been digged between Maissau and Eggenburg.

Therasburg formation (V.H.)

Towards the west the gneisses of the Thaya-batholith are overlain by a metamorphosed pelitic to psammitic sequence called "quartzite-micaschist series" by HÖCK and VETTERS 1975. Intrusiv contacts are nicely preserved in some places especially in the northern part. Recently HÖCK et al. 1990 introduced the term "Therasburg formation" for the whole sequence. It consists of micaschists partly with a considerable amount of albite and/or oligoclase leading to fine grained gneisses. Shales and greywackes may be considered as educt of this rocks. The more feldspar-rich varieties form fine grained strongly foliated gneisses termed Therasburg gneisses by HÖCK 1983. In some parts the relative abundance of blue-green amphibole indicates a possible origin of these rocks from either andesites or diorites. Quartzites are intercalated with the gneisses and micaschists as layer from a few centimeter up to several meters. The high ore content of these rocks is well known for some time. Recently LIBOWITZKY (1989) interpretes micaschists and gneisses with a large amount of magnetite and ilmenite as Precambrian black sands. The assumed stratigraphic position is inferred from some preserved intrusive contacts and migmatites of the Cadomian Thaya-batholith as Precadomian. Therefore the whole sequence must be older than 550 to 600 M.a.

Stengelgneis of Weitersfeld (V.H.)

A distinct gneiss body termed "Weitersfelder Stengelgneis" separates the Therasburg formation from the tectonically higher sequence of the Pernegg formation (HÖCK et al. 1990). The Therasburg gneisses and the Weitersfeld gneisses have been considered as coherent gneiss body (Weitersfelder Stengelgneis) by WALDMANN (1922, 1930, 1951), but have to be separated based on field and petrographic evidence. The Weitersfeld gneiss sensu strictu is restricted to the northern part of the Moravian zone (compare the geological map of F.E.SUESS 1912) showing a granitic composition with a partly well developed Augen-structure.

Pernegg formation (V.H.)

The Pernegg formation ("marble-micaschist series" according to HÖCK and VETTERS 1975) comprises micaschists, calcschists and pure marbles, which grade into each other. The marbles prevail in the upper part of the sequences as coherent layers, partly as

elongated lenses. Compared with the Therasburg formation the micaschists are rich in mica (biotite and muscovite) and have less quartz and feldspar. The protolith is a shale-limestone sequence. Transitions from micaschists to gneisses are missing.
The uppermost part of the marbles is formed by a very distinct horizon of calcsilicate schists, the socalled "Fugnitzer Kalksilikatschiefer". It is an only several meters thick layer consisting of quartz, plagioclase, K-feldspar, amphibole, clinopyroxene, calcite, epidote etc., sometimes also found as small layers and lenses in the above lying Bittesch gneiss.

The age of the Pernegg formation is not known. Its stratigraphic classification depends mainly on the solution of two still debated questions: (1) the age of the Bittesch gneiss and (2) the problem of a preserved intrusion contact between the Bittesch gneiss and the Fugnitz calcsilicate schists. The latter is advocated by FRASL (1983) and BERNROIDER (1989) on the basis of the aplitic veins in the Fugnitz schists. The discussion on the age of the Bittesch gneiss centers around three conflicting age determinations:

790 M.a.	(S.SCHARBERT 1977)	Rb/Sr whole rock
560 M.a.	(MORAUF and JÄGER 1982)	Rb/Sr whole rock
480 M.a.	(v.BREEMEN et al. 1982)	Rb/Sr whole rock

Bittesch Gneiss (V.H.)

It is the uppermost unit of the Moravian zone and has been considered its most typical member. It is a highly deformed orthogneiss with a well developed Augen-structure. Dark amphibolite layers up to 50 cm thick are restricted to the uppermost 20 to 30 meters. These layers, parallel to the regional s-planes are repeated many times in a relatively small section and were taken as indication of a volcanic origin at least for the upper part of the Bittesch gneiss, with interlayering of rhyolitic and basic lava flows (FRASL 1970). Recently FRASL (1989) is more inclined to interpret these amphibolites as highly deformed dikes in a former granitic body.

The Bittesch gneiss has a striking similarity with the Dobra gneiss from the Moldanubian zone (FRASL 1970) not only in composition and structure, amphibolite layers (dikes) are also found in the Dobra gneiss. This feature has caused several authors to suggest a close tectonic connection between both and ascribe the Bittesch gneiss to the Moldanubicum (MATURA 1976, MATTE et al. 1985).

METAMORPHISM (V.H.)

FRASL (1968, 1970) in developing the ideas and results of F.E.SUESS, WALDMANN and PRECLIK presented a three stage evolution concept for the metamorphism:
1) the old Moravian phase connected with the intrusion of the Thaya batholith
2) the middle Moravian phase forming the regional metamorphism and
3) the young Moravian phase as a retrograde stage.

The first stage restricted to the surrounding of the batholith is probably of Cadomian age according to the close relation to the Thaya pluton and its radiometric age dating. The area with the best relicts is found in the northernmost part of the Austrian Moravicum east of the ruin Kaja close to the Thaya valley, were migmatitic structures are still preserved. Mineralogical relicts are possible pseudomorphs after cordierite and almandine-rich cores of garnet with a distinct two phase growth pattern (HÖCK et al. 1990).Besides Fe the old garnets are relatively rich in pyrop (up to 10 mol%) but poor in grossular and spessartine. All elements show a sharp increase and decrease respectively between core and rim, the latter having formed during the middle Moravian phase.
The question whether the Fugnitz silicateschists are originally formed by a contact metamorphism caused by the intrusion of the Bittesch gneiss magma, as advocated by FRASL (1983) and BERNROIDER (1989) remains an open problem, also the question of the according age of the metamorphism.

The regional metamorphism of the middle Moravian phase has taken place during the Hercynian orogeny. Recent $^{40}Ar/^{39}Ar$ plateau ages on amphiboles from amphibolites in the Bittesch gneiss give 328,7 $\pm$ 3,3, muscovites from the Bittesch gneiss 328,7 $\pm$ 0,3 and the Stengelgneis of Weitersfeld yields 328,5 $\pm$ 0,7 Ma (DALLMEYER et al. this volume). Already F.E.SUESS 1912 and later on PRECLIK 1937 and FRASL 1970 pointed out, that the metamorphic grade is highest in the western part and decreases toward the south, the east and the north. Therefore the metamorphism is inverse in respect to the structure with the structurally highest units exhibiting the high grade part of the metamorphic zonation. In 1975 V. HÖCK introduced four mineral zones with different assemblages in the metapelitic rocks striking a somewhat oblique (SW-NE) to the regional structure (S-N to SW-NE) especially in the southern part of the Moravicum. The first and southernmost zone (1) shows only assemblages with phengite and chlorite. With increasing temperature biotite appears in addition (zone 2) and later on garnet (zone 3). In the western(northern)most zone (4), staurolite + garnet + biotite is the typical assemblage, while chlorite disappears as a stable phase. An albite/oligoclase transition zone has been added by FRASL 1983 to the zone concept in addition based mainly on the albite-oligoclase distribution in the gneisses.

Within the Pernegg formation a two phase growth of garnet (zone 4) is widespread with an inclusion free or inclusion poor core and a distinct rim, rich in inclusions at its inner part. The outermost zone is again poor on inclusions (quartz and some ilmenite). In some cases radial growth patterns in the core are developed (star-garnet) with some also radial orientated quartz inclusions. This phenomena has been described for the first time by FRASL 1981. The garnets are rotated synkinematically in respect to the first schistosity. Chemically the garnets show a typical bell shaped zoning pattern with Mn and Ca rich cores and Fe/Mg rich rims. Garnet-biotite geothermometry according to the model of HODGES and SPEAR 1982 gives temperatures between 580°-600°C for the garnet-staurolite-garnet-biotite zone (4) and around 580°C for the garnet-biotite zone. The transition from the garnet + biotite + chlorite zone and the garnet + biotite + staurolite zone is due to the discontinous reaction:

$$\text{Mu} + \text{Chl} + \text{Gr} = \text{Staur} + \text{Bio} + H_2O$$

According to THOMPSON 1976 the equilibrium temperature of this reaction should be at 580°C at 5 kb PH_2O, which fits very well the temperatures deduced from garnet-biotite geothermometry.
In the absence of Al_2SiO_5 phases pressure estimates are difficult to assess, but have been taken here arbitrarely as 5 to 7 kbars. This is in accordance with first results from phengite-barometry (MASSONNE and SCHREYER 1987), carried out on K-feldspar and biotite bearing gneisses of the Moravian zone. Si contents in phengites of 3.25 to 3.30 pfu result in 5 to 7 kbars pressure at temperatures between 580° and 600°C.

The retrograde, young Moravian phase is not very well known. Both, the Therasburg and the Pernegg formation are affected by this late event. The older (middle Moravian) minerals such as staurolite, garnet and biotite are completely changed to chlorite and muscovite. But often only retrograde chlorite is found as reaction rims around staurolith and garnet. Sometimes biotite has quantitatively disappeared, leaving only some garnets and staurolith relicts in a chlorite + muscovite + quartz matrix. The inverse metamorphism of the middle Moravian phase can be explained by the thrusting of the hot crustal block of the Moldanubian zone over the Moravian zone, rapidly decreasing towards the south, the east and also towards the north.

DESCRIPTION OF STOPS

STOP No. 1: Cadomian Core Granites of the Thaya Batholith (G.FRASL, F.FINGER)
Limberg, 4 km NE of Maissau: large quarry in the Gänsgraben;
ÖK 50, sheet 20, Hollabrunn; 7913 R: 014.600/ H: 384.500

The quarry exposes a massive, medium-grained pink granite, the so-called Maissau variant of the "Hauptgranit" type, which is here only very weakly metamorphic and deformed. The rock consists on average of ca. 30% perthitic K-feldspar, 35% acidic plagioclase (somewhat filled with clinozoisite); 25% quartz; 4-5% green (!) biotite. There is some secondary stilpnomelane, chlorite and muscovite. A chemical analysis (XRF) of the Maissau granite is: SiO_2 72,63; TiO_2 0,09; Al_2O_3 14,91; FeO_{tot} 1,41; MnO 0,03; MgO 0,31; CaO 2,10; Na_2O 3,86; K_2O 3,57; P_2O 0,06; H_2O 0,82 (wt.%); - Zr 228; Sr 76; Rb 189; Ba 740 ppm. The rock is an example of the low Sr - high Zr subtype of the "Hauptgranit".

In the quarry the metagranite is cross-cut by a steep dark lamprophyre dike (amphibole-minette). The biotites of the dike are euhedral and brown in thin section. They are obviously of magmatic origin, in contrast to the green metamorphic biotites of the enclosing metagranites. We therefore conclude that the lamprophyre postdates the Variscan orogenic event.
Further reading: FINGER, F. et al. 1989, REISS 1952.

STOP No. 2: Granitoids of the Thaya Batholith with various dikes; Variscan deformation and metamorphism close to amphibolite fazies (G.FRASL, F.FINGER)
Pulkau; Roadcut 2000 m NW of the church
ÖK 50: sheet 22 Hollabrunn; 7913 R: 013.850/ H: 398.200

The roadcut exposes a weakly deformed medium grained light variety of the "Hauptgranit"-type with granodioritic composition (45% plagioclase, 14% K-feldspar, 36% quartz, 4% biotite). A chemical analyses of the granodiorite yielded the following values: SiO_2 72,41; TiO_2 0,24; Al_2O_3 14,13; FeO_{tot} 1,90; MnO 0,04; MgO 0,63; CaO 2,57; Na_2O 4,03; K_20 3,07; P_2O_5 0,08; H_2O 0,93 (wt%); Zr 146; Sr 308; Rb 116; Ba 603 ppm. The rock belongs to the high Sr - low Zr granodioritic subtype of the "Hauptgranit".

Significant for the metamorphic overprint are the stability of olive-brown metamorphic biotite (unmixing of sagenite, leukoxen and titanite) and the prevailing recrystallization of plagioclase to oligoclase (An 22-27; partly "filled by microlitic clinozoisites and white mica, but also with some garnet).

Here the granodiorite has been crosscut first by aplites and pegmatites, and then by more or less lightcolored granodiorite-porphyritic dikes. All these dikes experienced the same metamorphism as the granodioritic host rock, but the flat NNE-SSW stretching lineation is clearly visible only in the very fine-grained porphyritic dikes.

Even though we are here 4 km inside of the Thaya batholith, this lineation still belongs to exactly the same deformation regime as that of the higher nappes of the Moravian Zone, e.g. the Bittesch gneisses with their often extreme deformation (comp. stop 6 S of Messern). Consequently the Variscan dextral transpressional shearing of the western margin of the Bruno-Vistulian Block, which formed particularly the longstretched body of the Bittesch gneisses, reaches in this W-E cross profile through the Moravian Zone from Messern down to Pulkau. This indicates a width of this shearing zone of at least 25 km.

From this stop towards the east (which means in the direction of the elongation of the said profile), some hilly outcrops of the same granodiorite are distributed between Neogene sediments of the Molasse Zone as far as to the Wartberg N of Zellerndorf. On this additional range of 15 km, the Variscan deformation and metamorphism is fading away, and there inner parts of the Pre-Variscan Bruno-Vistulian Block are well preserved on the whole.

Further reading: FRASL 1983, FRASL 1977

STOP No. 3: Migmatic roof of the Thaya-batholith (V.HÖCK)

Road Pulkau - Weitersfeld; Roadcut 550 m E Passendorf, immediately S of the bridge across the Ebrechts river;

ÖK 50, sheet 21, Horn; 6916 R: 712.950/ H: 399.950

Biotite-micaschists of the Therasburg formation are intruded by tonalites, granodiorites and pegmatites of the Thaya-batholith. The magmatic contact is overprinted by the Hercynian regional metamorphism.

The micaschists form elongated bodies within the tonalite. The following minerals can be observed: muscovite, biotite, some amphibole, quartz, plagioclase (oligoclase), clinozoisite, garnet is rare. Turmalin, apatite , zircon, sphene are accessory minerals. A characteristic feature is the enrichment of ilmenite and magnetite, the latter causing a distinct positive magnetic anomaly. Chlorite is mainly a product of the later retrograde metamorphic event and is formed mainly at the expense of biotite and garnet.

The tonalites consist of plagioclase (oligoclase), quartz, biotit and some amphibole, K-feldspar is generally absent, clinozoisite is common. They show some petrographic similarities with the more tonalitic types of the Therasburg gneisses.

From the intrusion relation between the micaschists and the Cadomian Thaya-batholith (SCHARBERT and BATIK 1890) an Upper Proterozoic age of the Therasburg formation seems possible.

Further reading: LIBOWITZKY 1989

STOP No. 4: Stengelgneis of Weitersfeld (Pleissing Nappe) (V.HÖCK)
Weitersfeld; small quarry below the Church of Weitersfeld;
ÖK 50, sheet 8, Geras; 6912 R: 711.500/ H: 405.300

The quarry is the type locality of the so-called Stengelgneis of Weitersfeld, a highly deformed Augen-gneiss of granitic composition. It is restricted to the northern part of the Moravian zone and must be separated on a petrographic basis from the Therasburg gneisses with granodioritic to tonalitic composition.

The K-feldspar Augen are the most characteristic feature and are often still euhedral, twinned and contain oriented inclusions of plagioclase. They are embedded in a matrix of biotite, muscovite, plagioclase (An 25) K-feldspar and quartz. Clinozoisite and amphibole are missing. Geochemically they are relatively high in SiO_2 and K_2O, Rb , but somewhat depleted in CaO and MgO, with I-type features. Based on their trace element distribution they are interpreted by BERNROIDER 1989 as volcanic arc granites.

The foliation in the quarry is very flat, almost horizontal. The lineation following the general trend dip slightly towards NE.
In general the texture, structure, mineralogy and geochemistry of the Stengelgneis of Weitersfeld resembles the Bittesch gneiss (Hattey quarry, Stop No..) rather than the granodiorite- and tonalite-gneisses of the Thaya-batholith or the Therasburg gneisses.
$^{40}Ar/^{39}AR$ determination on muscovite concentrates resulted in Variscan cooling ages at 328,5 $\pm$ 0,7 Ma (DALLMEYER, this volume)
Further reading: BERNROIDER 1989, FINGER et al. 1989.

STOP No. 5: Micaschists of the Pernegg formation (V.HÖCK)
Roadcut 1250 m S of Pernegg at the road Mödring-Pernegg;
ÖK 50, sheet 21, Horn; 6916 R: 698.950/ H: 399.050

In the roadcuts typical garnet-staurolite-biotite micaschists are exposed with staurolites up to 1 cm in size. Quartz, oligoclase, muscovite and ilmenite are additional components. The garnets are of special interest: They exhibit a two phase growth with an inclusion poor core and a distinct inclusion rich rim (especially its inner part). Radial growth patterns are commonly developed within the core. The garnets are rotated synkinematically in respect to the first schistosity. According to FRASL 1981 there is no common rotation pattern.
Chemically the garnets show typical bellshaped zoning patterns with Mn and Ca rich cores and Mg ans Fe rich rims. The element distribution does not reflect in general the

radial shaped optical pattern except for some weak indication of the Ca distribution. Temperatures inferred from coexisting garnet (rim composition) biotite pairs are in the range of 580°-600°C. In the absence of any alumosilicate phase the pressure estimates taken from phengite barometry measured on some Bittesch gneiss samples, are in the range of 5-7 kbars.
The age of the protolith is not known, the age of the regional metamorphism is most probably Hercynian (compare stop 4 Weitersfeld).
Further reading: HÖCK et al. 1990

STOP No. 6: Uppermost part of the Bittesch gneiss with amphibolites (V.HÖCK)
Quarry Hattey; Road Poigen - Messern, in the Taffa valley1 km S of Messern;
ÖK 50, sheet 20, Gföhl; 6915 R: 691.400/ H: 397.300

The quarry is situated in the uppermost part of the Bittesch gneiss with the interlayers of amphibolites. While other stops in the Bittesch gneiss (Stop No. Stockergraben, Stop No. Teichwiesenbachtal) are devoted to the structural features, the petrography will be studied here. The Bittesch gneisses are highly deformed Augen-gneisses with mainly granitic to sometimes granodioritic composition, with plagioclase (oligoclase) generally prevailing over K-feldspar. The latter forms the Augen with sometimes nicely preserved oriented inclusions of plagioclase. Quartz and feldspars build up over 90 % of the mineral content, the rest consists of biotite, muscovite, some late chlorite, garnet, apatite and ironoxides.

The amphibolite layers vary between few centimeters to half a meter in thickness. They consist of green amphiboles (magnesio-hornblende) An-rich plagioclase (40 - 50 % An), which is inversely zoned, some biotite, sphene, ilmenite, apatite and some late chlorite. The amphibolites are restricted to the uppermost 30 meters and were often believed to be remnants of a volcanic event, thus advocating an effusive nature of the Bittesch gneiss at least for its upper part. More recently FRASL 1989 interprets the amphibolites as dikes in a granitic body.

$^{40}Ar/^{39}Ar$ plateau ages from amphiboles and white micas yield 328,7 $\pm$ 3,3 Ma and 328,7 $\pm$ 0,8 Ma respectively, indicating a relative rapid cooling of the Hercynian metamorphism (DALLMEYER et al., this volume).

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THE MOLDANUBIAN REGION IN BAVARIA

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REGIONAL GEOLOGY

As laid out in the introductory chapter by FRANKE, the Moldanubian Region is subdivided into two main units, the Moldanubian sensu stricto, and the Tepla-Barrandian (or Bohemian). The main part of the Tepla-Barrandian lies on Czecho-Slovakian territory, and will not be visited. The excursion will only show the southwestern extremity of the Tepla-Barrandian (Zone of Tepl-Taus = Tepla-Domazlice: ZTT) and a western outlier, the Zone of Erbendorf-Vohenstrauß (= ZEV) (see Fig.1).

MOLDANUBIAN s.str.

The Moldanubian s.str. in Bavaria is part of the low-pressure unit as defined in the chapter on metamorphism by BLÜMEL. It is a vast paragneiss region with migmatite zones, which is intruded by numerous , mainly (per)aluminous granitoids. With the exception of the Oberviechtach area (see stop no. 11), the Moldanubian of Bavaria does not contain HP- and MP-units comparable with those of the Gföhl Terrane in the

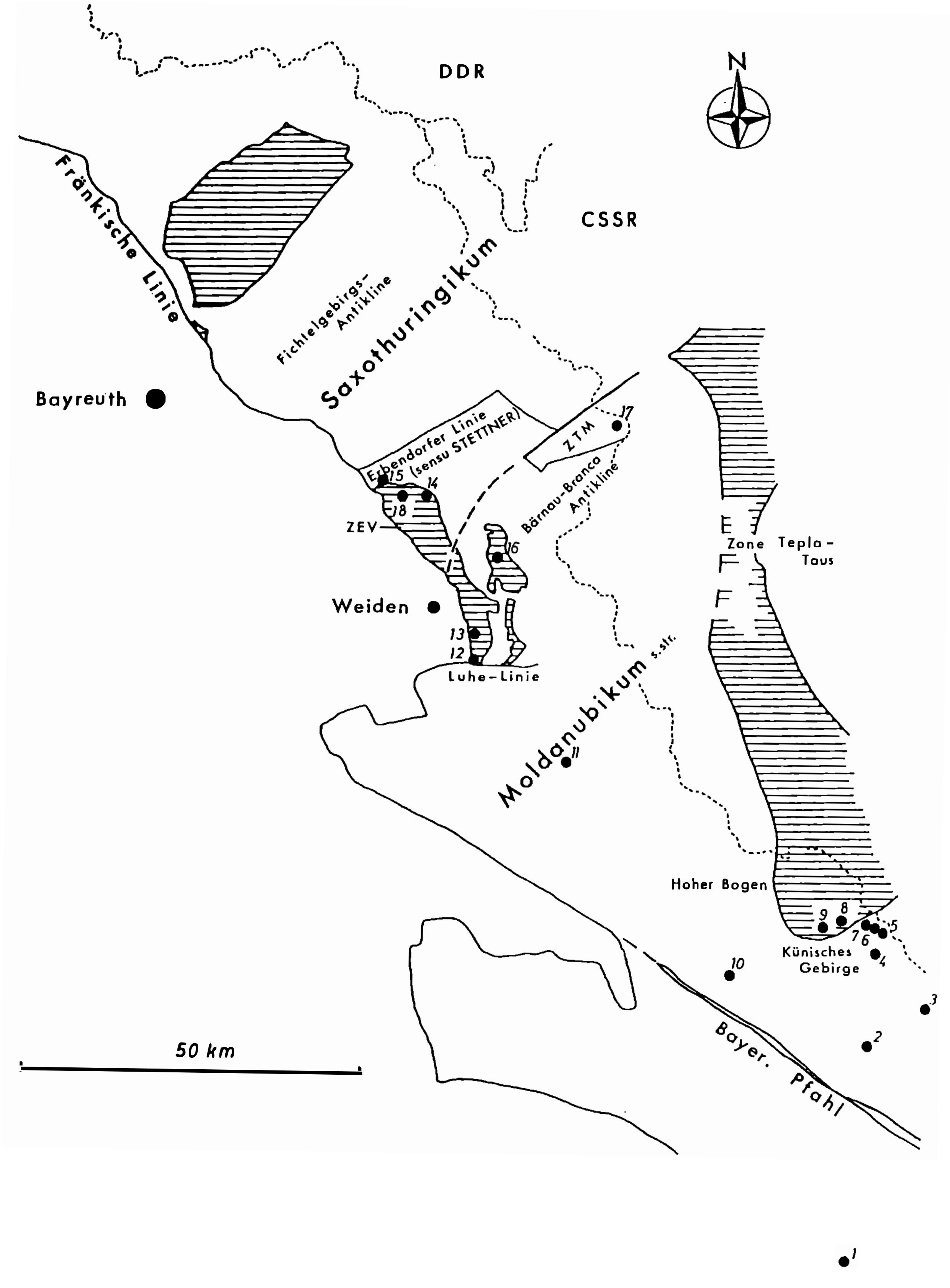

Fig.1: Location of stops in the Bavarian part of the Bohemian Massif.
Horizontal ruling: MP/HP - units.

Austrian Waldviertel, and was therefore correlated, by TOLLMANN (1982) with the Drosendorf Terrane (see the contributions by FRANKE and by WEBER & DUYSTER).

The Moldanubian in Bavaria occurs in two areas (see Fig. 1 in BLÜMEL's contribution on metamorphism): a northern domain, which is a gently N-dipping antiform (domain 2 in the resp. Fig.), and a southern domain, which is an ENE-dipping monocline (= "Bavaricum" of G.FUCHS; domain 3 in the resp. Fig.). Moldanubian metasediments typically comprise cordierite-sillimanite gneiss anatexite, garnetiferous cordierite-sillimanite anatexite, biotite-plagioclase gneiss anatexite (+/- garnet), and calcsilicate gneiss (diopside + hornblende + andesine + quartz + titanite +/- garnet). Siliceous marble (Passau area, Arber Mts.) may contain wollastonite, chondrodite, vesuvianite, garnet, and (only near Passau) forsterite. Amphibolites often contain diopside and with a few exceptions lack relics indicative of an earlier HP stage (see the contribution on metamoprhism). Metamorphic transition into low-grade areas (Saxothuringian E of Tirschenreuth, Küni'sches Gebirge; see Fig.2 and Fig.1 in BLÜMEL's contribution on metamorphism) is demonstrated by the sequence sillimanite micaschist, andalusite micaschist (with cordierite, garnet & staurolite), and phyllitic biotite-garnet micaschists. The occurrence of kyanite micaschists in the E part of the Küni'sches Gebirge (VEJNAR 1963 and unpubl.) needs further clarification (lower temperature gradient or tectonic intercalation?). Maximum metamorphic grades are attained by orthopyroxene + garnet + cordierite migmatites (in the northwestern Bayerischer Wald). LP metamorphism is clearly regional (i.e., syntectonic), since porphyroblastic andalusite is rotated, sillimanite (in fold hinges) recrystallized, and cordiertite often polygonized (outside shear zones!) The age of the regional anatexis has been dated by concordant U/Pb data on monazite at two localities of the northern Bayerischer Wald (321 +/-7 Ma and 325 +/- 10 Ma, GRAUERT et al. 1990).
The age of the protoliths is largely unknown. Local findings of microfloras revealed sediments dating into some level at about the Precambrian/Cambrian boundary, and into the Upper Silurian; the presence and extent of a pre-Variscan (Cadomian) basement is, so far, hypothetical (see the contribution by FRANKE).

In the south-central Bayerische Wald and in parts of the southern Oberpfälzer Wald, LP amphibolite facies rocks have been reworked into "Perlgneis" (Fig.2 and Fig.1 in BLÜMEL's contribution on metamorphism) which is an augen-mylonite with porphyroclasts of feldspar and cordierite embedded in a weakly foliated matrix of quartz, biotite and eventually Al_2SiO_5 polymorphs (sillimanite ± andalusite). Non-penetrative reworking (strain partitioning) has resulted in an intimate association of Perlgneis with undeformed regional LP rocks, transitions between both types occuring

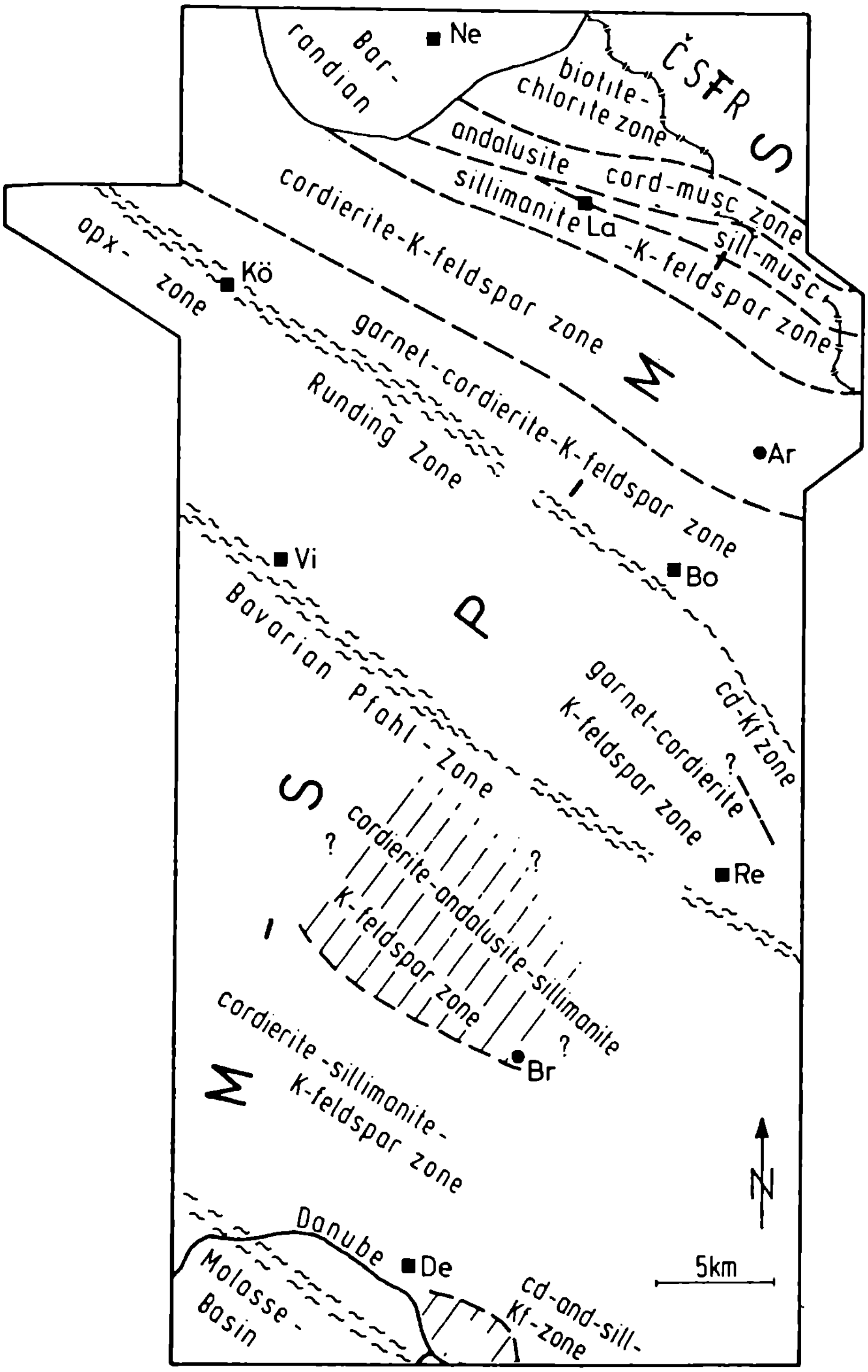

Fig. 2: The Moldanubien of the Bayrischer Wald between the Barrandian (metabasites and paragneisses of the Neukirchen-Kdyne area) and the Tertiary of the Molasse Basin. The map shows the mineral zones of the pre-mylonitic part of the Low Pressure Unit toward N of the Bayrische-Pfahl-Zone (BPZ) and the mylonitized part of the LPU towards S of the BPZ (incl. mylonites of the Rundinger Zone). Abbreviations: Ar Arber (1455 m), Bo Bodenmais, Br Breitenauriegel (1114 m), De Deggendorf, Kö Kötzting, La Lam, Ne Neukirchen b. Hl. Bl., Re Regen, Vi Viechtach.

frequently. Other mylonites with a distinct foliation define narrow NNE-dipping shearzones, in which they are retrograded into greenschist facies (locally also ultramylonites), among them (from N to S): Runding Zone, Bayerische Pfahl Zone (with quartz-lodes) and Donaurandbruch-Aicha-Hals Zone (Fig.1 in BLÜMEL's contribution on metamorphism). Recrystallization generally is confined to biotite, however in the Runding Zone feldspar and cordierite locally are polygonized or recrystallized. Cordierite in un-reworked paragneiss ("Geschonte Serie" G.FISCHER 1939) displays perfect lattice orientation with X^{cord} a^{rock}, Y^{cord} $B^{WSW\text{-}ESE}$ and Z^{cord} c^{rock}. Toward and into shearzones, this pattern is increasingly altered by rotation of cordierite around the X-axis yielding a bc-girdle (subgrains, neoblasts; BEER 1981; FISCHER 1939). The quartz subfabric of paragneiss seems to lack distinct patterns. However mylonites produce a pseudo-two-girdle combined with a small-circle girdle (Runding Zone), Maximum I and II (Perlgneise and Bayerische Pfahl Zone) and an oblique girdle (Pfahl Zone with dextral strike-slip component) (BEER 1981). These shearzones possibly relate to plate-indentation of a south-German block (VOLLBRECHT,WEBER & SCHMOLL 1989).

Mineral-zone mapping in the Bavarian Moldanubicum (BLÜMEL 1972, 1981, 1983; BLÜMEL & SCHREYER 1976, 1977; SCHREYER & BLÜMEL 1977; WAGNER-LOHSE & BLÜMEL 1984, 1986) reveals (Fig. 1 in BLÜMEL's contribution on metamorphism):

(1) seven mineral zones of progressive LP metamorphism, (2) two mineral zones of Perlgneis metamorphism, (3) the wide extension of the cordierite-potash feldspar zone, (4) the antiformal structure of the Moldanubian in the Oberpfalz with the core of cordierite-potash feldspar zone framed by the sillimanite zone and with the ZEV and ZTT on the flanks and (5) the absence of andalusite and lower-grade rocks of the LP sequence at the tectonic contacts with the overlying ZEV and ZTT, which belong to the MP unit (see below).

Partial melting commences in part of the cordierite - potash feldspar zone. In metapelites, the first leucosomes are leuco-"tonalitic" to leucogranitic (in cases containing flecks of cordierite) and associated melanosomes are enriched in biotite, cordierite and sillimanite. In the cordierite-garnet-potash feldspar zone, the leucosomes are granitic and may contain cordierite and even garnet in addition to biotite; the melanosome is restitic (=devoid of quartz) and contains cordierite(eventually rimming garnet), sillimanite, green spinel, magnetite, biotite and (antiperthitic) oligoclase. Rocks of the orthopyroxene zone are hypersthene - garnet - cordierite migmatite (leucosome: opx + gt + kf + pl + qu; melanosome: gt + opx + cord + bio + kf + pl + qu + ilm + pyr + graph) and two-pyroxene-plagioclase-biotite paragneiss.

Isograd reactions of progressive LP metamorphism are:

(1) chlorite + muscovite + quartz = andalusite (+cordierite) + biotite + H_2O
(2) andalusite = sillimanite (fibrolite pseudomorphs after andalusite)
(3) $muscovite_{ss}$ + quartz = sillimanite + $K\text{-}feldspar_{ss}$ + H_2O
(4) sillimanite + biotite + quartz = cordierite + k-feldspar + H_2O (or cordierite + melt)
(5) sillimanite + biotite + quartz = cordierite + garnet (+spinel) + melt
(6) biotite = orthopyroxene + garnet + melt

Reactions (1) and (2) are due mainly to increasing temperature conversely to (3) - (6), which probably occurred during decompression.

Garnet assemblages are observed in nearly all mineral zones; their absence in the sillimanite zones is due to unfavorable rock composition. At low grades garnet is rich in Mn (and Ca) but with rising metamorphic grade it increasingly turns into almandine-pyrope (chemically homogenized with secondary Mn-rich rim). Staurolite (ZnO < 3.2 wt.%) assemblages are found in the biotite-garnet-chlorite zone and the andalusite-cordierite-muscovite zone; relics of staurolite may be traced as far as into the cordierite-potash feldspar zone (rimmed by cordierite, plagioclase or garnet). For localities on isograd (5), PT-conditions of 4kbar and 690^0C are determined using the invariant cordierite thermobarometer of LEE & HOLDAWAY (1977). For cordierite-sillimanite-andalusite Perlgneis, PT-conditions of 2.8kbar and 555^0C at $X^{H\ O}$ 0.5 were obtained (HOLDAWAY 1971; HOLDAWAY & LEE 1977) which precludes partial melting. Indeed discordant anatectic mobilisates are not observed in Perlgneis and migmatization phenomena in the Perlgneis area are always bound to relics of the earlier regional LP stage. Confining pressures of Perlgneis metamorphism overlap with those of the regional LP metamorphism, allowing only a slight decompression (less than o.5 kbar).

ZONE OF ERBENDORF-VOHENSTRAUSS (ZEV) AND ZONE OF TEPLA-DOMAZLICE (ZTT)

The greater part of the Zone of Erbendorf-Vohenstrauß (ZEV) is built up by an association of high-grade paragneiss and amphibolites (incl. metagabbro and serpentinite) with minor marble, orthogneiss and meta-pegmatoids (Fig.3). Paragneisses generally contain the assemblage garnet + kyanite and/or sillimanite + biotite + muscovite + oligoclase + quartz + ilmenite + rutile; occasional sillimanite-biotite coronae rimming garnet point to decompression. Locally staurolite-kyanite-garnet-two mica gneiss occurs (Altenstadt-Denkenreuth; FRANK 1986; RÖHR & v.GEHLEN 1989). The assemblage garnet + sillimanite + biotite + k-feldspar + quartz is found in some KTB drill core specimen and in the Almesbachtal (FRANK 1986). Similarly migmatization is sparse (some KTB drill core specimen and quarry Blockhütte).

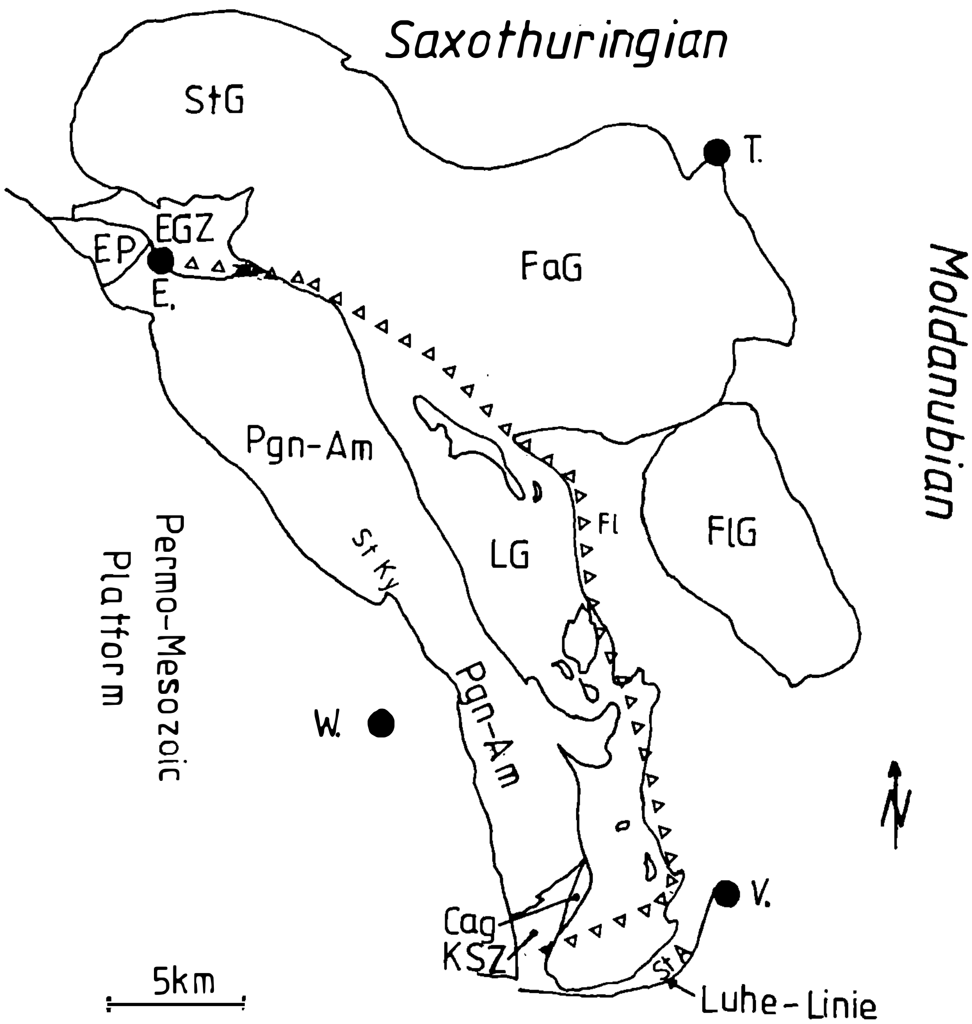

Fig. 3: Rock association of the ZEV (Zone of Erbendorf-Vohenstrauss): Pgn-Am Paragneiss-amphibolite association, Cag Cordierite augen gneiss, EGZ Erbendorf Greenshist Zone, KSZ Kaimling Schuppen Zone, St Ky Staurolite Kyanite gneiss, FaG Falkenberg granite, StG Steinwald granite, FlG Flossenbürg granite, LG Leuchtenberg granite, EP Erbendorfer Paläozoic., Fl mylonite zone near Floss, StA Steinach aureole; E. Erbendorf, T. Tirschenreuth, V. Wohenstrauss, W. Weiden.

Mylonitic garnet-sillimanite-two mica gneiss from the drill-hole Püllersreuth (depth: 300m) shows clearcut bands with segregation quartz parallel to the schistosity. Sr homogenization in this gneiss was found to roughly coincide with the hornblende cooling age of the associated amphibolites, however quartz segregation definitely is younger (365-350 MA; ALBAT, GRAUERT & HANSEN 1990). Ultrabasic intercalations within amphibolite probably derive from spinel harzburgite which was retrograded to a chlorite-talc-hornblende serpentinite with relictic orthopyroxene and chromite/picotite (v.GEHLEN et al. 1989). Amphibolites of the ZEV are grouped into flaser amphibolite (±garnet), striped and schistose amphibolite and metagabbro; geochemically they

resemble recent E-MORB's or intra-plate tholeiites and N-MORB's respectively whereas the metagabbros (reaction-textures see the contribution on metamorphism by BLÜMEL) range in between the two (SCHÜSSLER, RICHTER & OKRUSCH 1989). The same authors find a depletion in P and LREE, which they refer to contact metamorphism and to post-granitic hydrothermal alteration. Like many paragneisses, also amphibolites show indications of high-T mylonitization being porphyroclast/neoblast relations and deformed fleck-like hornblende plagioclase neosomes. This deformation clearly correlates with the tectonic thrusting of the ZEV (see the contrib. by BLÜMEL). Subsolidus conditions of most paragneisses with staurolite are 7-7.5kbar and 530-600^{0}C (RÖHR & v.GEHLEN 1989; further data see the contribution by BLÜMEL), but partial melting (?) in amphibolites may be further indications of a separate PT history as already stated for the older stages of metamorphism (see the
contribution by BLÜMEL).
In the northern ZEV, graphite is enriched in fault-zones within paragneiss which contains minor "primary" graphite. Model calculations have shown (ZIEGENBEIN et al. 1989): (1) Secondary graphite probably derives from CH_4-CO_2-H_2O solutions saturated with C by reaction of H_2O with the gneiss graphite (2) Cooling of the ternary fluids and loss of H_2O will precipitate disorderd graphite.
At the southern margin of the ZEV, the paragneiss-amphibolite association is "cut" by the SW-NE trending "Schuppenzone Kaimling" (Fig.3), which comprises kyanite granulite (rare relics), sillimanite-biotite mylonite, orthogneiss, serpentinite and rare garnet-pyroxenite (VOLL 1960, KLEEMANN manuscript). The granulite facies rocks seem to have evolved like the Gföhl migmatites (Austria) ending up in HT-mylonites. Toward NE of the Kaimling Schuppenzone, cordierite augen-mylonite exists (VOLL 1960; Fig.3), which probably derives from kyanite granulite, cordierite resulting from the reaction: garnet + Al_2SiO_5 + quartz (KLEEMANN, manuscript).
The internal structure of the ZEV is - due to sparse exposures - poorly known. Structural sequences within single outcrops are recognized, however their correlation is hampered by late block-faulting. For the KTB drill-hole section, a tentative block diagram was presented by HACKER, KOHL, RÖHR & SIGMUND (1989) and by MÜLLER, TAPFER, EMMERMANN & WIMMENAUER (1989). Accordingly, in the first 3000 m, a SW-dipping schistosity with flat NW-SE trending fold axe dominates. This stockwerk ends up with a sub-horizontal foliation below which an E- to NE-dipping schistosity prevails. The reconstruction demonstrates the steep inclination of the foliation of the ZEV, which nobody had expected from the surface structure.

The ZEV is intruded by the Leuchtenberg granite (321MA), which produced thin contact-aureoles with cordierite, andalusite or sillimanite and even cordierite + garnet

+ sillimanite + biotite + k-feldspar + quartz (Steinach-Aureole, OKRUSCH 1971; Fig.3). It is interesting to compare the depths of the single stages in the evolution of the basement close to the granite:

	(1)	(2)	(3)	(4)
stage	MP metam.	LP metam.	contact metam.	thrusting of ZEV onto
	(± 380MA)	(± 325MA)	(± 320MA)	LPU(305MA)
depth	≥ 7kbar	3-4kbar	±3.5kbar	±3kbar
	gt+ky(/si) +bi+ms	gt+si+ bi+ms	gt+cord+ si+bi+kf	wol+an+ gro+qu

(KLEEMANN, manuscript)
It is obvious from these data that the main uplift of the MP rocks occurred already in Devonian time, i.e., prior to the LP metamorphic event, during and after which the MP rocks remained in more or less the same crustal level.

At the northern margin of the ZEV, the Erbendorf Greenschist Zone is found (Erbendorf Linie redefined: thrust zone between northern ZEV and LPU: BLÜMEL 1986), which comprises metabasites incl. metagabbro, serpentinite and phyllite obviously retromorphosed (Fig.3). Contact metamorphism at granite plutons produced serpentinite hornfels with enstatite + spinell, whereas phyllite and metabasite with actinolitic hornblende + andesine ± diopside (although in contact with granite) lacks equivalent facies. Blackwall mineralization occurs at granite dikes and spreads into the ultrabasic wallrock. The Erbendorf Greenschist Zone compares well with the "Phyllit-Grünschiefer-Serie" of the MM (KREUZER et al. 1989; MATTHES & KNAUER 1981; MATTHES & OLESCH 1989).

The exact delimitation of the ZEV klippe is a controversial issue. Local occurrences of graphite-quartzites (HEINICKE & VOLLBRECHT 1989) at the eastern margin of the MP rocks possibly represent a separate thrust sheet. The eastern boundary (i.e., the structural base) of the ZEV proper is probably marked by mylonites and serpentinites (KLEEMANN et al. 1989). Little is known about a possible western continuation of the ZEV under the Mesozoic cover beyond the "Fränkische Linie" (Franconian Line, the boundary fault with the Mesozoic foreland). The few drill holes which have attained the basement have not encountered any MP rocks. Toward the SW, the next occurrence of MP metamorphic rocks is at the northern margin of the Black Forest (DEUTSCH 1988).

The Zone of Tepla-Domazlice (ZTT) comprises the metamorphosed western edge of the Tepla-Barrandean, which is made up by metagreywackes, metapelites, meta-lydites, meta-spilites and - near Marianské Lazné (Marienbad) - metabasites with eclogite (Fig.1 in BLÜMEL's contribution on metamorphism). The age of regional metamorphism is deduced from discordantly overlying Paleozoic strata (Plzen-Pribram) as Cadomian (e.g.VEJNAR 1966). In the Domazlice region MP metamorphism increases toward W and SW from biotite via garnet, staurolite and kyanite to sillimanite as the isograd index mineral over a distance of ca. 10 km (VEJNAR 1981). The isograds cut ± rectangularly the Cadomian mega-structure (B_1: SW-NE), but are subparallel with the N-S fold axe (B_2: cleavage folding; VEJNAR 1966). Contact-aureoles of basic and acidic plutons overprint the regional mineral zones (VEJNAR 1986). K/Ar dating on hornblende and micas gave Early Devonian ages similar to those in the ZEV and MM (KREUZER et al. in print). Doubts on the Cadomian age already were raised on account of the petrologic similarity with the ZEV and MM, the structural discordance of B_2 to B_1 and the distance of the Domazlice region to the Cadomian discordance (BLÜMEL 1981).
The southernmost edge the ZTT contains the Neukirchen-Kdyne Pluton (see the contributions on magmatism by OKRUSCh et al. and by BLÜMEL). The relations of this pluton to medium-grained amphibolite (Hoher Bogen) and fine-grained amphibolite (?meta-spilite) are - in absence of relevant exposure - not clarified yet. Recent field-mapping in the Hoher Bogen area shows that small bodies of undeformed gabbro are surrounded by "haloes" of massive undeformed amphibolite which in turn are encompassed by medium-grained amphibolite (SEIBERT, PAULI & FRANKE, pers. comm.). Here gabbro obviously predates high-T deformation. This seems to be at variance to the observation of contact-aureoles further toward N (see above), but may be resolved by referring the high-T deformation to late thrusting of the ZTT. In the Tepla area the isograd pattern (width ca 7km) is somewhat different from that of the Domazlice area, since it shows the sequence biotite > garnet > sillimanite > migmatite and a vast metabasite body with kyanite eclogite and serpentinite (SUK et al. 1973; FEDIUKOVA 1985). The absence of the low-T polymorphs of Al_2SiO_5 obviously is due to unfavorable rock composition. It is the biotite- and the garnet isograd which seem to connect both areas of the ZTT (Fig.1 in BLÜMEL's contribution on metamorphism).

The ZTT is delimitated toward W - i.e., against the NW-Bohemian Moldanubicum (being part of the LPU) - by the Czech Pfahl Zone and toward SE by the younger Central Bohemian Lineament. Beyond the former shearzone, sillimanite gneiss and cordierite migmatite follow similar to the situation near the ZEV. Both these shear zones converge toward SW and thus delimitate the SW corner of the Tepla-Barrandian unit, which is occupied by the mafic rocks of the Neukirchen-Kdyne area. The age relationships between these two shear zones are as yet unknown.

DESCRIPTION OF STOPS

Stop No. 1: Cordierite-pearlgneiss, banded gneiss and calcsilicate gneiss, Moldanubian (P.BLÜMEL)
Abandoned quarry near Vordertausch on the road Deggendorf-Hengersberg, 4 km SE of Deggendorf
TK 25: 7244 Deggendorf, R 45 73 700/ H 54 07 150

Situated near the southern margin of the pearlgneiss area, the outcrop impressively demonstrates the shearing deformation during pearlgneiss metamorphism. Disk-shaped tectonic inclusions of
banded gneiss and calcsilicate gneiss represent remnants of the LPU. The axes of rare sheath folds in such inclusions are subparallel with the mica lineation of the pearlgneiss. The average mode of cordierite pearlgneiss is: quartz 33%, plagioclase (An 20-35) 36%, potash feldspar 4%, biotite 20%, andalusite 0.5%, sillimanite 1%, cordierite 4%, accessories (ilmenite, zircon, apatite, secondary muscovite and chlorite) 1.5%. The assemblage cordierite (X_{Mg} = 0.575) + sillimanite + biotite (X_{Mg} = 0.431) + potash feldspar is the most magnesium-rich so far analyzed in the Bavarian Moldanubicum, thus plotting toward the Mg-rich edge of the "reference sample" from Brennes. On the basis of the cordierite composition in the low-variance assemblage (HOLDAWAY, 1971) the PT-conditions of metamorphism are deduced as: $P = 2.8 \pm 0.4$kbar and $T = 555 \pm 50$ C0 for a fluid composition of XH O = 0.4.

STOP No. 2: Light colored garnetiferous sillimanite blastomylonite of the Runding Zone, Moldanubian (P.BLÜMEL)
Abandoned quarry at road Drachselsried-Bodenmais, 1.2km SE Drachselsried.
TK 25: 6844 Lam, R 45 75 000 / H 54 40 950

The Runding Zone is a steeply NNE-dipping shear zone up to 2km wide, which extends over ca. 60 km between Cham and Grafenau intersecting the garnet - cordierite - potash feldspar zone of the pre-mylonitic LPU. Anatectic metasediments and granitoids incl. stock granites are transformed through "Gleitbrett" tectonics into high-temperature mylonites. Hornfels-like dark, and fine-grained para-blastomylonites contain augen of cordierite, garnet and feldspars within a recrystallized matrix of feldspar, biotite and quartz. The pole figure of quartz gives a/c left girdle parallel with the mylonite-s (typical of "Mylonite I", BEHR et al., 1980), which overprints an older pseudo-two-girdle probably deriving from regional metamorphism (BEER, 1981).

In the quarry at Drachselsried mainly light-colored garnetiferous blastomylonites with narrowly spaced schistosity planes are exposed. This somewhat orthogneiss-like rock forms a small lens within para-blastomylonites outcropping near the entrance of the quarry. The estimated modes of the light-colored garnetiferous blastomylonites are: garnet 1%, sillimanite (prismatic needles) 3%, biotite 3%, orthoclase-perthite 34%, oligoclase 30%, quartz 28% and accessories (green spinel, ilmenite, apatite) 1%. The stable assemblage is garnet + sillimanite + biotite + potash feldspar + quartz. Garnet is analyzed as alm 88.8 pyp 3.8 spe 6.0 gro 1.4 in the rim portions and with alm 88.3 pyp 5.7 spe 4.6 gro 1.4 in the cores. X_{Fe} of biotite is 0.282. Green spinel was found to be a zincian hercynite. In the AFM-projection, the 3-phase field garnet - sillimanite - biotite is plotted tentatively bearing in mind that Mn-free iron-rich bulk compositions possibly produce sillimanite-biotite assemblages at the given metamorphic grade. The AFM-position of the other 3-phase field cordierite - sillimanite - biotite is roughly located by the bulk composition of associated cordierite - biotite blastomylonite at intermediate X_{Fe} of the rock. Thus the metamorphic grade of the locality may roughly be compared with the cordierite - potash-feldspar zone

STOP No. 3: Anatectic cordierite gneiss, garnet gneiss and garnet meta-aplite, Moldanubian (P.BLÜMEL)
Road-cut E Brennes, Brennes-Bayerisch Eisenstein, 2.5km WNW of Bayerisch Eisenstein.
TK 25: 6845 Bayer. Eisenstein, R: 45 85 900 / H: 54 44 050

The biotite - sillimanite gneisses grade toward the southwest into stromatitic cordierite metatexites of the Arber mountain range. Biotite gneisses (partly anatectic), anatectic hornblende gneisses, and lenses of wollastonite marble are subordinate. This gneiss region represents the wallrock of the Moldanubian granites, which apparently are absent in the micaschist region of the Küni'sches Gebirge (Bavarian for "Kings Mts.").

The main rock type, a metatectic biotite - sillimanite - cordierite gneiss with intercalated garnet gneiss and concordant dikes of garnet meta-aplite, is exposed in a road cut between Brennes-Sattel and Bayerisch Eisenstein. A large-scale whole rock isochron from this locality has yielded an age of 488 ± 20 Ma (GRAUERT et al, 1974). LP metamorphism and anatexis is dated by a Rb/Sr small scale isochron and U/Pb monazite with ca. 320 Ma (GRAUERT, GROSSE-WESTERMANN & ALBAT, manuscript). The leucosomes of the main rock type contain quartz, plagioclase (An 20-28), perthitic potash feldspar, and rarely cordierite (in patchy aggregates). The melanosomes are composed of cordierite, fibrolitic sillimanite, biotite, plagioclase (An

20-32), potash feldspar and quartz. The average mode is: quartz 20%, plagioclase 10%, potash feldspar 13%, biotite 18%, sillimanite 11%, cordierite 27% and accessories (ilmenite, pyrite, zircon, apatite, monazite) 1%.
In the AFM-plot, the cordierite gneiss metatexite is represented by the 3-phase field cordierite (X_{Mg} = 0.512) - sillimanite - biotite (X_{Mg} = 0.366). This 3-phase field replaces part of the 2-phase field biotite - sillimanite found for the sillimanite - potash feldspar zone. The divariant reaction thus derived is biotite + sillimanite + quartz + cordierite + potash feldspar + H2O. In the microtexture of the rock this reaction is expressed by spatial seperated inclusions of biotite and sillimanite and, more frequently by sillimanite-free peripheries in cordierite intergrown with biotite. This reaction is the main cordierite-producing reaction in the Moldanubicum. Fe-garnet in the assemblage with sillimanite, biotite, potash feldspar and quartz of associated paragneiss and orthogneiss is manganiferous (< 18.7 mole-% spessartine).

Brennes is situated at the low-temperature margin of the cordierite-potash feldspar zone in the pre-mylonitic LPU. Consequently, with further increase of metamorphism (in this mineral zone), the 3-phase field cordierite - sillimanite - biotite will shift toward Fe-rich AFM-field compositions. This shift is analyzed with a X_{Mg} of 0.085 for cordierite. It terminates by the tie-line "flip" biotite - sillimanite to garnet - cordierite, which gives rise to the new 3-phase field garnet - cordierite - biotite characterizing the garnet - cordierite - potash feldspar zone.

STOP No. 4: Andalusite micaschists of the Künisches Gebirge, Moldanubian (P.BLÜMEL)
Road-cut at the Schmelzerriegel, 1.7km N of Lam
TK 25: 6644/6744 Rittsteig, R: 45 76 450 / H: 54 53 500

A road-cut at the Schmelzerriegel north of Lam exposes steeply NE-dipping andalusite-cordierite-garnet micaschists which are part of the micaschist region in the Küni'sches Gebirge. Discontinous mica laminae alternate with quartz segregetion bands. Minute zig-zag folds accompany the flexural-folded quartzitic bands. Within the micaceous layers, prisms of transparent, pale red andalusite are visible directly adjacent to concentrations of biotite. Particular large crystals of andalusite have been found near or within lenses of bullquartz. The average mode of the andalusite-cordierite-garnet micaschist is: quartz 28%, muscovite 25%, biotite 21%, oligoclase (An 20-26) 9%, andalusite (with inclusions of staurolite) 7%, cordierite 2%, garnet 5%, ilmenite + hematite 1%, accessories (zircon, monazite, apatite, tourmalin) 2%.

The critical mineral assemblages in the outcrop are: cordierite (X_{Mg}=0.648) + andalusite + biotite (X_{Mg}=0.497) + muscovite (3.15 Si-atoms/formula unit) + quartz + ilmenite + hematite + pyrite, and andalusite + biotite + muscovite + quartz + ilmenite + hematite + pyrite. In the AFM-projection they plot in a 3-phase field and two adjacent 2-phase fields, respectively, which together embrace the AFM-field of pelitic rock compositions. The mineral reaction introducing cordierite and andalusite is: Chlorite ((intermediate X_{Fe}) + muscovite + quartz + cordierite + biotite + H_2O. Garnet, which occurs in the assemblage with andalusite, biotite, muscovite, quartz, ilmenite and pyrite, is normally zoned and contains Mn-rich cores and Mn-poor rims. Since even the rims contain considerable amounts of MnO (< 2.8 wt.% MnO or < 10.8 mole%- spessartine) these compositions cannot be plotted on the THOMPSON-projection. It may well be that this "minor" component together with CaO stabilizes garnet in low-pressure metapelites.

Metapelites in the eastern part of the andalusite-cordierite-muscovite zone (E and NE of the locality) may contain the mineral assemblage staurolite + andalusite + biotite + muscovite + quartz + ilmenite. This staurolite is chemically homogeneous and contains 2.00-3.18 wt.% ZnO (=11.0-19.2 mole% Zn-staurolite). Also staurolite inclusions in andalusite of the locality contain minor ZnO.

INTRODUCTION TO STOPS NOS. 5 - 9
(Chr.PAULI, J.SEIBERT, J.BEHRMANN & W.FRANKE)

Stops. nos. 5- 9 are situated in the region of the terrane boundary between the Tepla-Barrandian and the Moldanubian s.str.(Fig.4).
The Moldanubian consists of rather monotonous metapelites with intercalations of quartzite and marble and some greenschist.. Their metamorphic state is described in the respective contribution by BLÜMEL and in the description of the individual stops. Until recently, the Moldanubian metamorphic rocks had been considered as an old, even pre-Cadomian basement. Recent investigations have revealed, that metamorphism occurred in the L.Carboniferous (see the contribution by AHRENDT), and that even the protoliths are much younger than expected: In the area of stops nos. 5-9, E.REITZ has detected microfloras indicative of the Proterozoic/Cambrian boundary (REITZ & HÖLL 1988) and of the latest Silurian (PFLUG & REITZ 1987).

The Moldanubian rocks have undergone a LP metamorphism of varying grade (see the contribution by BLÜMEL), and polyphase synmetamorphic deformation. Two early increments of deformation have only survived in feldspar porphyroclasts. The third and

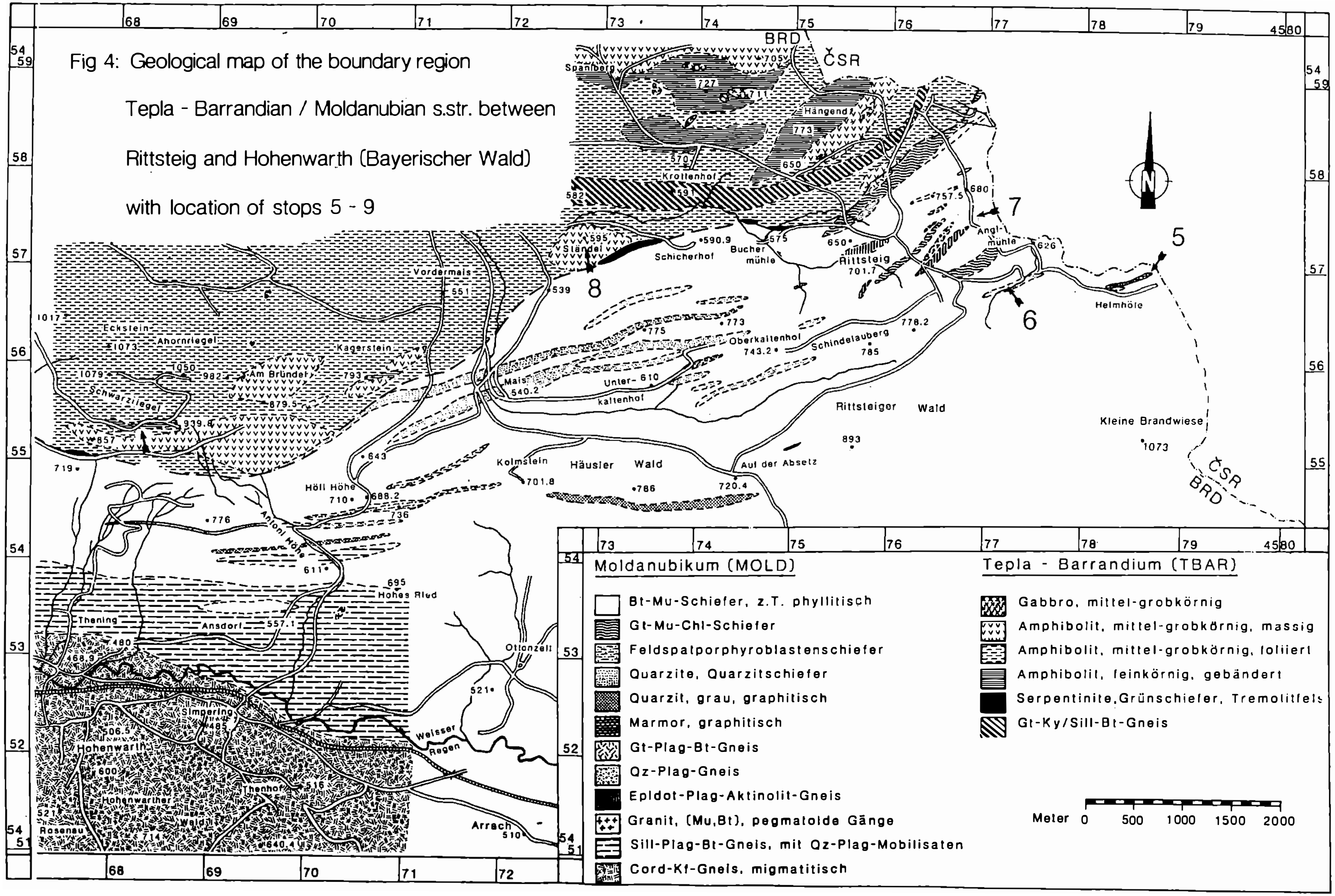

Fig 4: Geological map of the boundary region Tepla - Barrandian / Moldanubian s.str. between Rittsteig and Hohenwarth (Bayerischer Wald) with location of stops 5 - 9

main foliation (SM3) dips steeply to the N. A well-developed stretching lineation shows variable dips between NNW and ENE. Quartz c-axis fabrics, snowball-andalusites and -garnets, as well as shearbands document tectonic transport down dip, i.e., grossly towards N to E. A later deformation (DM4) has produced asymmetric folds (mostly with an "s"-like asymmetry in horizontal section), with steeply plunging fold axes. A last increment of deformation (DM5) has affected both the Moldanubian and the Tepla Barrandian rocks along the boundary, which is now in subvertical position.
The dextral component of shearing observed during DM3 agrees with observations in Czecho-Slovakia further E, where the TB/MOL boundary has been described as a dextral transcurrent shear zone (see MATTE et al. 1990, cum lit.) In the metabasites of the TB, the oldest and the main foliation (ST1) dips steeply to the N. Hornblendes define a well-developed NE-dipping lineation. Shearbands, s-c fabrics and sigma-porphyroclasts consistently indicate tectonic transports top to the SW. A younger, WSW-trending foliation (DT2) is only developed in discrete shear zones. Shear criteria reveal tectonic transports down dip toward the N to E. DT2 probably correlates with DM3 in the Moldanubian rocks.

It is possible that the earlier, SW-directed transports in the TB correlate with the LP-metamorphism, which has also affected the TB (K/Ar data, SCHÜSSLER et al. 1989), and reflect thrusting of the TB over the Moldanubian. SW-directed shearing is not detectable in the Moldanubian rocks, but might have been obliterated, in these quartz-rich rocks, by the later phases of deformation. Alternatively, the SW-directed shear criteria observed in the TB might relate to the earlier MP-metamorphism.
These questions require further structural studies along the western margin of the TB.

Stop No. 5 - Moldanubian marbles
Abandoned quarry near farm "Helmhöfe", 2 km E of Rittsteig, at the border towards the CSFR
TK 25: 6744 Rittsteig, R 78 700/ H 57 120

The quarry exposes massive marbles with graphitic bands. Foliation is parallel to these bands and is defined by lensoid domains of differing grainsize. Under the microscope, there is no preferred orientation of twin lamellae.
In similar rocks on Czecho-Slovakian territory, microfloras suggest an age about the Silurian/Devonian boundary (PACLTOVA, oral comm.). In that case, the Moldanubian marbles might represent a metamorphosed equivalent of the Siluro-Devonian carbonates in the Tepla/Barrandian terrane.

Stop No. 6 - Moldanubian micaschists and quartzite with dextral shear
"Am Lüsten", 750 m E of Rittsteig, S of the road to Anglmühle
TK 25: 6744 Rittsteig, R 77 340/ H 57 600

Crags in the wood expose micaschist and quartzite. Shear bands at the dm- to m-scale indicate tectonic transport toward the NE. Small-scale folds developed mainly in the quartzites probably correspond to DM4.

Stop No. 7 - Phyllitic micaschists of the "Küni'sches Gebirge", (Bavarian for "Kings Mts."), Moldanubian (P.BLÜMEL)
Anglmühle, 1 km E of Rittsteig, close to the border Bavaria/CSFR
TK 25: 6744 Rittsteig, R 76 880/ H 57 700

The northwestern corner of the micaschists in the Küni'sches Gebirge comprises a variegated lithologic association of phyllitic micaschists, graphite quartzite, marble, orthoschists and epidote-amphibolites. In the micaschists, Silurian spores and Cambrian microfossils were recognized (PFLUG & REITZ 1987). Metapelites contain porphyroblasts of biotite and albite with helicitic inclusion-trails (quartz, ilmenite, rutile and chloritoid) embedded in a matrix of muscovite, chlorite, quartz and ore minerals. Regional LP metamorphism in the Moldanubian, in this outcrop, reaches a minimum as indicated by the assemblage biotite + chlorite + garnet + muscovite + quartz. This assemblage is stable at 450-550 ^{o}C in LP (and even MP) metamorphism (SPEAR & CHENEY 1989).
The outcrop is small and largely overgrown, but permits to recognize the main foliation (here: DM3) and a younger fracture cleavage.

Stop No. 8 - Metabasites of the "Hoher Bogen" area (Tepla/Barrandian)
"Ständel", hill 300 m E of Lambach
TK 25: 6744 Rittsteig, R 72 940/ H 57 390

Crags in the wood expose black amphibolites and pyroxenites with leucocratic, plagioclase-rich dikes, which represent part of the Cambrian mafic intrusion (Neukirchen-Kdyne pluton). The dikes have been deformed into tight to isoclinal, upright folds with subhorizontal, E-trending axes. The axial plane foliation corresponds to the regional s1 in the TB (ST1).
A second set of quartz-plagioclase-dikes, which are undeformed, cut across the older foliation.

Stop No. 9 - Amphibolites of the "Hoher Bogen" Massif with ductile shear zones

Forest road (not open to the public) towards the top of the Hoher Bogen, 5-6 km E of Madersdorf, 400 m S of Schwarzriegel hill
TK 25: 6743 Neukirchen bei Heilig-Blut

Crags along the road expose banded amphibolite. The well-developed foliation (ST1), defined by quartz/plagioclase-layers and by shape orientation of hornblende, dips steeply to the N. The hornblendes show a NE-dipping stretching lineation related with ST1. Sigma-clasts of hornblende indicate top to the SW tectonic transport. ST1 is cut by WNW-trending discrete shear-zones (ST2), which show tectonic transport downdip to the N to NE. ST2 possibly correlates with DM3 of the Moldanubian rocks to the S.

STOP No. 10 - Variscan high-temperature mylonites in the segments between Bavarian Pfahl and Rundinger Zone (L.MASCH)
Quarry Flammried near Zandt 2km NW of Miltach,
TK 25: 6842 Miltach R: 45 53 940 / H: 54 48 150

The quarry exposes up to 20 m of paragneiss-mylonites of the segment between the large scale mylonite zones of the Bavarian Pfahl and the Rundinger Shear Zone. Rb/Sr data (KÖHLER et al.1989) hint a paragneiss of Caledonian age as protoliths, whereas the mylonitization is correlated with the last isotope homogenization at variscan age. The mylonites are of the high-temperature type with quartz, feldspars and the minor cordierite being plastically deformed and recrystallized in the stability field of potash feldspar - cordierite - sillimanite - garnet. A mylonitic foliation and stretching lineation is imposed and LPO's of quartz c-axes show strong concentrations (Y-maxima). Slightly deformed portions have preserved gneissose and anatectic minor structures. A small granite dike is contemporaneous to mylonitization and thus moderatly deformed.
further reading: CETIN (1986), KÖHLER et al. (1989)

STOP No. 11 - Polymetamorphic peridotites, pyroxenites, eclogites and metapelites (P.J.O'BRIEN)
Winklarn, 6km SE Oberviechtach; Galgenberg quarry, SE of village
TK 25: 6540 Oberviechtach R: 45 35 400 / H: 54 76 000

The roadstone quarry at Winklarn reveals generally good relationships between polymetamorphic basic, ultrabasic and pelitic rocks. The major rock type (and the one quarried) is a serpentinized amphibole-peridotite with relics of olivine, amphibole and orthopyroxene and with a bulk composition corresponding to harzburgite or dunite. Relics of chrome spinel (50 wt% Cr_2O_3) led GEHLEN and SCHMITT (1989) to interpret these rocks as remnants of sub-oceanic mantle. The peridotite is cut by thin (generally < 10cm) pyroxenite bands containing an amphibolite facies olivine (Fo90) + orthopyroxenes (En90) ± clinopyroxene (diopside) + amphibole (magnesiohornblende to tremolite) + aluminous spinel (Cr_2O_3 5-15 wt%) assemblage. An enrichment of Al_2O_3 at the rims of both orthopyroxene (core 0.15, rim 1.26 wt%) and spinel is possibly the result of garnet breakdown although genuine garnet peridotites or their retrograde equivalents have not been found.

Some bands show enstatite pseudomorphed by talc + olivine. In places the serpentinite is cut by peraluminous andalusite-bearing granites.

The serpentinites are in tectonic contact with a unit of eclogites, pyroxenites and paragneisses above and below the access road at the eastern quarry face. The contact is a steep NE-dipping zone of friable, pale green, predominantly tremolite-tremolitic hornblende rock. East of this contact are NNW-striking, steeply E-dipping paragneisses, garnet pyroxenites, garnet-spinel websterites and Fe-rich orthoamphibole-bearing gneisses.

In hand specimen, typical metabasites show red-brown garnet set in variable proportions of pale green symplectitic clinopyroxene and black amphibole. More retrograded rocks are lighter coloured due to increased plagioclase contents. The metabasites often appear to be banded but apart from monomineralic garnet layers the banding is usually the result of differential retrogression whereby layers with residual garnet are interspersed with garnet-free diopside + plagioclase + amphibole layers. Geochemically they correspond to LREE-depleted N-type MORB tholeiites. The deduced eclogite facies assemblage of garnet + omphacite + rutile ± quartz ± kyanite ± clinozoisite is never retained intact. Garnet, sometimes in monomineralic bands, shows a wide compositional variation

Alm 38-56 Pyp 12-37 Grs 14-29 Sps <7.5 (range of all analyses). Grains can have chemically homogeneous cores or Fe-rich cores coupled with rising Mg/Fe. Garnets are usually rimmed by a radial kelyphite of Mg-hastingsite + plagioclase (An 65-70) ± spinel: rarer are earlier plagioclase + orthopyroxene kelyphites. Clinopyroxene occurs in a number of textural varieties. Unaltered omphacite (cpxI), is found as armoured relics in garnet and has the highest jadeite content (XJd = 0.25-0.35). Matrix grains (cpxII) show tiny exsolved albite-rich plagioclase laths and so have reduced jadeite contents (XJd = 0.15-0.25). Rims of cpxII - cpxIIb - altough devoid of exsolved plagioclase laths and in optical continuity, have even lower jadeite contents (XJd < 0.15). In most cases cpxII is replaced by vermicular diopside (cpxIII) + plagioclase (An 15-25) symplectites themselves overgrown by later Mg-hornblende or Mg-hastingsite + plagioclase (An 40) diablastic aggregates. Reaction of garnet with adjacent quartz has produced coronas on the quartz of orthopyroxene (inner) and diopside (cpxIV) (outer) and plagioclase (An 30-60) against garnet. Some quartz grains are rimmed by hedenbergite-rich clinopyroxene. Kyanite is always replaced by symplectitic hercynite + anorthite masses whilst clinozoisite is pseudomorphosed by anorthite aggregates full of tiny opaque grains. Groundmass rutile is replaced by ilmenite and later titanite.

The textures indicate a multistage metamorhic history probably starting in the amphibolite facies (low Mg garnet cores with amphibole inclusions) and continuing through eclogite (=700^{o}C, >15kbar), high pressure granulite (=800^{o}C, >12kbar), medium pressure granulite (>800^{o}C, 8-10kbar) and amphibolite (=700^{o}C, <8kbar) stages (P-T from Grt-Cpx, Grt-Opx, Cpx-Opx and Grt-Amph geothermometry, Ab-Jd-Qz and Grt-Qz-Cpx-Opx-Plag geobarometry).

Fine grained metabasites are found as sets of thin (5-10cm) layers interbedded with pelitic gneisses in the upper E quarry face. In hand specimen a handlens is needed to identify the tiny garnets. The geochemical and petrological features are identical to that of the coarser-grained metabasites.

Garnet pyroxenites and garnet websterites are also found in situ in the basite-pelite sequence of the E quarry face. In hand specimen the pyroxenite contains an interlocking "mesh" of orange-brown garnet surrounding well preserved pale green clinopyroxene and dark green amphibole: thin black amphibole-rich alteration bands cut the samples. Although normatively olivine tholeiites, these rocks are enriched in Mg, Cr, Ni and LREE (La = 50x chondrite) and depleted in alkalies relative to the "normal" basites. Garnet is essentially homogeneous - Prp45 Alm38 Grs13 And4 - whilst clinopyroxene is diopside with minor Na and Al (Jd0-7 Acm0-7 CaTs1-3). Other primary phases are pale-yellow Mg-hornblende, rutile and apatite. Retrogression is restricted to minor growth of green tschermakitic hornblende at garnet-cpx contacts and thin bands where garnet is replaced by opx, spinel and Mg-hornblende.

The websterite is easily distinguishable in its coarse variant with rusty-brown laths of altered opx up to 5cm long randomly intersected by pale yellow-green cpx. The cpx is clearly rimmed by black amphibole. Red garnet sits as relics within kelyphite spots up to 10mm in diameter and sometimes earthy brown iddingsitised olivine can be seen. The olivine (NiO = 0.3 wt%) and orthopyroxene (Al_2O_3 = 0.15-1.0 wt%) of the websterite are more Fe-rich - Fo73 and En78 repectively - than those of the serpentinite or layers in serpentinite: clinopyroxene is diopside (X_{Mg}=0.9, Al_2O_3 < 1 wt%).

Amphibole inclusions in cpx are pargasitic hornblende whilst the amphibole replacing cpx is tremolitic or actinolitic hornblende. Garnet is Mg-rich - Prp 53 Alm 30 Grs 16 Sps 1 - with slight zoning to higher Fe/Fe+Mg at rims. The complex kelyphite around garnet comprises an early opx (X_{Mg} = 0.65, Al_2O_3 = 2-3 wt%) + vermicular spinel (X_{Mg} =0.39, Cr_2O_3 < 1.5 Wt%) intergrowth (sometimes recrystallized to a coarser-grained variant (opx; X_{Mg} = 0.69, spinel; X_{Mg} =0.42, Cr_2O_3 < 0.5 wt%) usually partially overgrown by magnesiohornblende and, even later, anorthite. Spinel unrelated to garnet breakdown contains 3-4 wt% Cr_2O_3 and is richer in iron whilst spinel inclusions in garnet have high Mg (X_{Mg} = 0.55-0.6) and little Cr. Primary rutile (Cr_2O_3 = 1.3 wt%) and secondary ilmenite (MgO = 2.8-3.5 wt%, talc (X_{Mg} = 0.95) and clinochlor complete the picture. Preliminary geothermobarometry indicates a high pressure evolution comparable to that of the eclogites.

Gneisses enclosing the metabasites are folded and tectonised stromatic metatexites. Large poikiloblasts of cordierite (X_{Mg} = 0.6-0.7) overgrow elongate red-brown biotite (X_{Mg} = 0.4-0.6,
TiO_2 up to 5.8 wt%) and sillimanite aggregates in most samples. A later reversal of this reaction sees the replacement of cordierite by a more prismatic sillimanite and small biotites. Garnet showing an early replacement by biotite + plagioclase, exhibits strong near-rim Fe and Mn enrichment coupled with Mg and Ca depletion (core: Alm 53 Prp 30 Grs 14 Sps 3, rim: Almc 73 Prp 15 Grs 2 Sps 10). The relatively high Mg and Ca of the garnet cores and hercynite-rimmed sillimanite pseudomorphs after kyanite are evidence of the former high-pressure nature of these rocks. Pressure estimates above 11kbar using the assemblage garnet - aluminosilicate - quartz - plagioclase (GASP) are comparable to those of the high pressure granulite stage in eclogites. Taking garnet rim compositions, the assemblage garnet - rutile - quartz - aluminosilicate - ilmenite (GRAIL) indicates pressures around 7-8kbar (at 700^{o}C). These pelitic gneisses therefore could share the same or a large part of the tectonometamorphic history of the eclogites.
In the lower E quarry face, below the entrance road, metabasites are interbedded with paragneisses containing, in hand specimen, purple-red garnet, black amphibole and biotite. In thin section the garnets can be seen to be surrounded by symplectites of pleochroic orthopyroxene with either plagioclase or ilmenite: an additional phase gedrite, clove-brown orthoamphibole. This assemblage is variably overgrown by green hornblende and biotite.
further reading: O'BRIEN (1989), v.GEHLEN & SCHMITT (1989)

STOP No. 12: Clinozoisite-amphibolite and garnet-micaschist at the base of the ZEV nappe (U.KLEEMANN)
Michldorf, 10km SE of Weiden (Opf.); new quarry
TK 25: 6339 Waldthurn, 6439 Tännesberg, R: 45 17 250 - 45 17 600 / H: 54 95 850 - 54 96 350.

The quarry of Michldorf is situated at the borderzone between the allochthonous "Zone of Erbendorf-Vohenstrauß" (ZEV) and the parautochthonous Saxothuringian-Moldanubian zones (Fig.5).

In the northern part of the outcrop, a clinozoisite-amphibolite body is exposed. It contains a steeply dipping to vertical, NE-SW-striking foliation, and a SW-plunging stretching lineation. The mineral paragenesis hornblende - oligoclase - chlorite - sphene - quartz indicates lower amphibolite facies conditions (SCHÜSSLER 1986). K/Ar dating of hornblende gave ages of 380-399 Ma. (KREUZER et al. 1989). Towards the southern contact, a progressive change to the greenschist-facies assemblage chlorite - actinolite - albite is observed.

The garnet - micaschists in the southern part of the quarry show a two-stage deformation history. An older S_1, which is parallel to the compositional layering (probably S_0), was folded into tight upright folds with shallow SW-plunging fold axes. The dominant cleavage is now the near-vertical, NE-SW-striking axial plane cleavage S_2. Quartz inclusion trails in garnets are oriented parallel to S_1 with sigmoidal curvatures at the porphyroblast margins into the matrix S_2. Hence garnet growth is syn-D_2. The mineral

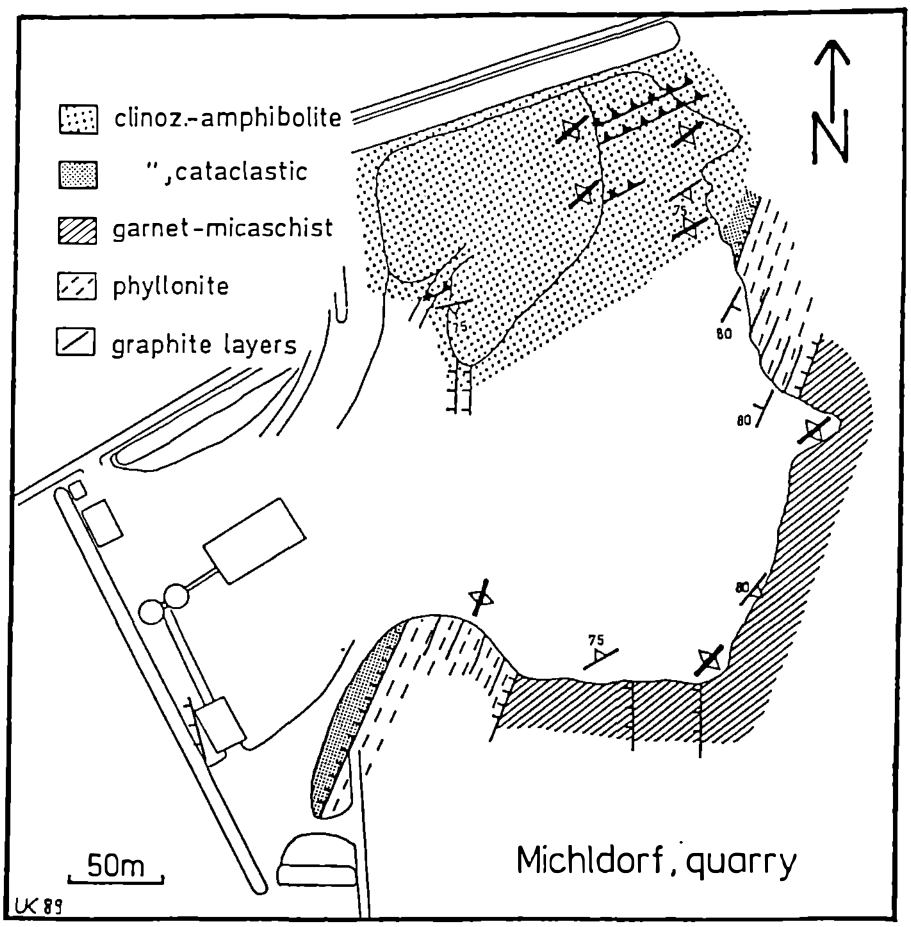

Fig.5: Geological and tectonic sketch map of the quarry Michlsdorf (KLEEMANN 1989).

assemblage garnet (alm 53-63 grand 23-25 spess 20-7 pyr 3-5) - biotite - phengitic muscovite - oligoclase - quartz - graphite - calcite - rutile/sphene formed under lower amphibolite facies conditions (garnet-biotite thermometer T approx. 500^{o}C, phengite-barometer P > 3kbar). Most garnets have a prograde zonation with spessartine-rich cores.

Between the amphibolite and the micaschists, a retrograde shear zone with graphite-rich layers is exposed. This shear zone crosscuts the main foliation in the micaschists and the amphibolites.

Possible correlations of the exposed rocks with the major tectonic units, and the significance of the shear zone within the regional tectonic framework will be discussed.

further reading: HEINICKE (1987), KREUZER et al. (1989), SCHÜSSLER (1987), VOLL (1960)

STOP No. 13 - Zone Erbendorf-Vohenstrauss, southern part: amphibolites intercalated into paragneisses, cut by a leucocratic orthogneiss and a pre-Variscan pegmatite. (U.SCHÜSSLER)

Oedenthal, 7km SE of Weiden, quarry "Scharnagel" 500m W of Oedenthal

TK 25: 6339 Waldthurn, R: 45 17 000 / H: 55 00 750

In the quarry one of the numerous amphibolites of the Zone Erbendorf-Vohenstrauss (ZEV) is exposed. The amphibolite body is several decameters in thickness, NE-dipping, and bordered by a kyanite-bearing garnet - muscovite - biotite - plagioclase - paragneiss. The hanging wall is marked by a subconcordant, pre-Variscan pegmatite, containing dark aggregates of biotite which is partly replaced by chlorite. Another typical mineral of the pegmatite is a green apatite (moroxite). In the southern corner of the quarry, a discordant, very light orthogneiss formed by feldspar, quartz, white mica and less garnet occurs.

The amphibolite of the quarry belongs to a massive to schistose, partly striped type, typical for the southern part of the ZEV. It is formed by tschermakitic hornblende (63 vol.%) and plagioclase (34 vol.%) with andesine/labradore composition, inversly zoned. Rare accessories are sphene, apatite and opaques. The amphibolite sometimes contains small lenses (up to 10cm) rich in biotite, or thin layers of feldspar, quartz and partly scapolite. The layers may be intensively folded in a small scale. In their chemistry, the amphibolites are subalkaline, tholeiitic, and compare well with modern normal-MORB compositions. This is typical for amphibolites of the southern ZEV (see also chapter pre-Variscan magmatism and SCHÜSSLER et al., 1989).

Radiometric dating: 10 muscovite fractions from two paragneiss-samples and one orthogneiss sample gave concordant K/Ar dates ranging between 366 and 373 Ma. Hornblendes of two amphibolite samples are dated with 377 and 378 Ma (KREUZER et al., 1989). These ages point to the end of the last metamorphic event in the western part of the ZEV. They are corroborated by U/Pb and Rb/Sr age determinations (TEUFEL, 1988).

Whole rock compositions (quarry):

SiO_2	47.8	47.2	48.1
TiO_2	2.27	1.41	2.19
Al_2O_3	15.0	15.1	14.3
Fe_2O_3	1.28	1.25	1.33
FeO	10.1	9.05	9.86
MnO	0.16	0.15	0.17
MgO	6.77	8.91	6.20
CaO	11.7	11.6	13.0
Na_2O	2.64	2.51	2.03
K_2O	0.30	0.21	0.43
P_2O_5	0.28	0.11	0.27
H_2O	1.1	1.3	1.1
CO_2	<0.1	0.12	0.2
TOTAL	99.4	98.92	99.18
V	330	290	322
Cr	197	428	200
Co	41	55	35
Ni	86	182	83
Rb	<4	<4	5
Sr	207	203	234
Y	28	26	32
Zr	184	108	192
Nb	15	7	17
Ba	126	90	165
Ce	23	11	20

Hornblendes (quarry):

SiO_2	45.0	44.2
TiO_2	1.55	1.42
Al_2O_3	12.0	11.5
Fe_2O_3	0.64	0.44
FeO	14.7	15.6
MnO	0.21	0.27
MgO	9.81	9.35
CaO	12.1	12.5
Na_2O	1.00	1.25
K_2O	0.37	0.53
TOTAL	7.38	97.06

cations calculated with 23 O:

Si	6.657	6.619
Al	1.343	1.381
(Z)	8.000	8.000
Al	0.744	0.655
Ti	0.172	0.159
Fe^{3+}	0.071	0.049
Mg	2.165	2.087
Fe^{2+}	1.821	1.952
Mn	0.026	0.034
(Y)	4.999	4.936
Fe^{2+}	---	---
Mn	---	---
Ca	1.915	2.009
Na	0.085	---
(X)	2.000	2.009
Na	0.202	0.362
K	0.069	0.101
(A)	0.271	0.463

STOP No. 14: Flaser amphibolite, paragneiss and granite dikes of the western part of the Zone of Erbendorf-Vohenstrauss (P.BLÜMEL, E.STEIN)
Rupprecht quarry, 1km N of Windischeschenbach
TK 25: 6138 Erbendorf, R: 45 11 500 / H: 55 19 500

The quarry exposes flaser amphibolite (typical variant of the northern and central ZEV), minor paragneiss and subhorizontal granite dikes. With regards to Mg, Fe_{tot} + Ti and Al the flaseramphibolite has tholeiitic character, but is richer in Fe than schistose and striped amphibolite (e.g. Oedenthal) (SCHÜSSLER, RICHTER & OKRUSCH 1989).

Flaser amphibolite has the mineral assemblage hornblende + oligoclase + quarz + titanite (+biotite) (+garnet), which seems to have recrystallized during/after high-T deformation. Calcsilicate layers contain clinopyroxene + clinozoisite + quartz. Porphyroclasts of hornblende (diameter: less than 1cm) and irregularly formed patchy neosomes with hornblende and plagioclase seem to indicate a pre-mylonitic migmatization. However associated paragneisses of the area do not give the requisite high temperatures (see A5 and B3b) leaving two explanation open to discussion: (1) syn-/postdeformative down-grading of paragneiss or (2) tectonic association of paragneiss with amphibolite. The Falkenberg granite (321 Ma; see A4) closely adjacent toward E seems to induce poikiloblastic growth of hornblende.

Paragneiss and amphibolite display a layering of W-E orientation, which is intensively folded (cm-dimension). The upright open folds show two different orientations: (1) N-S (monoclinal symmetry) and (2) W-E (rhombic symmetry; coaxial with crenulation-lineation). The age relations are not clarified yet. In the amphibolite refolded isoclinal folds are observed which are absent in the paragneiss. An open undulation with W-E oriented fold axes corresponds to the open folds in paragneiss. Younger folding with steeply dipping B-axes eventually results from strike-slip tectonics thus pointing out the difficulties of structural analysis in the ZEV:
further reading: SCHÜSSLER et al. (1989)

STOP No. 15 - Serpentinite of the Erbendorf Greenschist zone (P.BLÜMEL)
Quarry on the road halfway between Erbendorf-Grötschenreuth, 1,5km NW Erbendorf
TK 25: 6138 Erbendorf, R: 45 03 200 / H: 55 24 000

The Erbendorf Greenschist Zone is disposed into a northern and southern segment separated by an intervening zone with metasediments ("Wetzldorf Serien"). Located at the northwestern margin of the southern segment the quarry exposes serpentinite excavated for the china industry. The strongly tectonized rock contains antigorite, lizardite and magnetite as the main phases and accessory chrysotile, chlorite, talc, carbonates, sulfide minerals and chromian spinel (MATTHES & KNAUER 1981).

The Erbendorf Greenschist Zone for a long time was considered to be the "type locality" for the tectonic boundary between the SAX and the MO. With the recognition of the two metamorphic units MPU and LPU it is redefined as the northern portion of the thrust-zone underlying the ZEV.

STOP No. 16 - Mylonite zone in the Moldanubian close the Zone of Erbendorf-Vohenstrauss (E.STEIN)
Road-cuts (open in 1988) E Floß on road Neustadt a.d. Waldnaab- Flossenbürg
TK 25: 6239 Neustadt a. d. Waldnaab, R: 45 22 61 / H: 55 10 61 to R: 45 23 05 / H: 55 10 04

The road-cut exposes mylonitized sillimanite-bearing biotite-plagioclase gneiss, calcsilicate gneiss, amphibolite and orthogneiss with less deformed but strongly retrograded cordierite gneiss.
Nearly all the described rocks suffered a strong mylonitic deformation leading to a penetrative mylonitic foliation, which is generally the oldest observable structural element.
Due to the lithology this mylonitic foliation differs in appearance.
Fine grained quartz rich paragneiss mylonites show strongly parallel oriented s-planes due to the alternating biotite rich (1mm thick) and quartz rich layers (3-5mm thick) gently dipping WSW. A tight mineral stretching lineation (biotite) is gently plunging WSW. Quartz rods and lenses up to dm-scale often develop monoclinic -clasts indicating the hanging wall movement to the WSW, too.
These quartz lenses and -clasts seem to be flattened perpendicular to the foliation during continuous deformation because most of them show an orthorhombic symmetry with respect to the mylonitic foliation.
These rock strata mostly are unfolded, even disharmonic intrafolial folds are very scarce. Finegrained calcsilicate intercalations show a similar texture. Coarser grained biotite micaschists and gneisses show a mylonitic fabric as well. Biotite rich layers (+/- 1-5 mm thick) anastomose around lensoid quartz and plagioclase microlithons (with diameters in cm scale).Mineral stretching lineations are defined by biotite and where present by

sillimanite, also plunging WSW. These rocks are intensively folded from cm- to m-scale. The monoclinic cylindrical folds are characterized by long limbs gently dipping to the WSW (258/28) and by short limbs steeply inclined to the S (190/65). Their fold axes are plunging to the WNW (290/25). According to these data folds show a SSW vergence. The fold hinges are thickened with respect to the limbs (ratio +/- 2:1). Folds are open to close with interlimb angles of about 40° to 80° and cylindrical.
A related crenulation cleavage spaced in mm scale developed subparallel to the axial planes. The crenulation lineation plunges to WNW (290/20).
The older mineral stretching lineation is refolded by this fold generation which occurred under decreasing pT-conditions in greenschist facies. In thin sections one can observe that biotite is replaced by chlorite.
In the outcrops it is obvious that these folded areas are bound by discrete mylonite zones in cm to m scale in which biotite is also replaced by chlorite. A slickenside lineation is defined by chlorite and muscovite.
With decreasing temperatures deformation concentrated on discrete mylonite zones whereas under higher temperatures a penetrative mylonitisation occurred. These deformation refer to thick homogeneous rock strata. In areas where those different lithologies are interbedded noncylindrical disharmonic intrafolial folds in cm- to dm-scale developed contemperaneously to the mineral stretching lineation. They are refolded by the younger cylindrical fold generation.
This ductile deformations are overprinted by different brittle faults. Generally four different systems can be distinguished:
- flat lying revese faults with a hanging wall movement to SW;
- steeply inclined reverse faults with the same sense of movement;
- flat lying normal faults with a hanging wall movement to SW;
- steeply inclined normal faults with the same sense of movement;

PT conditions of mylonitization are obtained from the reaction-texture of garnet-quartz symplectite growing at wollastonite/ plagioclase grain boundaries and from the conditions of sillimanite stability. Calculated with BEERMAN data for Xgr = 0.93 and Xan = 0.35 the reaction boundary wollastonite + anorthite = grossular + quartz cuts the other reaction curve sillimanite/ andalusite at ca. 3kbar and 540°C.

This mylonite zone is seen as part of the thrust-zone, along which the MPU was emplaced. The direction of thrusting obviously differs from the direction of compression active in the autochthonous during the climax of LP regional metamorphism.
further reading: KLEEMANN et al. (1989)

STOP No. 17 - Biotite sillimanite gneisses of the Zone of Tirschenreuth-Mähring (ZTM) (E.STEIN)
Road cut in the village Mähring
TK 25: 6041 Mähring, R: 45 37 450 / H: 55 30 900

The Tirschenreuth-Mähring zone as the N'margin of the Moldanubian (MO) lying between the city of Tirschenreuth in the W and the small village of Mähring in the E mainly consists of metapelitic and metapsammitic rocks which are intercalated with some amphibolites and calcsilicate-marbles. The stratigraphic correlation of these strata as "upper proterozoic -Brioverian" (STETTNER 1979) is based on lithostratigraphic comparisons with KETTNER's (1917) "Spilitic-series" of Bohemia. Mostly all the rocks are characterized by a strong mylonitic fabric. Mylonitization occured under amphibolite facies conditions developping a strong mineral lineation of biotite and where present of sillimanite, too. During decreasing temperatures mylonitization concentrated on discrete shear zones which are characterized by biotite-muscovite and chlorite-muscovite assemblages. Furthermore this zone was intruded by numerous granite sills which are largely undeformed (intrusion age: 317+/-3 U/Pb monazite TEUFEL 1988). Only a few outcrops show polyphase deformed biotite-sillimanite-k-feldpar gneisses which progressively change into cordierite-sillimanite-gneisses towards the south.
This road cut at the N'edge of Mähring is one of the best examples for polyphase deformed gneissic rocks in the ZTM.

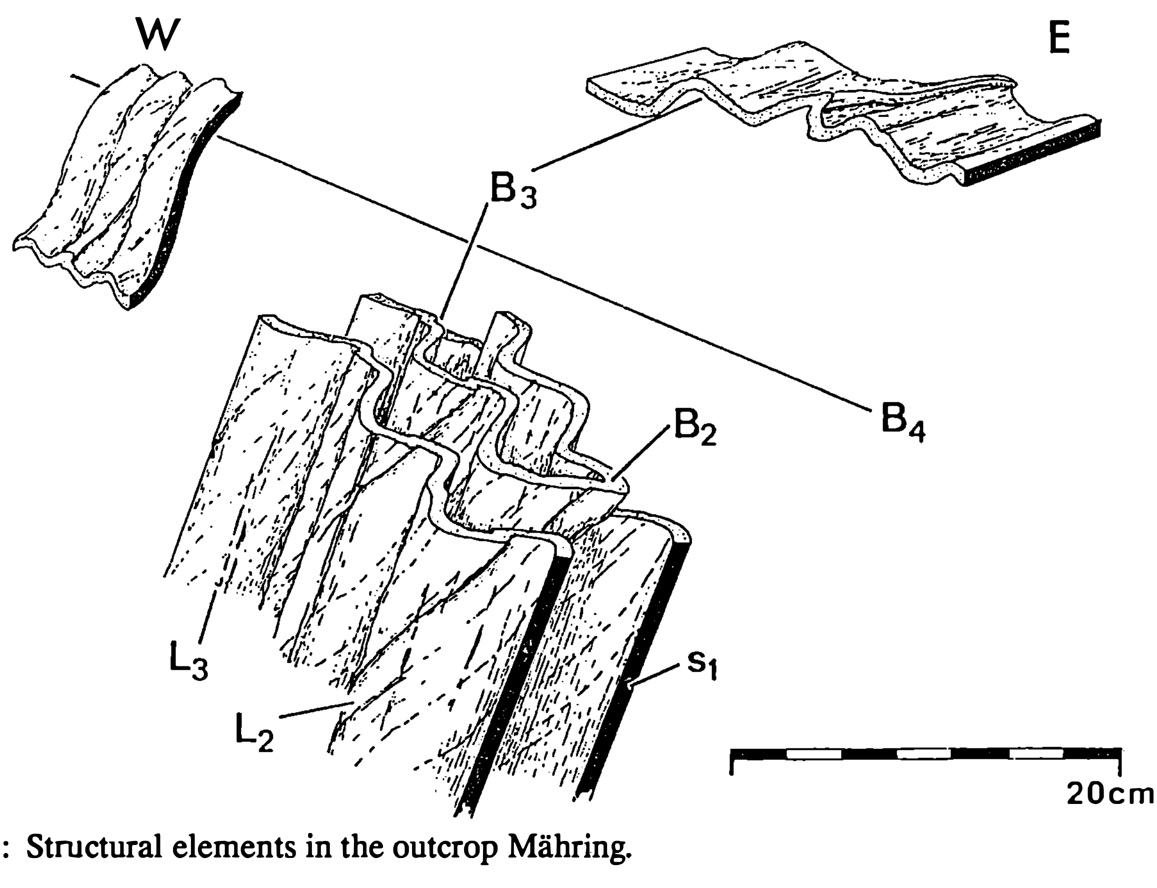

Fig. 6: Structural elements in the outcrop Mähring.

The oldest observable structural element is a metamorphic banding (S_1) at mm-scale. Dark, biotite-sillimanite rich layers alternate with light quartz and k-feldspar layers, respectively with some exudation quartzes being oriented parallel to the S_1-foliation. This layering is olded isoclinal in cm-scale. B_2-fold axes are oriented SW-NE. Only in the hinges of the small scale recumbent folds a related cleavage (S_2) can be clearly identified developing an intersection lineation (L_2).

D_2 elements are overprinted by a third deformation. Open upright D_3 folds in cm- to m-scale with orthorhombic to monoclinic symmetry and interlimb angles of about 120° are the most penetrative folds. Linear structural elements (B_3 fold axes and L_3 intersection lineation) as well as planar elements (S_3 cleavage, axial plane) show a NE-SW strike direction. The plunging of the linear fabric elements is controlled by the later refolding around NW-SE oriented B_4 fold axes (see Fig.6). This refolding led to the steeply inclined fabric in the foreground as well as to the flat lying fabric in the background of Fig.6.

further reading: KETTNER (1917), STETTNER (1979), TEUFEL (1988)

STOP No. 18: The Continental Deep Drilling Location near Windischeschenbach (Northern Oberpfalz, Bavaria) (H.MÜLLER, J.KOHL & C.RÖHR)

TK 25: 6138 Erbendorf, R: 45 08 590 / H: 55 19 865 , alt. 513.5m

1. KTB: The Continental Deep Drilling Program of the Federal Republic of Germany (KTB) is aimed to reach a temperature range of 250 to 300°C within a depth interval of 10 to 12 km in order to investigate processes and conditions in the lower continental crust. The well site selected lies at the NW border of the Zone of Erbendorf-Vohenstrauß (ZEV), which is interpreted as a nappe overlying the imbricated units of Saxothuringian (ST) and Moldanubian (MO). While the ZEV underwent a MP-metamorphism at 380 Ma, both ST and MO were overprinted by a LP-HT-metamorphic event at 320 Ma. All rocks transected by the pilote hole (final depth 4000.1 m) belong to the ZEV. The overall core recovery was 3600 m (core diameter 9.4cm). Drilling of the main well will start in September 1990.

2. Tasks of the field laboratory: The main task of the field laboratory situated immediately at the drill site is the investigation of core material, cuttings, drilling mud, fluids and gases.

- for quick operational decisions concerning drilling, sampling and testing
- for rock properties which are time-dependent or have to be monitored regularly and as a function of depth
- for correlation with borehole measurements

- for establishing basic informations for all individual research projects carried out at universities and other research institutes

Fig.7 summarizes the tasks of the field laboratory and its scientific structure.

3. Scientific results from the pilote well

Fig.8 shows a schematic profile of the pilote well (0-4000m). Down to 460m the borehole intersected a metamorphic volcanosedimentary sequence corresponding to surface outcrops: (garnet-)biotite gneisses alternate with garnet amphibolites with characteristic intercalations of calc-silicatic bands. Sections from 460 to 1160 m, 1610 to 3575 m consist of kyanite-sillimanite-garnet bearing biotite gneisses. Probable source rocks were (pelitic) graywackes. Between 2470 and 3250 m some minor layers of garnet amphibolite and garnet-hornblende-biotite gneiss occur. All these are amphibolite facies rocks with local greenschist to very low grade retrogressive overprint. Kyanite in the paragneisses documents the MP-metamorphic history, whereas most of the fibrolitic sillimanite is younger and probably due to decompression. Muscovite was formed in a later, diaphtoritic stage.

Between 1160 and 1610m and below 3575 m metabasic rocks consisting of amphibolites and metagabbros with meta-ultramafic layers were intersected. The amphibolites show variable textures from massive over weakly foliated/flaser-like to strictly foliated and are frequently penetrated by schlieren-like quartz-feldspar mobilisates. Main constituents are brown and olive-green, rarely blue-green hornblende, zoned plagioclase, garnet and, in some places, clinopyroxene. Metagabbros differ from the amphibolites by their relictic magmatic (ophitic) texture. In most places, this texture is highly obscured by metamorphic overprint. At 3776 and 3841 m biotite orthogneisses with local augen-texture occur. They are now of trondhjemitic composition, but chess board textured oligoclase-augen document a metasomatic change of K-feldspar into albite. Meta-ultramafic layers are interpreted as cumulates, enriched in Cr and MgO, but with moderate Al_2O_3 content. They correspond to former (olivin bearing) pyroxenites transformed to hornblendites (formation of anthophyllite, cummingtonite, actinolite, chlorite, phlogopite, talc, serpentine and calcite).

Amphibolites and metagabbros show symplectitic replacement of a (probable) former omphacitic clinopyroxene by diopside (Jd10-15) + plagioclase. This is ascribed to an early HP-granulitic stage. In amphibolite facies, most of the clinopyroxene was replaced by amphibole; garnet developed a reaction rim of plagioclase against hornblende.

From O to 2500 m the metamorphic foliation is steep to vertical, dipping SW (Fig.7). Below 2500 m the foliation is flattening, turns SE to NE at 3050 m and steepens again below 3200 m. Relictic isoclinal folds and a penetrative foliation document the oldest visible deformation. Still under ductile conditions the penetrative foliation was folded. Open folds and kink bands mark the transition to brittle deformation. Cataclastic

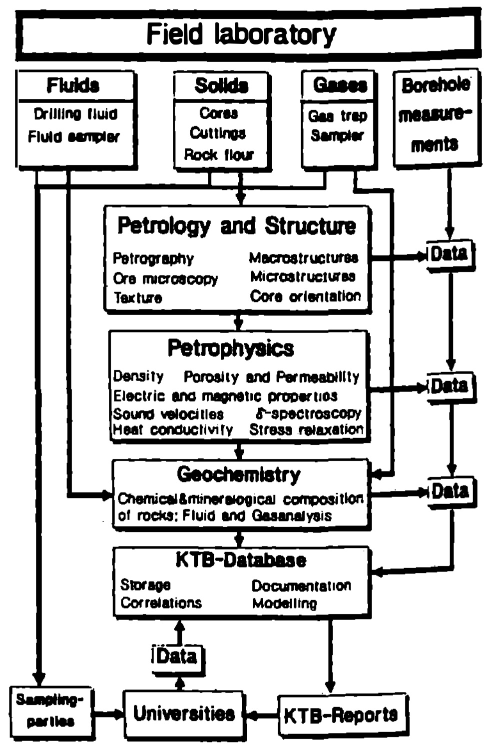

Fig. 7: Sampling and working scheme of the KTB field laboratory

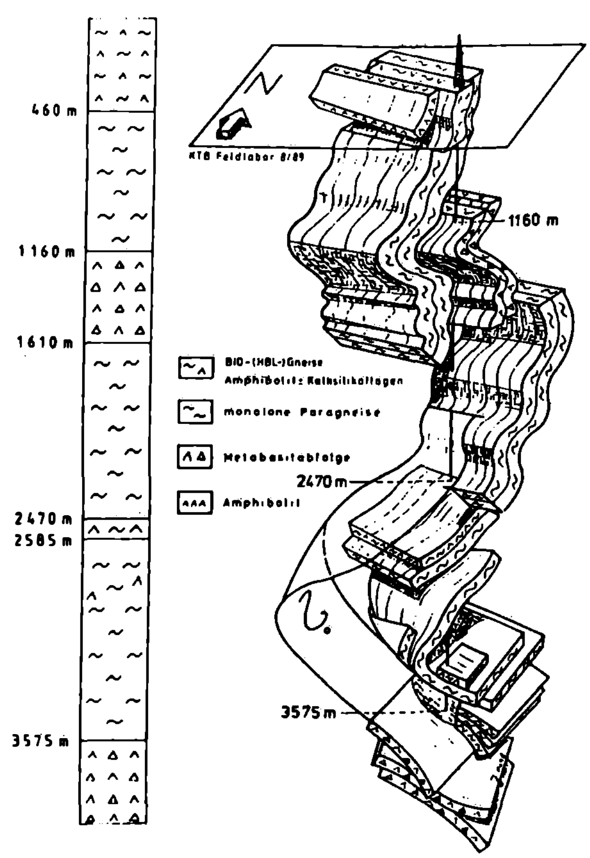

Fig. 8: Schematic profile and 3-D sketch of lithological units in the KTB VB (0-4000m).

structures result from two earlier phases of compressive and a younger phase of extensional stress. Cataclasites of several meters thickness with high graphite content correlate with the earlier compressive structures. These graphite-rich zones can be detected during drilling by an increase in methane and helium in the gas phase dissolved in the drilling mud.
The gneisses are cut by several lamprophyric and aplitic dikes which are slightly younger than the oldest cataclastic deformation. Joints are mineralized with prehnite, epidote, laumontite, quartz, calcite or K-feldspar. Below 3447 m out of several open joints mineralized with quartz + calcite or kaolinite + calcite an influx of saline formation waters (CaCl2-rich) into the borehole was detected by continuous analysis of the drilling mud.
The rock sequences intersected so far display a marked anisotropy for seismic velocities and thermal conductivity, a result quite unexpected on such a large scale. Mean Vp is 6kms-1. Mean rock density amounts for 2.75 gcm-3 in gneisses and 3.0 gcm-3 in amphibolites. Magnetic anomalies were detected within gneiss sequences as well as in metabasic rocks. Except in some magnetite bearing meta-ultramafic layers they are due to finely dispersed
pyyrhotite. Mean natural remanent magnetization is 0.3 Am-1. The anelastic strain retardation of the cores accompanied by the formation of microcracks and by acoustic emissions lasts for several days. The direction of the maximum principal strain retardation corresponds to the direction of the maximum horizontal principal stress (mean value N1550 E ± 10). Analysing the natural gamma radiation yields the content of radioactive minerals and heat production rate and serves as a calibration standard for logging results.

4. Petrology of metapelites in the KTB cores

A large part of the KTB drillcore are fine- to medium-grained metapelitic gneisses and micaschists. Their mineral content is fairly uniform throughout the profile drilled so far, whereas the relative proportions of minerals vary considerably. The most common assemblage in the metapelites is: GArnet, biotite, muscovite, sillimanite and/or kyanite, plagioclase, quartz. Accessory minerals are zircon, apatite, ilmenite, rutile, graphite, pyrite, chalcopyrite, pyrrhotite. In the uppermost 500m, Ca-richer rocks of probably tuffitic or epiclastic origin and amphibolites are interlayered with metapelites. The calic-potassic rocks of this interval have as major constituents garnet, hornblende, biotite, plagioclase, K-feldspar, sphene. The assemblages encountered are commonly not equilibrium parageneses, but rather a mixture of former high-grade parageneses, relics of early-formed minerals, and late minerals related to the P-retrograde and T-retrograde history.

Garnet is almandine-rich (typically 70-74% Alm-component). All the microprobe analyses obtained so far show homogeneous compositions from core to rim. The relatively high temperatures required for homogenization are confirmed by garnet-biotite thermometry. The high-temperature state of equilibration was reached at 660 to 710OC, between 5 and 8 kbar (REINHARDT & KLEEMANN 1989, REINHARDT et al. 1989).

Uplift-related reaction textures include sillimanite + biotite formed at the expense of garnet and muscovite, and ilmenite enclosing rutile (garnet + rutile > ilmenite + aluminosilicate + quartz). Many samples contain late muscovite, having replaced biotite and aluminosilicates. Of particular importance for the earlier metamorphic history is early-formed sillimanite enclosed in garnet. The P-T history involved early low- to medium-pressure conditions, then medium-pressure, and finally low-pressure/high-temperature conditions. As yet, there is no unequivocal evidence that thes rocks have experienced true high-pressure conditions.

If some preliminary evidence for high pressures obtained from metabasite samples (O'BRIEN, pers. comm.) is substantiated, it must be resolved whether HP conditions are obscured in the metapelites due to extensive deformational-metamorphic overprinting, or whether certain metabasites had a different metamorphic history as part of a separate tectonic unit.

further reading: REINHARDT et al. (1989), REINHARDT & KLEEMANN (1989)

5.The late- to post-Variscan brittle deformation history of the KTB pilot drill hole (G.ZULAUF)

Cataclastically deformed rocks are very abundant in the cores of the pilot hole. By means of cross-cutting relationships of veins, faults, sense of slip and synkinematic mineralization type within the different faults, we can distinguish phases of cataclastic deformations which were accompanied by retrogressive metamorphic conditions (Fig.8). The oldest brittle deformation features are subvertical tension gashes (filled with prehnite, epidote, quartz, potash feldspar) which are probably related to the intrusion of the nearby late Variscan Falkenberg granite.

The gashes were succeeded by late-Variscan reverse faults which have accommodated most of the brittle shear strain. These faults have formed under metamorphic conditions of the prehnite-actinolite facies and are crosscut by late-Variscan lamprophyres. Within the faults of the paragneisses, a conspicuous enrichment of graphite is present.

In the deeper part of the hole (> 3000m) one can distinguish two generations of late-Variscan reverse faults. Both dip to the E. The oldest faults display dip-slip movements (E-W compression). The younger ones are characterized by oblique-slip movement (ENE-WSW compression). In the middle and upper part of the hole, there is only one generation of late-Variscan reverse faults which are related to NE-SW compression.

The younger post-Variscan reverse faults have developed during a phase of N-S compression. At ca. 3700m, a switch from metamorphic conditions of the zeolithe facies to the prehnite-actinolite facies is indicated by the mineralization. After these phases of reverse faulting, strike-slip faults have formed. They are rare in the cores but are abundant in outcrops adjacent to the drill-site where they have formed during NNW-SSE to N-S compression.

The youngest brittle deformation features are normal faults which have formed during metamorphic conditions of the zeolithe facies. They comprise two generations. One has developed under N-S extension. The other reflects NE-SW extension.

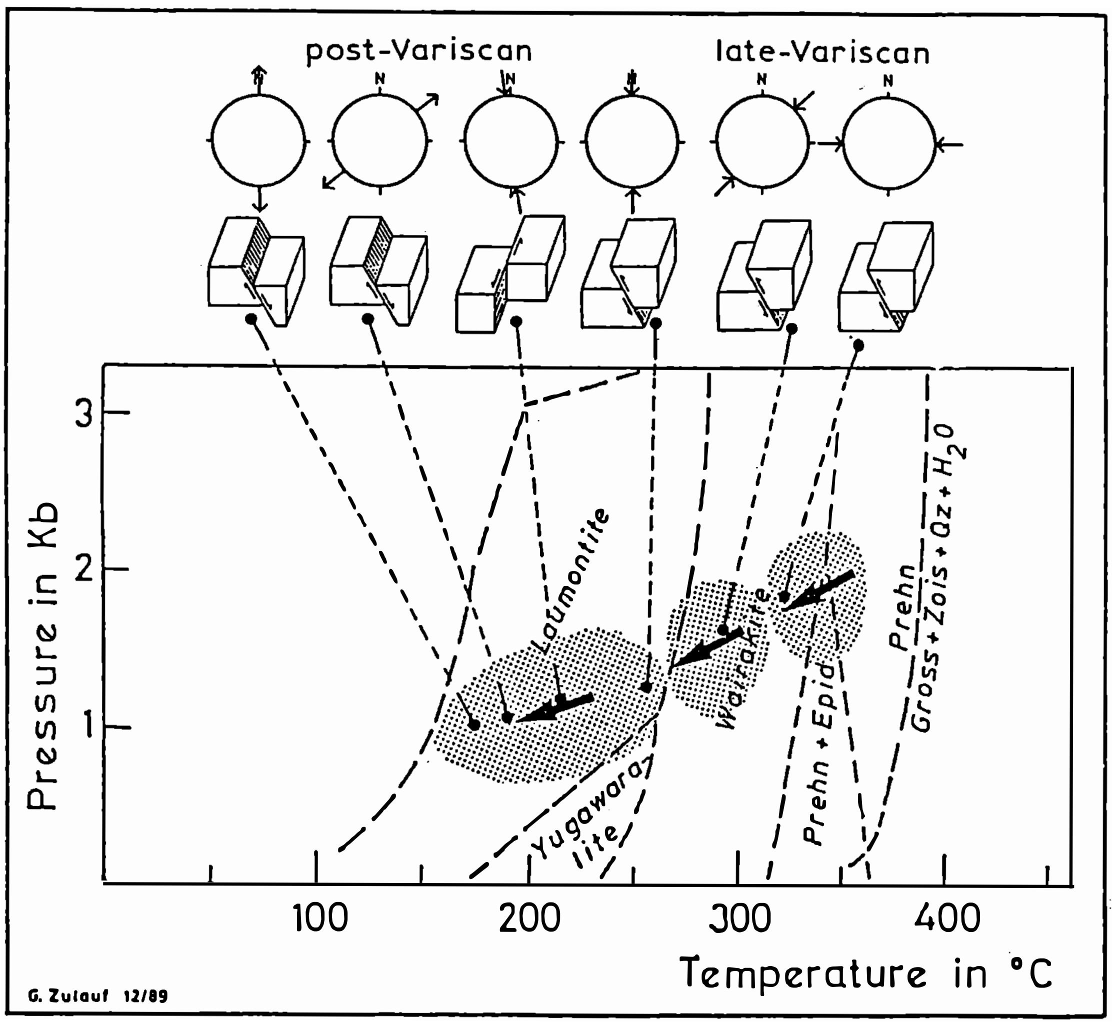

Fig. 9: Relations between metamorphic conditions and brittle deformation phases. A high late-Variscan geothermic gradient is presumed. The directions of compression (arrows point to the circle) and extension (arrows point away from the circle) are indicated in the upper part of the figure.

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SAXOTHURINGIAN ZONE

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REGIONAL GEOLOGY

As laid out in the introductory chapter by FRANKE, the Saxothuringian Zone occupies an internal position on the N flank of the Variscan Fold Belt in Germany. Its northern part, the Mid- German Crystalline Rise, represents the active, southern margin of the Rhenohercynian Basin to the N. The southern, less metamorphosed part represents a separate, Saxothuringian Basin. It is composed of an extensive parautochthonous Palaeozoic sequence ("Thuringian" Facies), which has been overthrusted from the SE by the allochthonous "Bavarian" Facies. The Bavarian facies rocks represent the bathymetrically deeper part of the Saxothuringian Basin. The Bavarian-type allochthon, in its turn, is overlain by crystalline nappes, which show close affinities with rocks encountered at the northern margin of the Moldanubian Zone (Zone of Erbendorf-Vohenstrauß = ZEV, the western part of the Tepla-Barrandian Terrane; see the contributions by FRANKE and by BLÜMEL). The crystalline allochthon in the Saxothuringian Zone can be regarded as a tectonic outlier of the Tepla/Barrandian Terrane.
The following lines summarize the stratigraphy and tectono- metamorphic development of the area. For details of the stratigraphy, the reader is referred to the reviews in FRANKE (1984b), HOPPE & SEIDEL (1974) and GANDL (1981).

STRATIGRAPHIC RECORD (Fig.1)

The Thuringian facies realm is characterized by sediments deposited in relatively shallow water. The Cambrian and Ordovician is composed of neritic clastic sediments (mainly quartzite/shale alternations), with occasional carbonates. Important outcrops of marbles in the core of the Fichtelgebirge Antiform are probably of Cambrian age (see the discussion in STEIN 1988). The derivation of the clastic materials is unknown. Since the deeper-water sediments of the "Bavarian" facies realm have been laid down in a position to the SE of the Thuringian facies, terrigenous material can only have been imported from the NW or else by axial transport. From a late Ordovician quartzite,

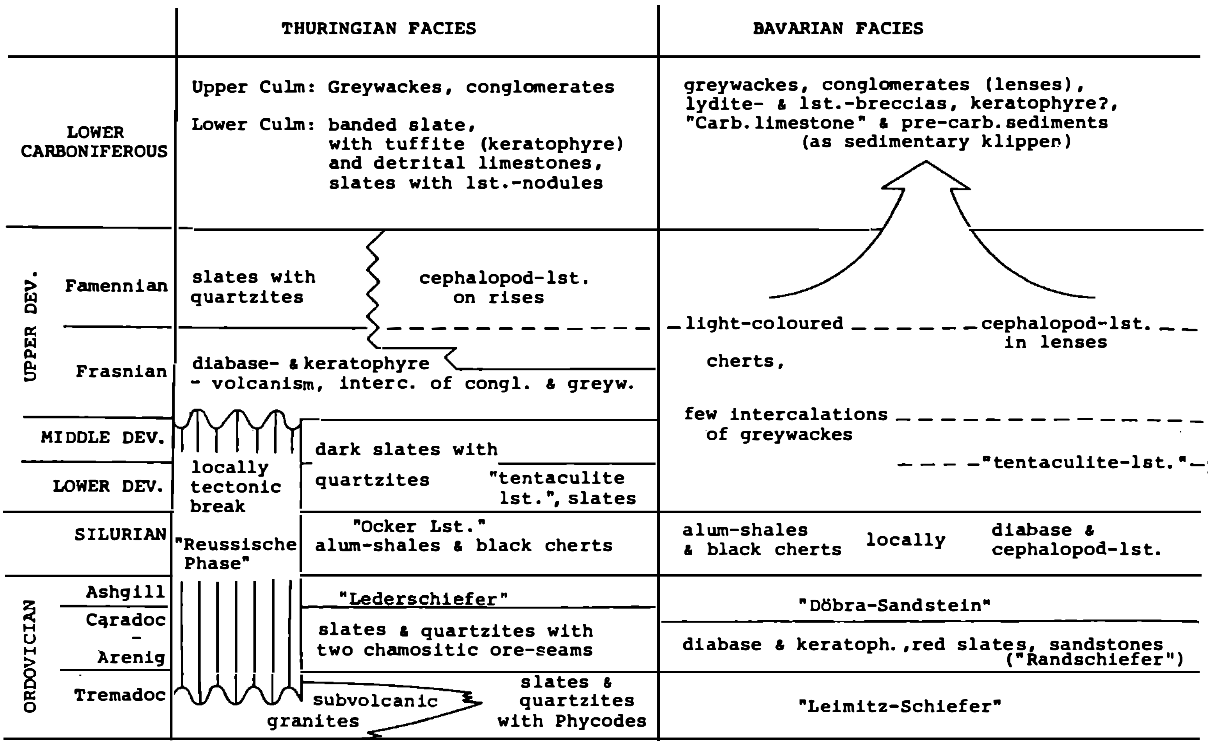

Fig. 18: Lithologic units and biostratigraphy of Ordovician through L.Carboniferous in the western part of the Saxothuringian Zone (modified after v. GAERTNER et al., 1968)

Fig. 1: Stratigraphy of the unmetamorphosed Palaeozoic sequences in the Saxothuringian Belt (from BEHR et al. 1982)

GRAUERT et al. (1973) have reported detrital zircons crystallized at about 560 Ma, which document a Cadomian event in the source area.

From the Late Ordovician onwards, the input of coarser grade clastic materials is greatly reduced, and the sequence is dominated by dark shales with pelagic fossils (graptolites, conodonts, dacryoconarids and rare ammonoids). The latest member of the Ordovician is a diamictite with occasional striated stones, which relate to the Saharan glaciation. The black graptolite shales of the Silurian probably record the post- glacial sea-level rise.

The Devonian is essentially composed of shales, with few and thin intercalations of fine grained sandstones which are still to be found at the Devonian/Carboniferous boundary. These clastics are probably derived from the Mid-German Crystalline Rise.
In Frasnian time, a narrow, NE-trending uplift has shed coarse- grained conglomerates and greywackes both towards the NW and the SE. These clastic sediments are devoid of metamorphic rock fragments, and contain only magmatic and sedimentary clasts of the Ordovician through Devonian "Thuringian" sequences. The uplifted area probably

corresponds to the brachyanticlinal structure of the Saxonian "Granulitgebirge" in E-Germany - possibly a Devonian metamorphic core complex.
The Lower Carboniferous is composed of dark shales, and - from the basal Viséan onwards - flysch sediments, which represent middle and outer fan environments.

Volcanism has a first maximum during the Ordovician. Felsic lavas and intrusives are widespread all across the Saxothuringian basin, from the Schwarzburg Anticline (BANKWITZ et al. 1989) over the Frankenwald ("Hirschberg Gneiss") into the Fichtelgebirge ("Epigneis"). Radiometric studies have yielded ages between 450 and 510 Ma, which is in accord with the intercalation of these rocks among Lower Ordovician clastic sediments. Basaltic volcanics are relatively rare; their composition resembles that of alkali-basalts (OKRUSCH et al. 1989, see also this volume). The Ordovician magmatism is clearly of intra-plate character; together with the thick sedimentary sequence, it indicates Early Palaeozoic rifting.

A second volcanic episode occurred in the Frasnian, in a NE- trending belt which also comprises the conglomerate-producing uplift mentioned above. The volcanic rocks are intercalated with, and occur as pebbles in the Frasnian clastic sequence. Embryonic coral/stromatoporoid reefs on volcanic mounds are proof of only moderate depths in the hemipelagic Devonian of the Thuringian facies.

Ordovician and Devonian rocks resembling the Thuringian facies also occur N of Erbendorf, at the southeastern margin of the Fichtelgebirge, where they have been overthrusted by the greenschists and higher-grade metamorphic rocks of the Tepla/Barrandian (Figs.3,4). As a peculiarity, the Erbendorf sequence contains greywacke turbidites (flysch) already in the Famennian (ADAM & REUTER 1981). The greywackes contain chromite, probably derived from obducted ophiolites (LUDWIG 1968).

The Bavarian facies Palaeozoic rocks generally represent deeper- water environments. Neritic clastic sediments with trilobite faunas are restricted to the Cambrian and Tremadocian. The Ordovician is dominated by a volcano-sedimentary sequence ("Randschiefer"), composed of bimodal volcanic rocks, pelagic shales, and some sandstone turbidites. The volcanic rocks have been extruded in an intra-plate setting (WIRTH 1978, see also the contribution by OKRUSCH et al.). A late Ordovician sandstone member ("Döbra Sandstone") can be read as the signal of the Saharan glaciation. The tectonic unit dominated by the "Randschiefer" contains, in its upper part, also Silurian sediments and a volcano-sedimentary association of Lower Devonian age (HAMMANN et al. 1989).

The Silurian is made up of black shales and cherts with graptolites. Light-coloured cherts with radiolarians represent the Devonian, and, locally, part of the Lower Carboniferous (BRAUN & SCHMIDT-EFFING 1988, SCHMIDT-EFFING 1988).
The Lower Carboniferous is composed of a flysch sequence, which represents slope and trench environments. The flysch contains pebbles and olistoliths derived from Cambrian through L.Carboniferous sequences of the Bavarian facies, which now occur in nappes overlying the flysch (see Fig.11).

PETROLOGY AND AGE OF THE MÜNCHBERG CRYSTALLINE NAPPES

In the Münchberg nappe pile, the unmetamorphosed "Bavarian" facies Palaeozoic sequences are overlain by several units which exhibit, from bottom to top, increasingly higher metamorphic grades (Figs.3,5):
"Phyllite-Prasinite Sequence" - a greenschist grade sequence composed of calc-alkaline mafic volcanic rocks (see the contribution by OKRUSCH et al.), intercalated with phyllites. The phyllites have yielded Proterozoic acritarchs (PFLUG & REITZ 1987, REITZ & HÖLL 1988). We are probably dealing with recycled Cadomian basement. Numerous lenses of serpentinite are intercalated at the boundary against the overlying unit. It is uncertain, wether the emplacement of these ultramafics relates to the Variscan or to an older orogenic cycle.

"Rand-Amphibolit" - massive amphibolite, partly garnetiferous, in epidote-amphibolite facies. The bottom and top have been transformed into mylonites; in the lower mylonite, the amphibolite has been partly retrogressed into greenschist facies. The age of the magmatic protolith is unknown.

"Liegend-Serie" - mainly meta-pelites and -greywackes, with large intrusive bodies of orthogneiss ("Augengneis"), and some metagabbro and -granodiorite. The age of the metasediments is unknown (?Proterozoic?); the orthogneiss has been dated at 499 +/- 20 Ma by Rb/Sr-WR (SÖLLNER et al. 1981a); U/Pb data on zircons and monazite from meta-gabbro and -granite likewise indicate intrusion at about 500 Ma (GEBAUER & GRÜNENFELDER 1979). These intrusive rocks record the same phase of crustal thinning and magmatism, which is also detectable in the unmetamorphosed Saxothuringian sequences (see above).

"Hangend-Serie" - a sequence dominated by mafic rocks such as amphibolites and hornblende gneisses, with only subordinate metasedimentary intercalations. At the base of the H.-S., there are intercalations of eclogite. Like some other eclogite bodies and lenses of serpentinite in the upper part of the "Liegend- Serie", these eclogites possibly represent a separate tectonic unit between the "Liegend-" and "Hangend-" sequences.

The age of the hornblende gneisses and amphibolites is largely unknown; the eclogite is derived from a MORB-type basalt crystallized at 525 Ma (U/Pb zircon, GEBAUER & GRÜNENFELDER 1979).

METAMORPHIC DEVELOPMENT

In the higher-grade members of the Münchberg pile, metamorphism is essentially two-stage: high- to medium-pressure conditions were followed by syntectonic re-equilibration at decreasing temperatures during nappe-thrusting. In the "Liegend-Serie", the pre-mylonitic assemblages are garnet + kyanite + biotite + phengitic muscovite + plagioclase + quartz + rutile + ilmenite (in the metapelites), and albite + zoisite + phengitic muscovite + quartz + rutile (in metagranitoids). For one metapelite, BLÜMEL (1986) obtained 8.2 kbar and 607 +/- 50 ^{o}C (GRAIL barometer, gt- bt thermometer). Mylonitization has started under these high metamorphic conditions, as it is demonstrated by newly grown garnet, and recrystallized kyanite, plagioclase and mica in high- T mylonites.
The eclogites originated from two geochemically different protoliths (MOR-type and high-Al-basaltic, MATTHES et al. 1975), probably of supracrustal origin. This is confirmed by intercalations of calcareous metapelites which contain textural relics of HP- and MP-assemblages (BLÜMEL 1986). Jadeite solid solution of less than 65% (O'BRIEN, unpubl.) gives P = 13 kbar for 600 ^{o}C; this minimum pressure increases to approx. 25 kbar, if the assemblage paragonite-omphacite-kyanite-H_2O and rare indications of former coesite inclusions in garnet are considered OKRUSCH et al., in press).

The timing of metamorphism in the Münchberg rocks is complex (see also the contribution by AHRENDT). The high-pressure metamorphism possibly occurred already in Silurian time (Rb/Sr-data of MÜLLER- SOHNIUS et al. 1987 and SÖLLNER et al. 1981a). Numerous isotope data ranging in the Early Devonian probably reflect early stages of uplift and cooling (STOSCH & LUGMAIR 1986, 1987; 395 Ma Sm/Nd mineral isochron, Rb/Sr mineral isochron of 394 +/- 14 Ma, and similar zircon data in GEBAUER & GRÜNENFELDER 1979). K/Ar ages on hornblende and micas from the "Rand-Amphibolit", "Liegend-Serie" and "Hangend-Serie" (KREUZER et al. 1989) range between 340 and 410 Ma, with a clear maximum around 380 Ma, without systematic differences between the three units. The cooling ages of hornblendes and micas are not significantly different from each other, which indicates rapid uplift and cooling. Cooling-ages from the metapelites in the phyllite/prasinite sequence are significantly younger (approx. 365 Ma) than those in the overlying, higher-grade units, which suggests that the greenschists were accreted later. K/Ar data from the clay-fraction of shales in the fossiliferous sequences of the Bavarian facies nappes, as well as from the Thuringian facies autochthon, range between 308 and 333 Ma, but have often been reset to Permian ages (AHRENDT et al., unpubl.). The data is in reasonable accord with the stratigraphic constraints on the age of very-low- grade metamorphism and deformation (see below).

Since the thickness of the Münchberg Klippe only amounts to approx. 4 km, the Thuringian autochthon is generally of very low metamorphic grade. The Carboniferous flysch of the Teuschnitz Syncline, to the NW of the Münchberg Klippe, only shows a weak fracture cleavage. In the central part of the Saxothuringian Basin, higher temperatures (up to greenschist facies) have only been attained in a WNW-trending transverse zone, which has experienced high heat-flow during and after tectonic deformation, and was intruded by granites in Late Carboniferous or Permian time (FRANKE 1984b, see also Fig.5).
Deeper structural levels with higher metamorphic grade are exposed in the Schwarzburg Anticline at the NW margin of the Saxothuringian Basin, where Early Palaeozoic and ?Proterozoic rocks up to greenschist grade have been brought to the surface by SE-directed thrusting (see below).
Higher metamorphic grades in the Saxothuringian (par)autochthon are also widespread in the Fichtelgebirge to the SE of the Münchberg Klippe, probably due to increasing tectonic burial towards the SW. In the Fichtelgebirge, metamorphism increases from the chlorite zone up to the staurolite-andalusite-muscovite zone, the latter indicating 2-3 kbar at 520-550 ^{o}C (MIELKE et al. 1978). Since the isograds have been folded by the D3 deformation, the higher-grade rocks occur in the core of the Fichtelgebirge antiform (see below, and the relevant contribution by BLÜMEL). For the same reason, the metamorphic grade decreases further S, in the Waldsassen Synform, and then shows a gradual increase across the Saxothuringian/Moldanubian boundary.

TECTONIC DEVELOPMENT

The most important tectonic feature encountered in the Saxothuringian Zone is the existence of a pile of nappes (the Münchberg Klippe), in which the stratigraphic and the metamorphic sequence are inverted (from top to bottom): Carboniferous, Silurian + Devonian, Ordovician, greenschist, epidote- amphibolite, kyanite-bearing gneisses + amphibolite + eclogite. After BEHR et al. (1982), this sequence can be explained in a subduction model, in which Palaeozoic sediments of the Saxothuringian basin (and probably also Cadomian basement rocks) are subducted towards the SE, and then obducted; the rising early-Variscan metamorphic rocks would then have sequentially accreted, on their way toward the surface, units of increasingly lower metamorphic grade and of younger age, until the newly assembled pile was emplaced, in late Lower Carboniferous time, on the Thuringian facies of the foreland (Fig.2).

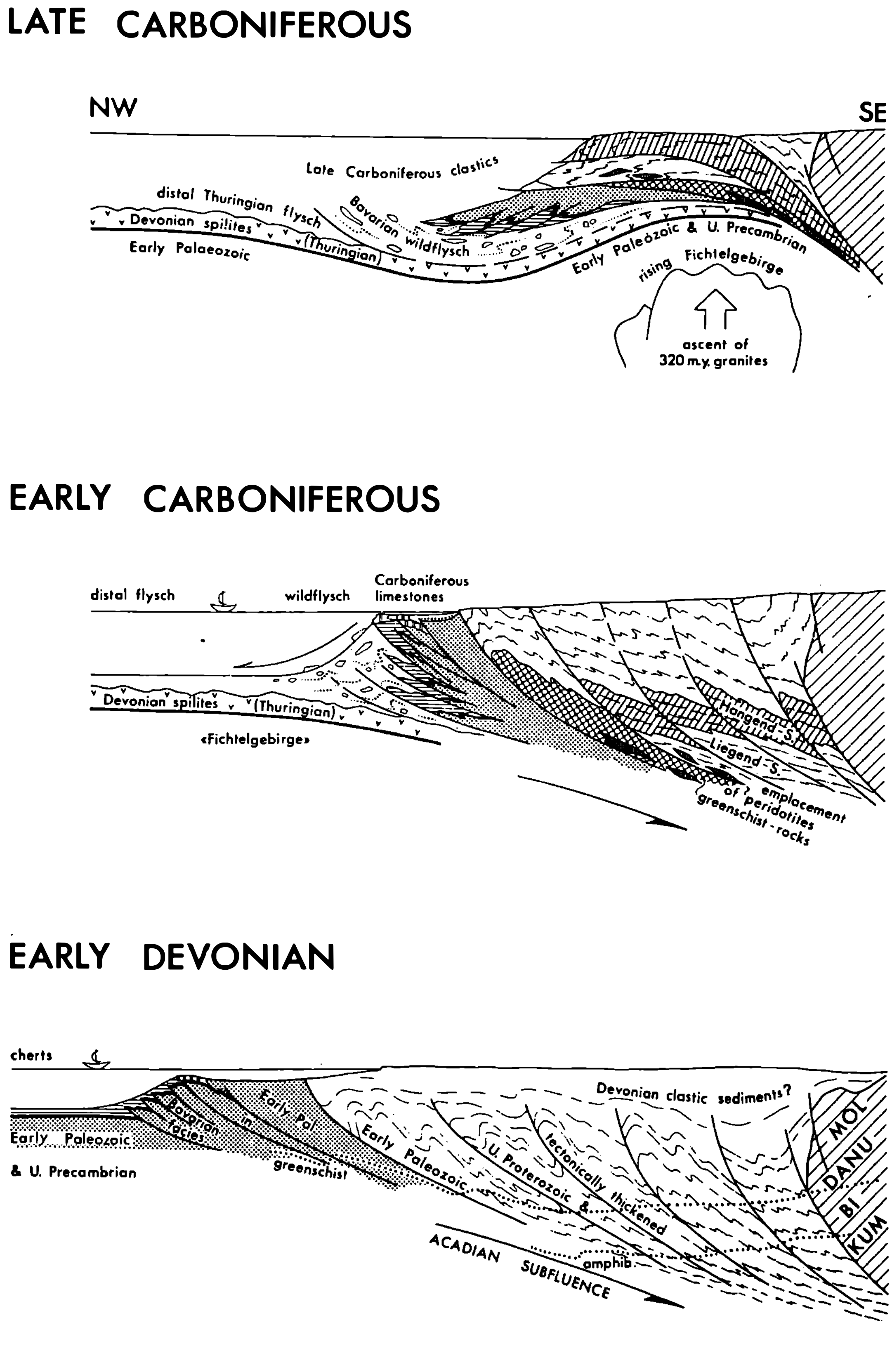

Fig. 2: Geotectonic "comic strip" of the development of the Saxothuringian Nappes (from BEHR et al. 1982)

Grossly NW-directed emplacement of the nappes is documented in the D1 deformation in the Saxothuringian allochthon (Bavarian facies unmetamorphosed nappes), and in the Thuringian autochthon of the Frankenwald and Fichtelgebirge areas (FRANKE 1984a,b; STEIN 1988). The intensity of D1 is seen to decrease toward the NW, so that, in the NW part of the Saxothuringian Basin, D2 is the first and main deformation.

The D2 deformation shows an opposed facing direction (toward S or SE). It is uncertain, whether this reversal is due to backthrusting in a generally NW-driving regime, or else represents a crustal-scale reversal of tectonic polarity (see the discussion in FRANKE 1989c and WEBER & VOLLBRECHT 1989). In the Fichtelgebirge, D2 is synchronous with the peak of low-pressure metamorphism. The lag of metamorphism behind the tectonic burial achieved during the D1 deformation (nappe thrusting) is readily explained with the poor thermal conductivity of rocks.

D3 has only been detected in the Fichtelgebirge and has brought about open folds with subvertical axial planes; the Fichtelgebirge Antiform is a major D3 structure (STEIN 1988). D3 refolds the isograds of low-pressure metamorphism (WAGENER-LOHSE & STEIN, unpubl.).

Since, in E-Germany, tectonic klippen of the Münchberg type are unconformably overlain by a latest Lower Carboniferous intra- montane molasse, and the youngest rocks affected by the deformation are also of late Lower Carboniferous age, all these deformational events must have taken place in the latest Lower Carboniferous (approx. 320-330 Ma).

The main deformation of the Münchberg crystalline rocks correlates with the Early Devonian, pressure-dominated metamorphism, and has been accomplished before the metamorphic rocks were emplaced over the unmetamorphosed Palaeozoic sequences.

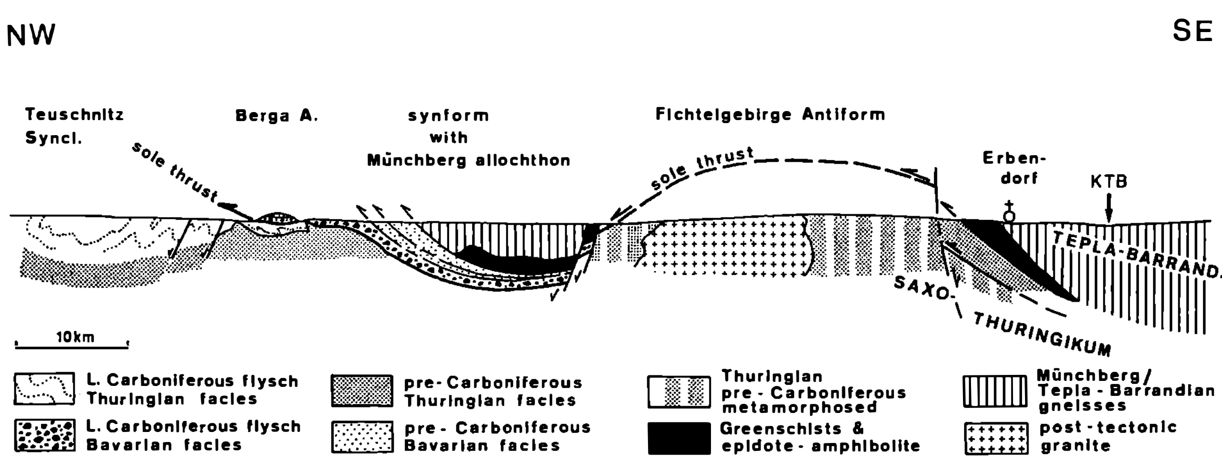

Fig. 3: Diagrammatic cross-section through the Saxothuringian Belt (from FRANKE 1989)

The synmetamorphic mineral lineation and asymmetric porphyroclasts indicate transport towards the SW. Polyphase refolding during uplift and cooling records that the direction of horizontal compression has rotated anti-clockwise into the direction of final emplacement toward the WNW (MOEHRMANN et al. 1989). The Münchberg rocks do not show any indication of a low- pressure metamorphic overprint - as indicated by the cooling ages, they had reached an elevated tectonic position already in the Devonian, so that they escaped the Lower Carboniferous low- pressure metamorphism going on at deeper levels.

Since calc-alkaline greenschists and medium-pressure metamorphic rocks formed around 380 Ma also occur at the NW margin of the Moldanubian region (Zone of Erbendorf-Vohenstrauß = ZEV, as part of the Tepla/Barrandian Terrane, see the contribution by BLÜMEL, the contribution by OKRUSCH et al., and MATTHES & OLESCH 1989), the crystalline rocks of the Münchberg Klippe must be interpreted as an outlier of the Tepla/Barrandian (Fig.3; see also Figs. 2-5 in the introductory chapter by FRANKE). The problematic nature of the tectonic boundary between the Saxothuringian and the Tepla/Barrandian is briefly treated in the introductory chapter by FRANKE.

The Saxothuringian Terrane and the boundary region with the Moldanubian Region further S (Moldanubian s.str. and Tepla/Barrandian) has been intruded by late- to post-tectonic granites, between approx. 320 and 290 Ma (RICHTER & STETTNER 1979, BESANG et al. 1976; see also the contribution by BLÜMEL). The composite granite massif of the Steinwald-Flossenbürg- Leuchtenberg granites has been intruded across the terrane boundary between 313 +/-17 (Rb/Sr WR, KÖHLER et al. 1974, Leuchtenberg; 311 +/-4 Ma Rb/Sr WR, WENDT et al. 1986, Falkenberg) and 283 +/-11 Ma (Flossenbürg, KÖHLER et al. 1974).

The main structural elements of the Saxothuringian Zone, and their tectonic interpretation are also corroborated by recent geophysical data. A reflection-seismic survey (DEKORP-4 line; DEKORP 1988, SCHMOLL et al. 1989, GEBRANDE et al. 1989) clearly shows a synformal array of reflections under the Münchberg Klippe, as well as the large-scale synforms and antiforms. Magnetotelluric soundings have revealed a coherent conductive layer (sediments!) at shallow depth under the crystalline klippe (HAAK & BLÜMECKE in KTB 1986). The SE boundary of the Saxothuringian Zone, in near-surface levels, is not clearly detectable in the seismic section; however, there is a zone of high reflectivity and seismic velocities up to 7 km/s dipping southwards from approx. 3 s TWT down to the Moho - possibly a slice of (ultra)mafic rocks inserted at the Saxothuringian/Tepla- Barrandian terrane boundary.

One possible interpretation of the structural relationships in the Saxothuringian Zone and the NW part of the Moldanubian region is depicted in Fig.4.

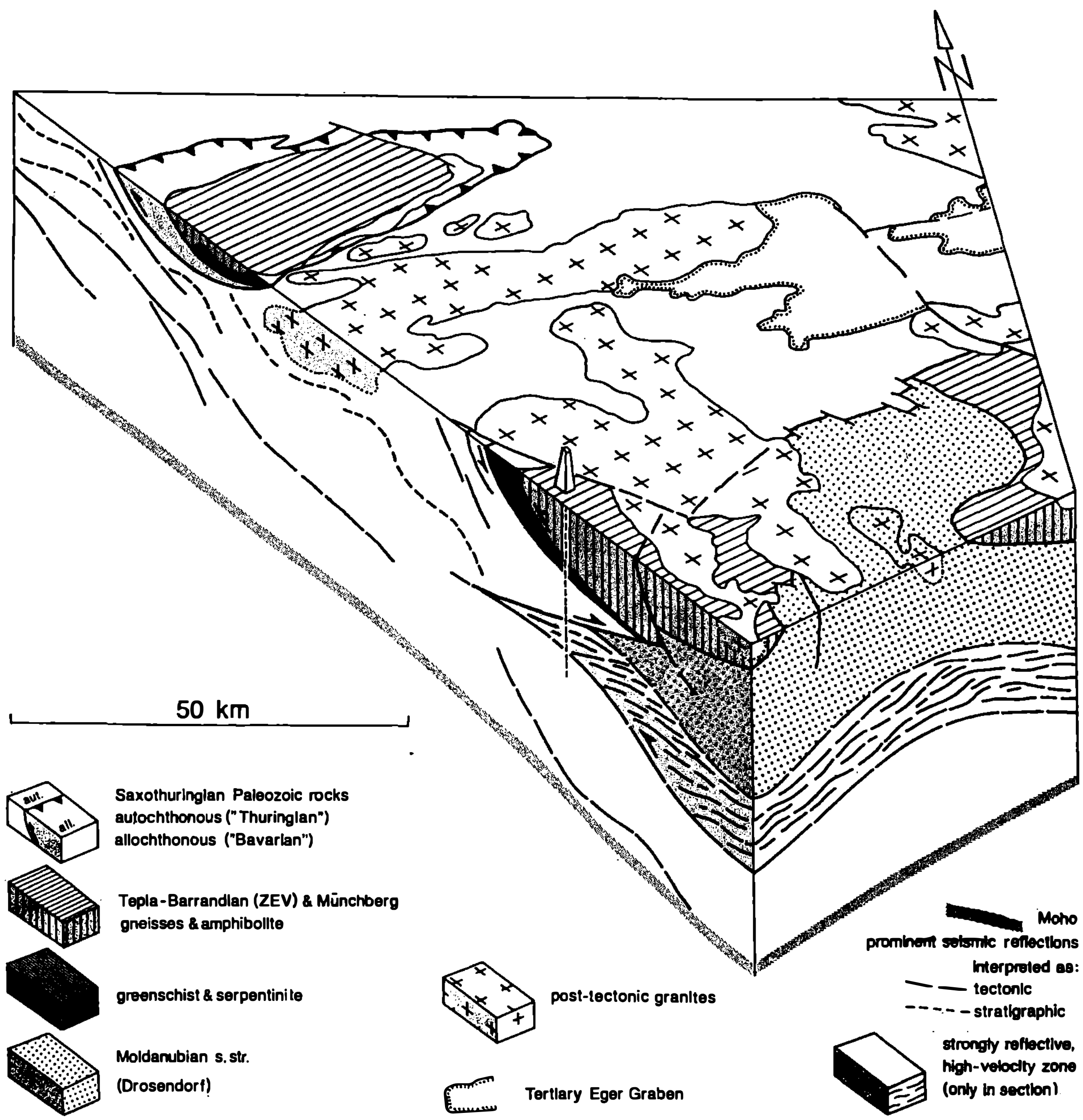

Fig. 4: 3-D structural model of the Saxothuringian/Moldanubian boundary region around the KTB drilling site (from FRANKE 1989)

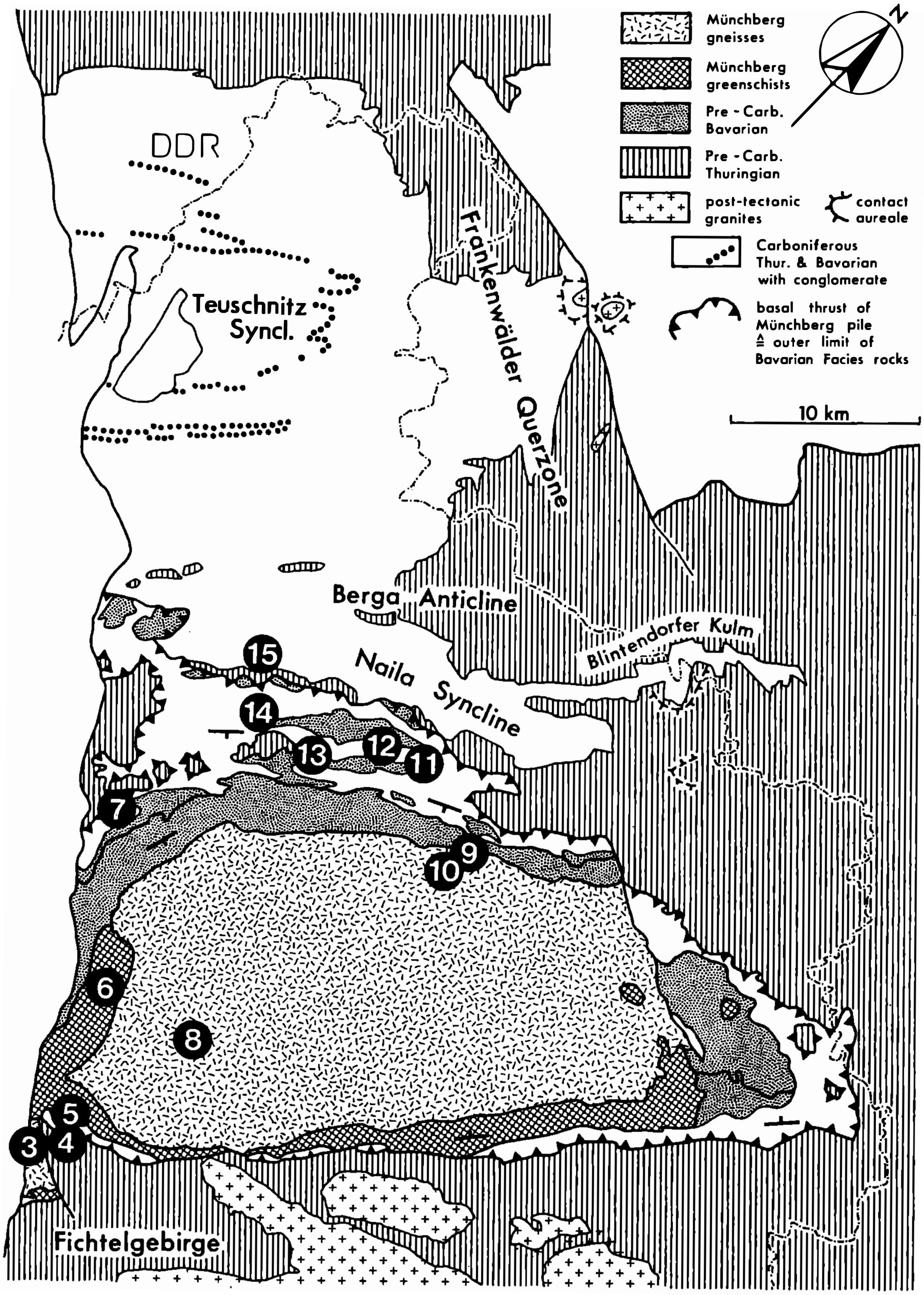

Fig. 5: Geological map of the Münchberg Klippe and the surrounding autochthon (from FRANKE 1984a), with location of stops nos. 3-15 (for nos. 1,2 see Fig. 6)

DESCRIPTION OF STOPS

Stop No. 1 - weakly metamorphosed ?Ordovician of the Erbendorf Palaeozoic Unit (E.STEIN)
Roadcut at Kranichstein Hill, 3 km SE of Trevesen
TK 25: 6137 Kemnath, R 44 99 850/ H 55 25 500

The roadcut exposes slates and sandstones which are assigned, on lithological grounds, to the L.Ordovician "Phycoden-Schichten" of the Thuringian facies. The low metamorphic grade is characteristic of the Erbendorf Palaeozoic unit, which probably represents a relatively high tectonic unit of the Fichtelgebirge Antiform, and was later downfaulted against the more metamorphosed Palaeozoic sequences immediately to the N (Fig.6, see also stop no.2).
Grey-green finegrained psammitic to pelitic layers alternate, at the mm-cm scale, with grey, corsegrained psammitic layers. Bedding is accentuated by detrital ore particles. In the psammitic layers, it is possible to observe cross lamination and graded bedding.
Bedding has been deformed into several generations of folds. Tight to isoclinal F1 folds with thickened hinges are very rare and only occur at the cm-scale. S1 is bedding-parallel. The structure of the outcrop is dominated by tight, upright folds on the cm- to m-scale, which are characterized by acute hinges. S2 is a prominent fracture cleavage and forms an intersection lineation s2/s1 parallel with the B2 axes.
Fabrics of the D3 deformation observed elsewhere are lacking in this outcrop. Kinkbands with NW-trending kink axes overprint the older structures and are responsible for the steep plunge of the B2 axes. These features are correlated with the regional D4 deformation.

Stop No. 2 - ?Ordovician in greenschist facies on the S flank of the Fichtelgebirge Antiform (E.STEIN)
Crag in the village of Trevesen in the Fichtelnaab Valley
TK 25: 6137 Kemnath, R 44 98 500/ H 55 28 125

The outcrop is situated at the SE flank of the Fichtelgebirge Antiform, and belongs to the main part of the Fichtelgebirge, where Palaeozoic sediments show higher metamorphic grades (see the contribution on metamorphism by BLÜMEL).
A crag of 10-15 m height exposes quartzites and black metapelites, which are assigned, by lithological comparison, with the L.Ordovician "Phycodenschichten", whose age has been ascertained by fossils at other localities. The stop is intended to demonstrate the higher metamorphic grade with respect to the rocks in stop no.1, which are thought to be of the same age, and the tectonic inventory, which is typical of the Fichtelgebirge.

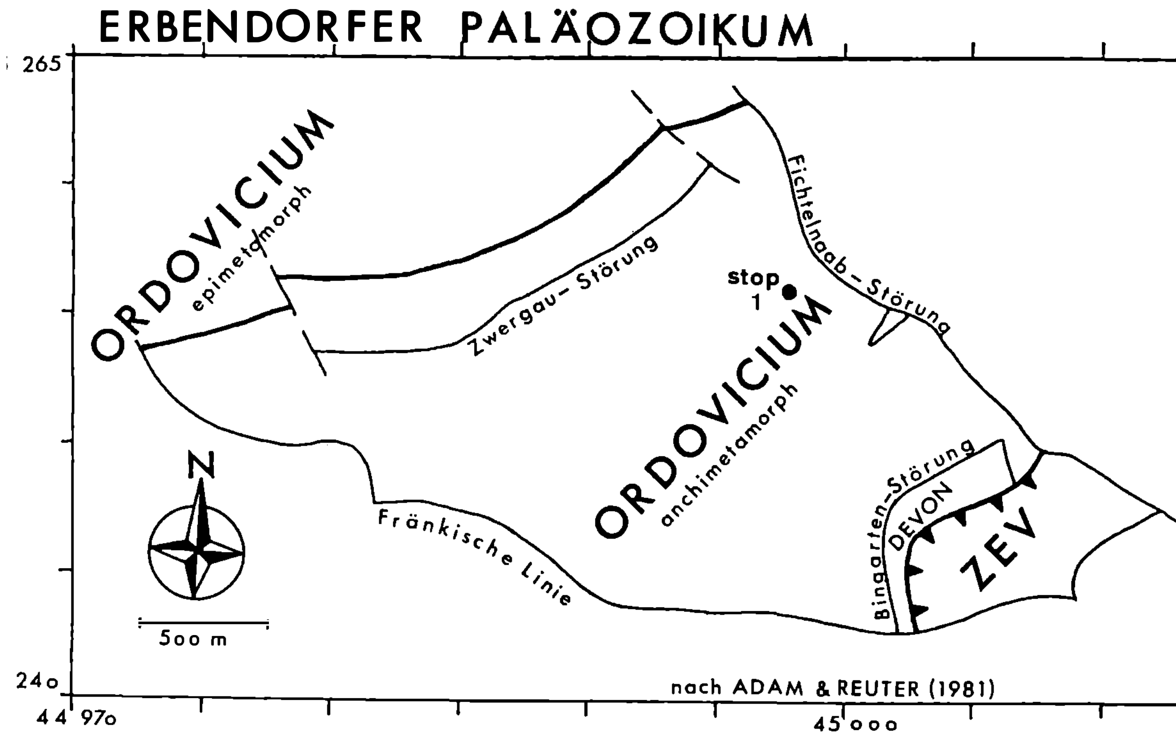

Fig. 6: Location of stop no.1 in the weakly metamorphosed Palaeozoic sequences NW of Erbendorf, between the greenschists and higher-grade rocks of the ZEV (SE) and the greenschist grade Palaeozoic sequences of the Thuringian facies at the SE margin of the Fichtelgebirge

Tectonic structures in the quartzites differ from those in the phyllites. Quartzites show a polyphase deformation (Fig.7). The oldest fabric preserved is a s1 schistosity on the mm-scale, which is preserved in the form of cleavage lamellae between s2 surfaces. The sigmoidal shape of the s1 lamellae is due to D2. S2 is the most penetrative an most prominent fabric. 1 cm thick quartz-rich layers alternate with s2-parallel, thin seams of biotite- and muscovite-rich material. Both s1 and s2 are refolded into open, upright folds on the dm-scale (B3), which trend NE.
In the phyllites, these NE-trending B3 folds are the only ones observed. Due to their high anisotropy, fold morphology and symmetry vary from close monoclinic to open

Fig. 7: Three phases of deformation in the ?Ordovician quartzites at Trevesen (stop no.2), from BEHR et al. 1985.

orthorhombic, either with acute or or with round hinges. The phyllites contain thin intercalations of quartzite which show the same tectonic inventory as the massive quartzites at the top of the outcrop. The phyllites must have undergone the same phases of deformation, but the foliation is composite (ss parallel s1 and s2), so that the different generations are not discernible.

Stop No. 3 - "Liegend-Serie" and "Hangend-Serie" of the Münchberg nappe pile (P.BLÜMEL)
Roadcut at S flank of the Königsstuhl Hill, immediately W of Bad Berneck
TK 25: 5935 Marktschorgast, R 75 900/ H 45 350

The eastern part of the roadcut and an old quarry expose banded hornblende gneisses with hornblende + plagioclase (+ garnet) (+ clinozoisite) (+chlorite) + quartz + titanite in the dark layers, and plagioclase + muscovite (+ biotite) in the leucocratic

layers. Large folds are upright or else show vergence toward W or E; their axes trend NNE.
500 m further W, the roadcut shows garnetiferous Augen-gneisses and blastomylonitic muscovite-biotite gneisses of the Liegend- Serie. They have been deformed into an E-facing antiform and abut against the Hangend-Serie at a subvertical fault.
Folding in both units is ascribed to the D3 deformation in the high-grade rocks of the Münchberg complex (VOLLBRECHT 1981).

Stop No. 4- Basalthrust of the Münchberg Nappe Pile (W.FRANKE)
Quarry of the SCHICKER comp., Rimlasgrund Valley N of Bad Berneck
TK 25: 5935 Marktschorgast, R 75 880/ H 46 300 (shear zone behind crusher)

At the W face of the entrance, Frasnian metabasalts are in tectonic contact with the hornblende gneisses of the preceding stop. The reverse fault dips approx. 60^{o} to the NE and was probably formed in the foreland of the Alpine collision, in Late Cretaceous time.
The quarry exposes Frasnian pillow lavas of the par-autochthonous Thuringian facies. In

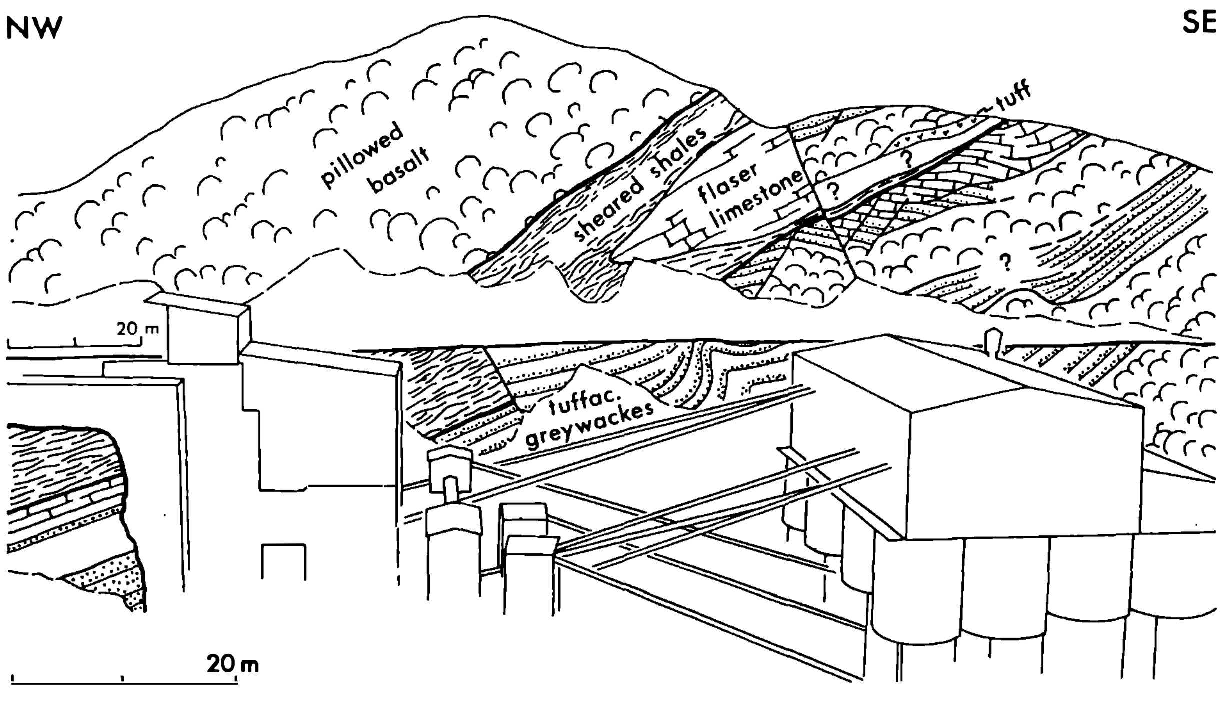

Fig. 8: Shear zone between the "Thuringian" autochthon and the overlying "Bavarian" flysch nappe - SCHICKER quarry (stop no. 4), from FRANKE (1984a)

the N part of the quarry, the metabasalts are overlain by greywackes (derived from th intra-basinal high long-strike of the Saxonian Granulitgebirge) and Frasnian pelagi limestones. This sequence is overlain and partly truncated by a shear-zone developed i L.Carboniferous shales and greywackes of the Bavarian facies, exposed behind the bi crusher. The shales show pervasive shear and contain tectonic lenses of greywackes pelagic limestones and metabasalts (derived from the Thuringian autochthon), as well a greywackes and shallow-water carbonates (Bavarian facies flysch). The metabasalt above the shear zone, in the upper part of the quarry wall, likewise represent a tectoni slice, which is overlain, to the N of the quarry, by another band of sheare L.Carboniferous shale. Tectonic mélange of this kind is regularly encountered at th base of the Münchberg Nappes. Drag folds in the Frasnian sediments indicate transpor toward the NW.

Stop No. 5 - Thuringian metabasalt overlain by sheared L.Carboniferous wildflysch an greenschists (W.FRANKE)
Sawmill of the WIRTH comp., at Hohenknoden N of Bad Berneck
TK 25: 5936 Bad Berneck, R 76 650/ H 47 300

The southern part of the profile exposes Frasnian pillow lavas of the Thuringiar autochthon, which represent the NE-ward continuation of those of the previous stop The metabasalts are overlain by an extremely sheared band of L.Carboniferous shales which are approx. 50 m thick and contain countless fragments of greywackes, variou shales and pyroclastics, metabasalts, and black radiolarian cherts. These competen inserts show strong cataclastic deformation. It is uncertain, if these clasts represen tectonic pickings from the autochthon, or else deformed sedimentary clasts, or both. Th black cherts (a typical lithology of the Bavarian facies Silurian) were probably firs emplaced by debris flows.

The sheared L.Carboniferous rocks are overlain by greenschists and phyllites, which belong to the "Phyllite-Prasinite-Sequence" - the lowermost of the metamorphic nappes in the Münchberg pile.

The sheared L.Carboniferous flysch sediments of stops nos. 4 and 5 show the strong tectonic reduction of the flysch nappe at the southern margin of the Münchberg Massif. The shallow northerly dip observed in both outcrops corresponds to their position at the southeastern margin of the Münchberg Synform.

Stop No. 6 - "Randschiefer Sequence", "Phyllite-Prasinite-Sequence", "Rand-Amphibolit" (W.FRANKE)
Schorgast Valley from the village center of Wirsberg eastward
TK 25: 5835 Stadtsteinach, R 72 040/ H 52 500 (Wirsberg, center)

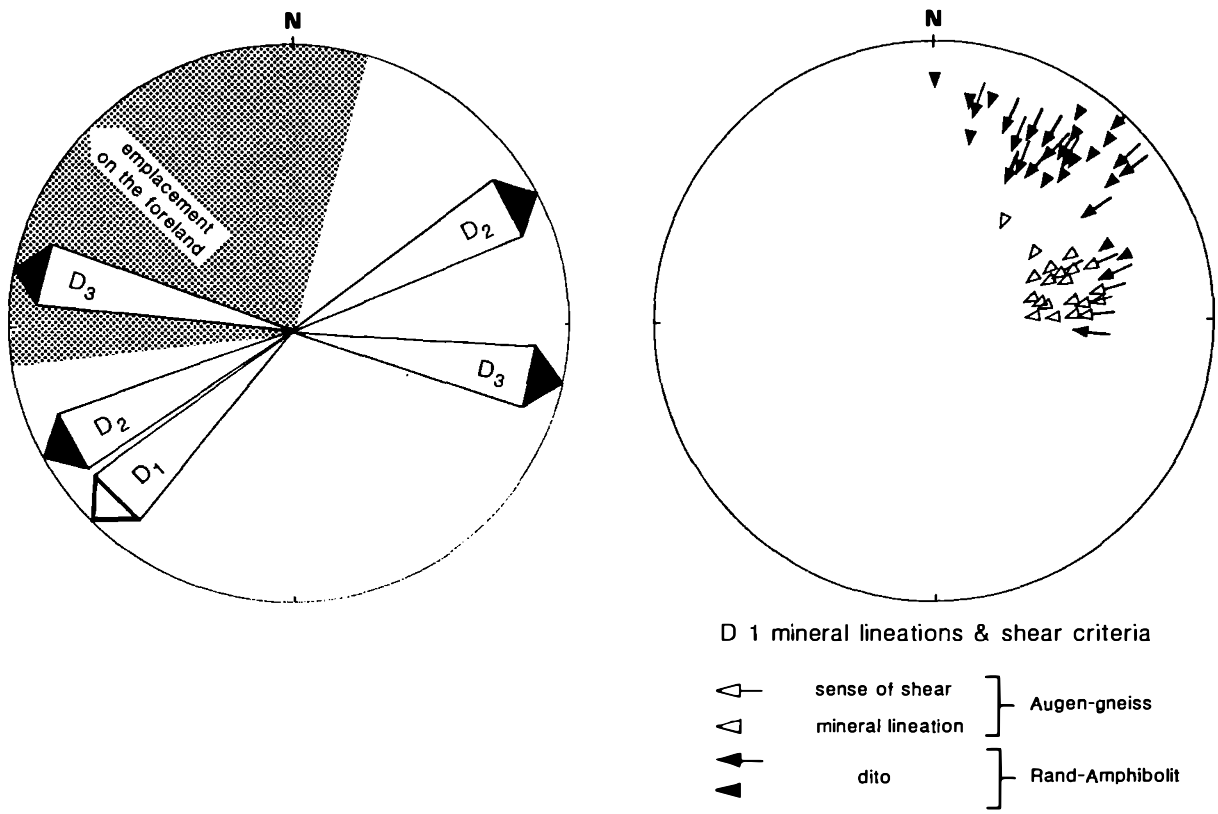

Fig. 9: (left): mineral lineations and shear criteria (sigma- clasts) in the metamorphic rocks of the Schorgast Valley (stop no.6); (right): tectonic polarity of successive stages of tectonic deformation in the metamorphic nappes of the Schorgast Valley. Both diagrams: Schmidtnet, lower hemishere; after MOEHRMANN et al. 1989.

The Schorgast Valley exposes a complete cross-section through the middle part of the Münchberg nappe pile. The tectonic sequence dips approx. 40^{o} to the NE, due to a late- or post-Variscan tilt along the "Franconian Line", the boundary fault of the basement against the Mesozoic foreland.

The knoll in the centre of the village consists of quartz- keratophyre (meta-rhyolite) and metabasalt, both probably of Ordovician age. The roadside outcrop at the NW flank of the knoll shows yellowish-grey shales and black shales & cherts; the latter are most probably of Silurian age. All these rocks are of very low metamorphic grade and form part of the "Randschiefer" nappe.

The overlying "Phyllit-Prasinit" nappe will be visited in crags on the N slope of the valley: banded greenschists (meta-tuffs) alternate with massive greenschists (metabasalts) and quartz- phyllites. Some outcrops show deformed, yet fairly well-preserved pillows. The greenschist nappe is overlain by the "Rand-Amphibolit" nappe, exposed along a narrow path on the N slope. The transitions from massive amphibolite in the centre (also exposed in a quarry) into the amphibolite mylonites above and below can be studied in numerous crags.

The Schorgast Valley turns toward SSE along the boundary with the overlying Augen-gneisses of the "Liegend-Serie", which are exposed in crags on the E slope. The Augen-gneisses have undergone ductile deformation with asymmetric clasts indicating transport toward SW. The boundary has suffered some cataclastic overprint.

Stop No. 7 - Basal thrust of the Münchberg Nappe Pile (W.FRANKE)
Quarry of the HEISS comp., E of Stadtsteinach
TK 25: 5835 Stadtsteinach, R 66 460/ H 59 300

The quarry exploits Frasnian metabasalt of the Thuringian autochthon. Two hematite seams at resp. near the top of the lavas represent the "Lahn-Dill" type of iron-ore. The lavas are overlain by pyroclastics and shales (still of Frasnian age).
This sequence is abruptly cut by a bedding-parallel fault, at which the Bavarian facies Carboniferous has been transported over the Thuringian autochthon. The Carboniferous consists of strongly sheared shales and some greywacke and conglomerate beds which show brittle boudinage. Numerous lenses of pelagic limestone and metabasalt up to 1m size are bounded by shear surfaces, but probably represent components of a deformed debris flow.
Brownish shales at the E margin of the quarry, which overlie the Carboniferous sediments, have been dated as Middle Cambrian (GANDL, pers.comm.). Like many other slabs of exotic rocks contained within the Carboniferous flysch, the Cambrian shales probably represent olistoliths.

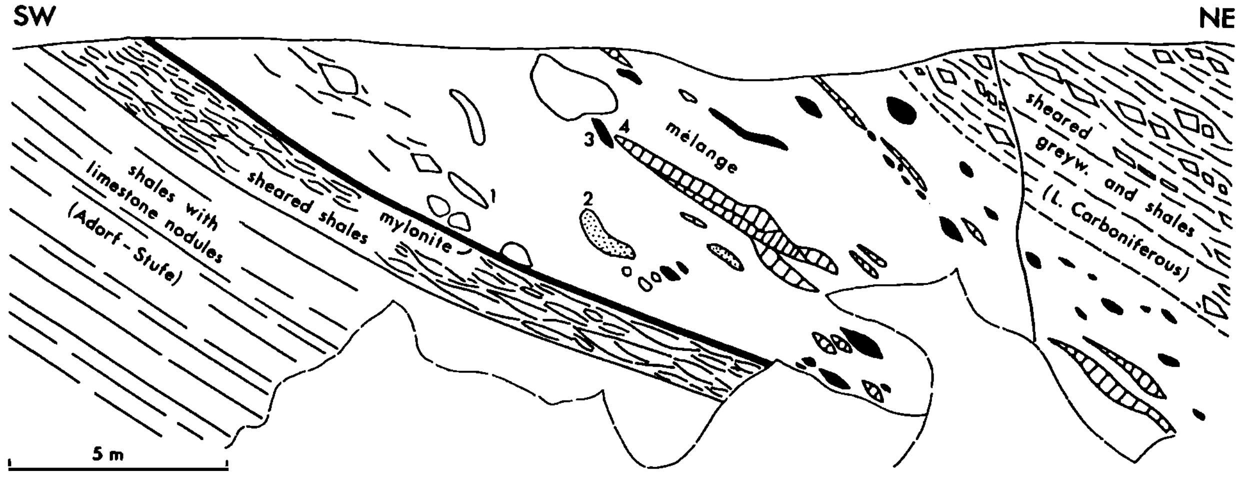

Fig. 10 - Basal shear zone of the Münchberg Nappes, with tectonic phacoids and/or olistoliths of: (1) inaccessible, unidentified; (2) L.Carboniferous greywacke; (3) metabasalt; (4) Devonian pelagic limestone. Same tectonic position as Fig. 8, but on the N flank of the Münchberg synform; HEISS quarry (stop no.7); from FRANKE (1984a).

Stop No. 8 - Eclogite! (P.BLÜMEL)
Top of the Weißenstein Hill
TK 25: 5836 Münchberg, R 77 960/ H 54 900

The contacts between the Münchberg eclogites and their country rocks are nowhere exposed, but mapping reveals that they are mainly inserted at the contact between the Liegend- and Hangend- Serie, or in the lower part of the latter. Dark eclogite varieties contain the assemblage omphacite + garnet + quartz + rutile (+hornblende) (+phengite), and the the lightcoloured varieties contain omphacite + garnet + quartz + rutile + kyanite and/or zoisite (+phengite). REE patterns and ND isotope data indicate, in the dark varieties, compositions close to MORB (with some hydrothermal alteration), whereas the light-coloured eclogites remind cumulates of continental basalts (STOSCH & LUGMAIR 1987). In addition, garnets mimetizing honeycomb- structures suggest a gabbroic protolith for the light-coloured variety (MATTHES 1979).
The dark eclogites at the Weißenstein form a body of 1500 m length trending SW-NE; as revealed by a research drilling, it extends downwards to 140 m depth, where it is underlain by paragneisses with staurolite + kyanite. A narrow dike of "albite-pegmatoid" with plagioclase (An 8-15) + muscovite (+zoisite) cuts through the eclogite and has transformed the wallrock into amphibolite (MATTHES 1979).
The composition of coexisting minerals in the eclogite is (FRANZ et al. 1986, MATTHES 1979, O'BRIEN & SCHMIDT in prep.):

clinopyroxene:	garnet:	Si in phengite:
diopside-hedenbergite 49-52.6	almandine 51-56	core: 6.95
jadeite 36.1-38.2	pyrope 19-24	margin: 6.70- 6.76
acmite 10.8-7.4	grossular 19-27	within garnet:6.49
CaTs 3.6-1.8	spessartine 1	

Ca in garnets distinctly decreases from core to rim at nearly constant Fe/Mg. With transition into the symplectite stage, a reaction rim with biotite + plagioclase is formed at phengite/quartz (or omphacite) contacts.
Radiometric ages of eclogite facies metamorphism range between 435 and 380 Ma. Further details about the composition and age of the eclogite may be taken from the contributions by OKRUSCH et al. and by AHRENDT.

Stop No. 9 - Augen-gneisses of the "Liegend-Serie" (W.FRANKE)
Schauenstein, crag at the SE wall of the Renaissance-style castle
TK 25: 5736 Helmbrechts, R 81 630/ H 71 540

The castle is built upon Augen-gneisses of the "Liegend-Serie". Large K-feldspar clasts set in a finer grained quartz/feldspar matrix still remind the magmatic protolith: Ordovician granite. The magmatic texture is cut by thin mylonitic seams which define a weak foliation. Feldspar clasts show incipient rodding (SW-NE); the asymmetry of the clasts indicates tectonic transport to the SW. The Augen-gneiss of this outcrop can be regarded as the protolith of the mylonites of the next stop.

Stop No. 10 - Augen-gneiss mylonites of the "Liegend-Serie" (W.FRANKE)
Cliff 500 m S of Schauenstein
TK 25: 5736 Helmbrechts, R 81 660/ H 70 920

Augen-gneisses of the "Liegend-Serie" have been strongly mylonitized. The size of the K-feldspar clasts has been ground down to a few mm. Feldspar shows superplastic deformation (VOLLBRECHT 1981). Quartz-feldspar aggregates define a pervasive mineral lineation oriented SW/NE. Mylonites of this type are regularly found at the base of the Augen-gneisses of the "Liegend-Serie"; because of their high quartz content, these rocks have predisposed the formation of a ductile thrust, along which the high-grade rocks of the Münchberg pile rose to the surface.

Stop No. 11 - L.Carboniferous conglomerate and limestone- olistolith, Bavarian facies (W.FRANKE)
Railway cut and disused quarry at Poppengrün (Döbra railway station)
TK 25: 5736 Helmbrechts, R 76 300/ H 72 800 (quarry)

The railway cut exposes structureless conglomerates and coarse- grained greywackes. The conglomerates are of late Viséan age and are now in (?erosive) contact with Tournaisian greywackes and shales (FRANKE 1984b); they probably represent the fill of a submarine canyon or channel. The spectrum of clasts comprises greywackes (?L.Carboniferous), grey and black cherts (Devonian and Silurian), dolomites and shallow-water limestones (L.Carboniferous), and occasional keratophyre (meta-trachyte, Ordovician). These clasts are clearly derived from the Bavarian facies rocks, which are now contained in the nappes that override the flysch; during the L.Carboniferous, these units were probably already assembled in an accretionary wedge, which fed the flysch basin.
The quarry shows various shallow-water carbonates (e.g., cross- bedded oolites), which have been dated as early Viséan (V1-V2a, MANSOURIAN 1979), i.e., as time-equivalent with part of the flysch. The limestones represent an olistolith, which was transported along with the conglomerates and came to rest near the base of the slope.

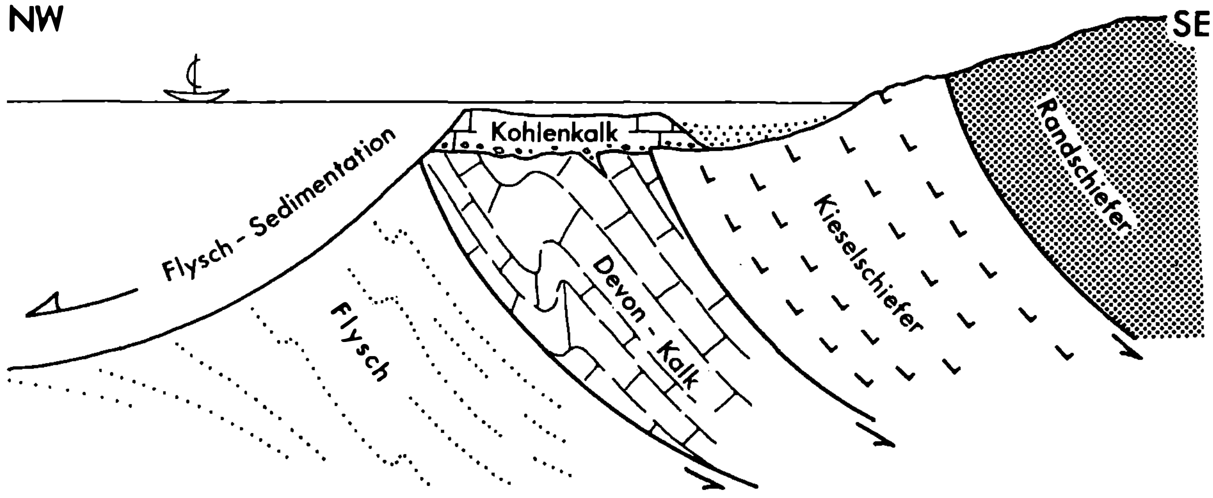

Fig. 11 - Tectonic model of the accretionary wedge at the SE margin of the Saxothuringian flysch basin (see stop no.12; from FRANKE 1984a)

Stop No. 12 - Bavarian facies wildflysch with olistoliths (W.FRANKE)
Sawmill of STRÖHLA comp., Rauschenhammermühle, SW of Schwarzenstein
TK 25: 5735 Schwarzenbach am Wald, R 71 970/ H 70 360

A roadcut alongside the sawmill exposes a Lower Carboniferous olistostrome. The matrix is structureless silty shale. It contains blocks of black shales and bedded cherts with radiolarians and graptolites (Silurian), and fine-grained grey sandstones, which represent the uppermost Ordovician of the Bavarian facies (Döbra Sandstone). Within one block of more than 50 m size, the Silurian and Ordovician occur in an overturned, yet coherent sequence.
The intercalation of sandstones in the topmost Ordovician is the signal of the glacio-eustatic drop of the sea-level caused by the Saharan glaciation.

Stop No. 13 - Devonian bedded cherts of the Bavarian facies (W.FRANKE)
Valley of the Wilde Rodach W of Schwarzenstein
TK 25: 5735 Schwarzenbach am Wald, R 71 520/ H 68 920

Numerous cliffs, especially on the E slope of the valley, expose grey to greenish bedded cherts with some shaly interbeds. Radiolarians and conodonts testify to the pelagic environment. This lithology is typical of the Bavarian facies, and has been shown to represent all of the Devonian and even the earliest Carboniferous (GANDL 1981, SCHMIDT-EFFING 1988).

The cherts have been deformed into tight folds with NW-trending axes. In general, folds in the unmetamorphosed Saxothuringian sediments are oriented SW-NE and face toward NW; exceptions like in this outcrop may be explained by external rotation of pre-existing folds into the direction of tectonic transport. Since the bedded chert of this stop is surrounded by L.Carboniferous flysch clastics, it is also possible that the slab has rotated during its emplacement as a sedimentary klippe.

Stop No.14 - L.Carboniferous flysch sediments of the Bavarian facies (W.FRANKE)
Roadcut S of Überkehr, at the junction of the road from Löhmarmühle with the federal road (B 173)
TK 25: 5735 Schwarzenbach am Wald, R 69 080/ H 69 480

The roadcut exposes proximal greywacke turbidites. Up to 50 percent of the beds consists of bioclastic carbonate debris which is derived, like the limestone olistolith of stop no. 11, from the narrow shelf at the internal basin margin. The outcrop shows tight, NW-facing folds with axial plane cleavage.
50 m to the N, there is an intercalation of 1 m of pebbly mudstone (with dolomite, chert and intraformational clasts). Deposition of the flow has triggered slump-folding in the underlying greywacke/shale packet. Slump folds - like the tectonic folds - face to the NW.
The combination of proximal greywacke turbidites, debris flows and slumps is typical of the Bavarian facies L.Carboniferous, which represents trench and slope environments.

Stop No.15 - Frasnian pillow lavas and conglomerates of the Thuringian facies (W.FRANKE)
Abandoned quarry 1 km SW of Bernstein am Wald
TK 25: 5735 Schwarzenbach am Wald, R 67 580/ H 70 540

The quarry has exploited the Frasnian pillow lavas of the Thuringian facies. They are overlain by pyroclastic breccias which contain well-rounded pebbles mainly of metabasalt and some clastic sediments. The metabasalt pebbles are evidently derived from the Frasnian lavas; apparently, volcanic materials have been uplifted up to or above the water table and were fragmented and rounded on the shore of minor islands within the Saxothuringian basin.
In the neighbourhood, these conglomerates contain also pebbles of Ordovician meta-trachytes and -rhyolites. The belt of conglomerates trends toward the Saxonian Granulitgebirge approx. 100 km to the NE; uplift and erosion in this area are probably related with the rise of the granulites, possibly as a metamorphic core complex.

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