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Tectonometamorphic evolution of the Bohemian Massif: evidence from high pressure metamorphic rocks

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Abstract The Variscan orogenic belt, of which the Bohemian Massif is a part, is typically recognized for its characteristic low pressure, high temperature metamorphism and a large volume of granites. However, there are also bodies of high pressure rocks (eclogites, garnet peridotites and high pressure granulites) which are small in size but widely distributed throughtout the Massif. Initially the high pressure rocks were considered to be relicts of a much older orogenic event, but the increasing data derived from isotopic and geochronological investigations show that many of these rocks have Palaeozoic protoliths. Metamorphic ages from the high pressure rocks define no single event. Instead, a number of discrete clusters of ages are found between about 430 Ma and the time of the dominant low pressure event at around 320–330 Ma.

Most of the eclogite and granulite facies rocks are assigned to allochthonous nappes that arrived close to the end of the low pressure event, but before final granite intrusion. The nappes contain a mixture of different units and the relationship between rocks with high pressure relicts and host gneisses with no apparent signs of deep burial is still problematic. Some of the high pressure rocks retain evidence of multiple stages of partial re-equilibration during uplift. Moreover, it can be shown in certain instances that host gneisses also endured a multistage metamorphic development but with a peak event convergent with one of the breakdown stages in the enclosed rocks with high pressure relicts. It thus appears that the nappe units are composite bodies probably formed during episodic intracrustal thrusting. Fluids derived from prograde dehydration reactions in the newly underthrusting slab are taken to be the catalysts that drove the partial re-equilibrations.

On the scale of the whole Massif it can be seen within the units with high pressure relicts that the temperature at the peak recorded pressure and that during the breakdown are variable in different locations. It is interpreted that regional metamorphic gradients are preserved for given stages in the history and thus the present day dismembered nappe relicts are not too far removed from their original spatial distribution in an original coherent unit. From the temperature information alone it is highly probable that the 'refrigerating' underthrusting slab was situated in the north-west. However, this north-west to south-east underthrusting probably represents the major 380–370 Ma event and is no guide to the final thrusting that emplaced the much thinned nappe pile with high pressure relicts.

Granite genesis is attributed to the late stage stacking, during the final Himalayan-type collision stage, of thinned crust covered by young, water-rich, sediments – erosion products of the earlier orogenic stages. Regional metamorphism at shallow depths above the voluminous granites was followed by final nappe emplacement which rejuvenated the granite ascent in places.

Key words Bohemian Massif – High pressure metamorphism – Tectonometamorphic evolution

Introduction

The late Palaeozoic collision of Laurasia and Gondwana to produce Pangea resulted in an 8 000 km long and up to 1 000 km wide orogenic belt running from the southern Appalachians and Ouachitas in the USA, via the Mauritanides in West Africa through most of Western and Central Europe, and possibly continuing benath the Carpathians before eventually reaching the Caucasus (see review of Matte, 1991). Within Europe this Hercynian or Variscan chain crops out in a series of Plio-Pleistocene

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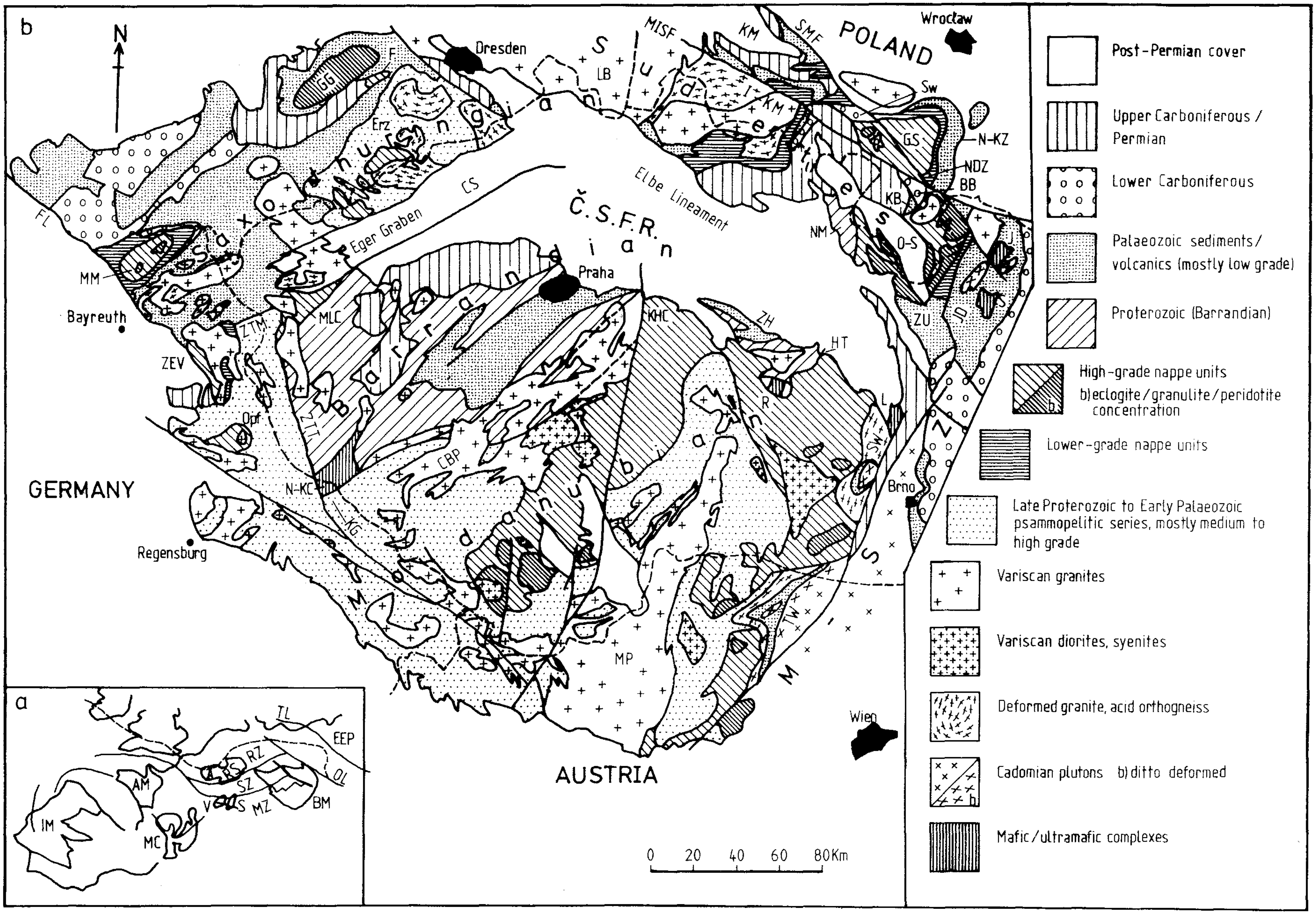

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N
Dresden
Wrocław
POLAND
GERMANY
AUSTRIA
Č.S.F.R.
Praha
Brno
Wien
Bayreuth
Regensburg
Eger Graben
Elbe Lineament
Saxothuringian
Sudetes
Barrandian
Moldanubian
Moravo-Silesian
GG
F
Erz
CS
FL
MM
ZEV
ZTM
ZTT
Opf
MLC
N-KC
KG
CBP
KHC
MP
LB
MISF
KM
SMF
Sw
GS
N-KZ
NDZ
BB
KB
NM
O-S
ZU
ZH
HT
R
L
SW
TW
0 20 40 60 80Km
Post-Permian cover
Upper Carboniferous / Permian
Lower Carboniferous
Palaeozoic sediments / volcanics (mostly low grade)
Proterozoic (Barrandian)
High-grade nappe units
b) eclogite / granulite / peridotite concentration
Lower-grade nappe units
Late Proterozoic to Early Palaeozoic psammopelitic series, mostly medium to high grade
Variscan granites
Variscan diorites, syenites
Deformed granite, acid orthogneiss
Cadomian plutons b) ditto deformed
Mafic / ultramafic complexes
a
IM
AM
MC
V
S
SZ
MZ
RZ
BM
TL
EEP
OL

◀ **Fig. 1.** a Variscan Europe. Broken line indicates deformation front. A, Ardennes; AM, Armorican Massif; BM, Bohemian Massif; EEP, East European Platform; IM, Iberian Massif; MC, Massif Central; MZ, Moldanubian Zone, OL, Odra Lineament; RS, Rheinisches Schiefergebirge; RZ, Rhenohercynian Zone; S, Schwarzwald; SZ, Saxothuringian Zone; TL, Tornquist Lineament; V, Vosges.
b Geological units and localities in the Bohemian Massif. BB, Bardzkie Basin; CBP, Central Bohemian Pluton; CS, České Středohoří; Erz, Erzgebirge; F, Frankenburg Klippe; FL, Franconian Line; GG, Granulitgebirge; GS, Góry Sowie; HT, Hlinsko Thrust; I-KM, Izera-Karkonosce Mountains; J, Jeseník; JD, Jeseník Dome; KB, Kłodzko Basin; KG, Künisches Gebirge; KHC, Kutná Hora Complex; KM, Kaczawa Mountains; L, Letovice; LB, Lausitz Block; MISF, Main Intra-Sudetic Fault; MLC, Mariánské Lázně Complex; MM, Münchberg Massif; MP, Moldanubian Pluton; M-SZ, Moravo-Silesian Zone; N-KC, Neukirchen-Kdyně Complex; N-KZ, Niemcza-Kamieniec Zabkowicki Formation; NDZ, Niemcza Deformation Zone; NM, Nové Město unit; Opf, Oberpfalz; O-S, Orlica-Śnieżnik unit; R, Ransko; S, Sobotín; SMF, Sudetic Marginal Fault; Sw, Swiebodzice Basin; SW, Svratka Window; TW, Thaya Window; ZEV, Zone of Erbendorf-Vohenstrauss; ZH, Železné Hory; ZTM, Zone of Tirschenreuth-Mähring; ZTT, Zone of Tepl-Taus; ZU, Zabřeh Unit

uplifted basement blocks surrounded by Mesozoic basins or troughs linked to the Alpine event. These basement units are (Fig. 1) the Iberian, Armorican, Massif Central, Vosges, Schwarzwald, Odenwald, Spessart and Bohemian massifs in the crystalline core of the orogen and the Harz Mountains, Rheinisches Schiefergebirge, Ardennes and South-west England in the more external flysch basins [see Franke (1989) for an overview]. To the north, Variscan rocks overlie Caledonian basement (Ziegler, 1984) and to the south they are found as disrupted basement units within the younger Alpine belt (Von Raumer, 1984). The easternmost massif, with which this paper is principally concerned, is the Bohemian Massif (Fig. 1) comprising parts of Czechoslovakia, Poland, Austria and Germany. The block is truncated to the north-east by the Russian Platform, parallel to which are major dextral north-west – south-east trending faults such as the Elbe and Tornquist Lineaments (Arthaud and Matte, 1977). These faults were important during post-orogenic basin formation but only serve here to shuffle and mask the relationships between the north-east and north-west of the Massif.

Recognition of regional differences in sedimentary, structural and metamorphic histories has, since the work of Kossmat (1927), allowed the Variscan belt to be subdivided into a number of distinct belts (cf. Fig. 1). These major divisions within the Bohemian Massif are the Saxothuringian (SZ),Moldanubian (MZ) and Moravian (or Moravo-Silesian) Zones. Early nappe concepts developed to explain the situation of high grade rocks in the SZ (e.g. Suess, 1912; Wurm, 1926) were discredited for many years (e.g. Cloos, 1927; Krebs and Wachendorf, 1973) but have now been resurrected following detailed geophysical and structural investigations (see reviews in Behr et al., 1980, 1984; Franke, 1989). Kober (1938) and later Fuchs (1971) and Tollmann (1982) delineated similar high grade nappes within the Moldanubian of Austria and Czechoslovakia. On this basis, and following the style of recent review papers (Franke, 1989; Matte et al., 1990; Matte, 1991), the nappe complexes will be treated here as separate entities. A further subdivision distinguishes the mostly weakly deformed and metamorphosed Barrandian block (Bohemicum of Chaloupský, 1989) in the centre of the massif from its more actively folded and recrystallized neighbouring blocks. The Bohemian Massif can thus be essentially described by six components: the (par)autochthonous Saxothuringian; the nappe units of the Saxothuringian; the Barrandian block; the Moldanubian; the nappe units of the Moldanubian and the Moravian (cf., Franke, 1989; Matte et al., 1990). Using this basic tectonic framework, the metamorphic characteristics of each unit will be described to determine temporal and spatial variations and correlations in the deduced pressure and temperature conditions encountered during the Variscan orogen. The aim is to find a coherent tectonometamorphic model that can account for the development of this corner of the Variscan chain and, hopefully, also be broadly applicable elsewhere in this orogenic belt.

Moravo-Silesian Zone

The Cadomian-consolidated Bruno-Vistulian block (Dudek, 1980), at the eastern and south-eastern border of the Bohemian Massif, is generally covered by Alpine and Variscan post-orogenic molasse but appears in a narrow zone at the margin of the massif where it has been partly reactivated by overthrusting of the Moldanubian gneisses (Suess, 1897). This area is known as the Moravo-Silesian Zone (MSZ). The MSZ basement south of the Elbe Lineament comprises the weakly deformed and metamorphosed I-type granitic to granodioritic (Finger et al., 1989) Thaya (in Austria) or Brno (in Czechoslovakia) batholith yielding ages of 550 Ma (Rb/Sr isochron, Thaya pluton, Scharbert and Batik, 1980) and 584 Ma (U/Pb, zircon, Brno pluton, Van Breemen et al., 1982). The batholiths are unconformably overlain by Devonian to Carboniferous sediments (Dvořak, 1982). Reactivation of the basement and cover during overthrusting by the hot MZ has caused thrust stacking and inverted metamorphism, now exposed, beneath the MZ, in the Thaya (in Austria) and Svratka (in Czechoslovakia) windows (Schulmann et al., 1991; Fritz, 1990). In the Thaya dome, garnet-staurolite-biotite schists, at the highest structural level, formed at around 580 – 600 °C, 5 – 7 kbar (Frasl et al., 1990) and during late Variscan times as evidenced by Ar/Ar cooling ages of 329 Ma (Dalmeyer et al., 1990); metamorphic temperatures decrease away from the MZ. The highest grade rocks of the Svratka window are kyanite-phengite-staurolite schists at the very base of the overriding MZ for which conditions of 700 °C and 8.8 kbar are estimated (Johan et al., 1990). The dome-like structures of the MSZ windows are interpreted as due to nappe stacking into basement duplexes in early north-east directed displacements followed by east vergent folding and semi-ductile strike-slip and normal faulting (Schulmann et al., 1991; Fritz, 1990).

The continuation of the MSZ to the north-east between the Elbe and Sudetic Marginal Fault Zones is found in the Jeseník Mountains, where its western margin is the Nyznerov thrust (Skácel, 1981). The basement here is the Keprník gneiss (546 Ma, Rb/Sr, Van Breemen et al., 1982) and the overlying Palaeozoic rocks, including a large volume of Devonian bimodal volcanics, are locally metamorphosed up to amphibolite facies in the overthrust zone (Suk et al., 1984; Souček, 1978). The Frasnian to late Visean Culmian basin, up to 4 km thick here, was involved in a major transpressive followed by transtensive deformation episode during the Westphalian (Rajlich, 1990a). Also in northern Moravia are the major mafic/ultramafic complexes of Jeseník and Sobotín showing a subalkaline tholeiitic geochemical signature and interpreted as possible ophiolites (e.g. Mísař et al., 1984). Further south, another 'ophiolite', the Letovice Complex found at the northern end of the Svratka window (Jelínek et al., 1984), shows the effects of at least seven stages of deformation (Bowes et al., 1980). North of the Sudetic Marginal Fault the Niemcza-Kamieniec Zabkowícki (N-KZ) formation, containing components of Vendian age (Gunia, 1979) and comprising mica schists with minor calcsilicate/limestones, acid and basic volcanics, quartzites and graphitic quartzites and some large bodies of mafic and ultramafic rocks, is separated from the higher grade crystalline of the Góry Sowie to the west by a major fault zone called the Niemcza Dislocation Zone (Dziedzic, 1985). Within the dislocation zone a younger sedimentary sequence, within which late Visean – early Namurian fossils are reported (Dziedzic and Gorecka, 1965), shows a monophase metamorphism (cordierite-sillimanite-andalusite-K feldspar) of higher grade than in the adjacent N-KZ convergent with the *overprint* in the marginal Góry Sowie gneisses (Dziedzic, 1985). The higher grade metamorphism led Bederke (1931) to consider the unit as a part of the Góry Sowie with the Ramzova overthrust separating it from the lower temperature garnet-staurolite-andalusite schists (with relict kyanite) of the N-KZ sequence: an interpretation incompatible with the palaeontological evidence.

Barrandian

The Barrandian block as defined here corresponds to the Bohemicum of Chaloupský (1989). The unit comprises an apparently continuous Cambrian to Mid-Devonian sedimentary sequence (Barrandian Basin) unconformable on a 7–8 km thick Proterozoic unit subdivided into a Pre-Spilitic Group of monotonous greywackes, a Spilitic Group of spilite-keratophyre and a Post-Spilitic Group of flysch and intercalated conglomerates (Kettner, 1917; Chlupáč, 1968). In the Spilitic Group, basic components dominate in the north-west, whereas acid components prevail in the south-east and frequent rhythmic tuffs, black shales, pyritic slates and cherts are reported. The block is bounded to the south by the dextral Variscan north-east – south-west trending Central Bohemian Shear Zone (Rajlich, 1987), now largely obscured by the undeformed Central Bohemian Pluton (331 Ma, Rb/Sr whole rock on granodiorite. Van Breemen et al., 1982) within which 'islands' of metamorphosed Barrandian rocks (both Palaeozoic and Proterozoic) are found (e.g. Chlupáč, 1981; Waldhausrová, 1984). The eastern margin against the MZ is the Tachov Fault and the north-west boundary against the SZ, hidden below non-metamorphic cover, is thought by Matte et al. (1990) to be a north-west directed thrust reactivated by a north-east – south-west trending dextral shear zone. The Barrandian is interpretated to re-emerge in the Železné Hory where, according to Tollmann (1982), the Hlinsko overthrust emplaces it over the MZ.

Metamorphism in the Barrandian ranges from prehnite-pumpellyite grade in metabasites in the synclinal core via chlorite, biotite, staurolite, garnet and kyanite zones to a sillimanite zone in the Teplá-Domažlice crystalline rocks (German names Tepl and Taus, thus ZTT) adjacent to the Bavarian Moldanubian (Vejnar, 1966). Losert (1967) reports garnet and kyanite zones in the Železné Hory. A metamorphic event before deposition of the Palaeozoic is generally accepted, although Matte et al. (1990) attribute all deformation and metamorphism to the Variscan event. Metamorphic zonation is difficult to evaluate in areas with multiple metamorphic events, however. In the westernmost part of the ZTT, Vejnar (1966) describes rocks with kyanite, which he correlates to an early Variscan event, overprinted by fibrolite and later prismatic sillimanite closely associated with the late Variscan granite intrusions.

In the ZTT at the western margin of the Barrandian block are found the large mafic-ultramafic complexes of Mariánské Lázně and Neukirchen-Kdyně (Fig. 1) with other smaller mafic complexes in between. The *ca.* 200 km^2 layered intrusion known as the Neukirchen-Kdyně complex comprises ultrabasites, gabbros, norites, granodiorites and ferrodiorites partly deformed and amphibolitized along south-east – north-west trending shear zones during the late Variscan (Vejnar, 1986). Coronas of orthopyroxene and amphibole + spinel have been observed between olivine and plagioclase in some of these rocks (Bues and Troll, 1991). The intrusion transects the regional metamorphic mineral zones and has imprinted a contact aureole up to pyroxene hornfels grade (Bues and Troll, 1991). Gebauer and Grünenfelder (1982) determined a protolith age of 530 Ma (U/Pb zircon) for a MORB-type metabasite of the complex, which thus indicates that the regional metamorphic zonation must be early Cambrian or older (Cadomian?), a fact compatible with the presence of staurolite + kyanite-bearing pebbles in the Cambrian conglomerates of the Barrandian Basin (Vejnar, 1971). However, the ages and relationships between the various rocks of this corner of the Barrandian block are far from certain and the results of ongoing investigations are needed to clarify the picture.

Mariánské Lázně Complex

Within the triangular metaophiolitic (Kastl and Tonika, 1984) Mariánské Lázně Complex (MLC) in the north-west of the ZTT three main zones, interpreted as separate thrust-bound units, are recognized (Jelínek et al., 1989). A unit of finely foliated amphibolites in the north-west is separated by a body of serpentinites from a central, higher grade, eclogite-bearing zone and a sequence to the south-east contains amphibolitic schists, with metagabbros and marbles, showing a metamorphic grade intermediate between the other two (Kastl and Tonika, 1984; Jelínek et al., 1989). The serpentinites, formerly spinel peridotites and harzburgites, are sometimes further recrystallized to tremolite-, talc- and chlorite-bearing schists in numerous shear zones. A variety of texturally and mineralogically distinguishable eclogites are found, broadly grouped into light kyanite-bearing and dark kyanite-free varieties; primary phengite, zoisite and hornblende are sometimes noted (Jelínek et al., 1989; O'Brien, 1991a; 1991b). Retrogression is usually well advanced but a complete transformation from fresh eclogite to completely recrystallized amphibolite, sometimes accompanied by evidence of strong deformation, can be traced in a single outcrop. The minimum conditions for the eclogite facies event are pressures greater than 14 kbar, temperature about 680 °C, with lower pressure overprints (including one still above 10 kbar) occurring at higher temperatures as deduced from the growth of sapphirine (after kyanite) and orthopyroxene (O'Brien, 1991a; 1991b). Metagabbros also show evidence for a high pressure event. Coronitic garnet growth, high pressure plagioclase breakdown and new ortho- and clino pyroxene development point to a static metamorphism at conditions above 10 kbar (O'Brien, 1991a). Geochronological results from the eclogites show a difference in age from garnet cores (433 ± 12 Ma) and garnet rims (375 ± 5 Ma) (Sm-Nd, gt-cpx, Beard et al., 1991): the latter value probably reflecting the amphibolite facies overprint as deduced by Schüssler et al. (1989) using the K/Ar method. The regional tectonic position of the MLC unit is unclear. Franke (1989) depicts the MM and ZEV as outlying nappes of the Barrandian block within which the MLC is included. In contrast, Matte et al. (1990) also link the MM, ZEV and MLC, but see them as part of a composite nappe pile marking a suture zone between the SZ and Barrandian block. The latter model requires the MLC to have fault/thrust boundaries with the rest of the Barrandian, but unequivocal evidence for such contacts is as yet lacking in this poorly exposed, peneplaned, uplift block.

Saxothuringian Zone

The SZ is typically exposed in Saxony and Thuringia between the major north-west – south-east trending Franconian and Elbe Line faults and continues into the Lausitz and Sudeten regions in the north and north-east of the Massif. It is characterized by a predominantly continuous Cambrian to Carboniferous volcano-sedimentary sequence, biostatigraphically well defined, generally of greenschist or lower grade, but locally up to amphibolite facies in the deeply eroded parts, showing a strong Variscan deformation and cut by post-tectonic granite plutons (Von Gaertner et al., 1968). This simple description glosses over a plethora of problems that the area exposes: problems that have caused heated debate for over a century. The main controversy is over the significance of small outcrops of high grade crystalline rocks and the anomalously developed sedimentary record in their immediate vicinity. The sedimentary piles have been subdivided into two groups showing a similar Cambrian to basal Ordovician sequence of neritic clastics and bimodal volcanics, but differing in their later Ordovician to Carboniferous development (see Von Gaertner et al., 1968; Behr et al., 1980; 1984; Franke, 1984). A 'normal' Thuringian facies, widespread in Thuringia and the Fichtelgebirge, is characterized by shallow water Ordovician deposits, shales and cherts of Silurian age, bimodal volcanics, hemipelagic sediments and reef limestones (also local uplift – post Givetian Reussische Phase) in the Devonian and relatively distal flysch in the Carboniferous. In contrast, the so-called 'Bavarian' facies is typified by bimodal volcanics and pelagic shales in the Ordovician, radiolarian cherts, black shales, pelagic limestones and basaltic volcanics in the Silurian and Devonian and relatively proximal flysch clastics of Carboniferous age. The restricted 'Bavarian' facies occurs around the so-called 'Intermediate Massifs' of Münchberg (the largest), Wildenfels and Frankenberg-Hainichen which lie in the Central Saxonian Lineament of the north-east – south-west trending Vogtland synform lying between the major antiforms of Berga to the north-west and the Erzgebirge-Fichtelgebirge to the south-east. The crystalline rocks of the massifs (hornblende schists, mica schists, augen gneiss and rare 'granulites') *overlie* low grade Palaeozoic rocks of the Bavarian facies. Some workers see the high grade rocks as klippen of far travelled nappes which collected and telescoped the deep water sediments of their underlying series during basin closure (see Behr et al., 1980; 1984): a similar evolution was suggested for some units in the Sudetes. Others, favouring an autochthonous development, interpret the gneisses and schists as basement uplifts, squeezed up and outwards over the modified sedimentary basins either side of the dome (e.g. Cloos, 1927). Nappe models have returned to favour following the recognition of the 'bowl-shaped' nature of the Münchberg Massif from deep seismic surveying and the frequency of horizontal rather than vertical structural features of the rocks therein (see reviews of Behr et al., 1980; 1984).

In the allochthonous model, the source of the nappes was believed to be south of the Fichtelgebirge in the area of Erbendorf where comparable mafic – ultramafic rocks are thrust over the Saxothuringian (e.g. Wurm, 1926).This was believed to mark the Saxothuringian – Moldanubian boundary, but it is now realized that the mafic rocks are part of another nappe, the Zone of Erbendorf-Vohenstrauss, that partly *overlies* this boundary (KTB, 1986; Weber and Vollbrecht, 1989). A small section of the Saxothuringian – Moldanubian contact zone is exposed in the northern Oberpfalz, but further east is hidden by granites, post-orogenic cover and tertiary basalts although gravity surveys confirm a simple extension across to the Elbe Lineament. In the Oberpfalz the contact is a ductile shear zone [Zone of Tirschenreuth-Mähring (ZTM)] within the vicinity of which a two stage retrogression is documented (Schreyer, 1966; Weber and Vollbrecht, 1989). A progressive metamorphic sequence is shown to smoothly pass across the boundary starting from a chlorite zone in the SZ up to a cordierite-K feldspar zone in the MZ: the latter isograd apparently follows the margin of the Barrandian block southwards until it is faulted out close to the Neukirchen-Kdyně Complex (Blümel, 1990). Structural elements point to an initial north-west directed compression followed by south-east directed backfolding in the SZ before the formation of large scale, upright, north-east – south-west trending open folds shared by both SZ and MZ (Stein, 1988; Weber and Vollbrecht, 1989). Late collisional deformation, probably related to the major faults such as the Franconian Line, led to south-west vergent structures in the SZ, MZ and nappe units in the north-west Bohemian Massif (Stein, 1988; Weber and Vollbrecht, 1989).

In the following sections the difficulties faced within the SZ are outlined with reference to the allochthonous units of the Münchberg Massif and Zone of Erbendorf-Vohenstrauss and the high pressure relicts in the Granulitgebirge and Erzgebirge.

Zone of Erbendorf-Vohenstrauss

The Zone of Erbendorf-Vohenstrauss (ZEV), within which the German Continental Deep Drilling (KTB) site is located, comprises a variety of metasediments and metabasites as well as minor acid orthogneisses and ultramafic rocks. In the paragneisses, spores, acritarchs and fusinite of Lower Devonian age as well as possible Cambrian acritarchs have been found (Pflug and Prössl, 1991) whereas the magmatic age of a metagabbro has been determined at around 494 Ma (U/Pb in zircon, Von Quadt, 1990). A medium pressure amphibolite facies event dated at around 380 Ma (Teufel, 1988; Hansen et al., 1989; Kreuzer et al., 1989) is the most prominent metamorphic feature with commonly a younger greenschist facies retrogression and lower grade phases in numerous generations of hydrothermal veins (Zulauf, 1991). Relicts of an earlier (398 Ma, Sm/Nd, Gt-WR, Von Quadt, 1990) higher pressure evolution were found in very rare retrograded eclogites and coronitic metagabbros recovered during the drilling programme. Coexisting minerals and inclusion suites confirm at least 14 kbar, 700 °C for the eclogite facies stage, whereas reaction textures and multiple mineral generations (e.g. four texturally and chemically distinct clinopyroxenes in the eclogites) indicate partial breakdown under high pressure granulite (transitional to high pressure amphibolite), medium pressure amphibolite and later greenschist to zeolite grade alteration (O'Brien et al., 1992). Early breakdown in these particular basites also occurred above 10 kbar, so as the host paragneiss unit is generally characterized by pressures below 10 kbar (Reinhardt, 1990), a tectonic juxtaposition is implied. In the southern part of the ZEV, between the villages of Michldorf and Kaimling, relicts of kyanite-bearing acid granulites, garnet pyroxenites and further coronitic metadolerites and metagabbros confirm the high pressure evolution, but seem to have been at slightly higher temperatures (> 750 °C) (Voll, 1960; Busch, 1970; Kleemann, 1991; O'Brien, unpublished data).

Underlying the ZEV to the north is the Erbendorf Greenschist Zone (EGZ) containing dominantly mafic rocks and ultramafic rocks metamorphosed to low amphibolite facies followed by a greenschist overprint (Matthes and Olesch, 1989). The unit, similar in character to the prasinite-phyllite series of the MM, is overthrust onto the Saxothuringian near Erbendorf (Wurm, 1926). Both the ZEV and EGZ are cut by late Variscan granites (300 – 320 Ma, data collated by Hansen et al., 1989) which have caused contact metamorphism (Schüssler, 1990; Matthes and Olesch, 1989). To the west the ZEV is terminated by the Franconian Line and to the north and south faults against the EGZ and Moldanubian, respectively. However, the eastern extent is in dispute. Kleemann (1991) took the location of major shear zones and a line of serpentinites as the limit of the ZEV with a medium pressure history. Everything between this limit and the more easterly extent of metakieselschiefer (graphitic chert) (Heinicke and Vollbrecht, 1989) would therefore be grouped under EGZ or as part of a mica schist zone. The whole of this assembly of units has been interpreted to overlie the Saxothuringian and Moldanubian and also the major shear zone (ZTM) between these major domains (KTB, 1986; Weber and Vollbrecht, 1989). However, some contacts at the margins of the ZEV may be due to younger (although still Variscan) reactivation, rather than representing primary nappe emplacement relationships (see Kleeman, 1991).

Münchberg Massif

Within the realms of the nappe model (e.g. Franke, 1984) five distinct layers are recognized in the nappe pile of the Münchberg Massif (MM). At the base is a collection of thin, stratigraphically inverted slivers (thrusted, not overturned) of Ordovician to Lower Carboniferous age comprising anchimetamorphic sediments, of deeper water character than the underlying autochthonous Palaeozoic, with intercalated tholeiitic and alkaline basalts and keratophyres (Franke, 1984). Overlying this is a unit of greenschist facies calcalkaline basalts, quartz phyllites (360 Ma, K/Ar, muscovite, Kreuzer et al., 1989) and minor serpentinites called the 'Prasinite-Phyllite series' (Okrusch et al., 1989). Next in succession, the 'Randamphibolite series' comprises various amphibolites of subalkaline tholeiitic affinity, yielding K/Ar hornblende ages between 370 and 400 Ma, contains minor calcsilicate layers and is retrograded to greenschist facies in marginal mylonite zones. A 'glaucophane-like' blue amphibole has been described from this unit (Emmert and Weinelt, 1962) and also from the comparable unit in the Intermediate Massifs to the north-east (Werner, 1989). The Liegendserie and overlying Hangendserie complete the nappe pile (cf. Stettner, 1960).

The Liegendserie is characterized by a monotonous metaclastic sequence with deformed granite intrusions (augengneiss), coronitic metagabbro and metagranodiorite and some serpentinites. Intrusion ages for the metagabbro and augengneiss are estimated at around 500 Ma (Gebauer and Grünenfelder, 1979; Söllner et al., 1981), whereas metamorphic muscovite and hornblendes yield K/Ar ages around 380 Ma (Kreuzer et al., 1989). Pressures of 11 kbar at 600 °C were estimated as the peak conditions in the corona gabbros: strong evidence for an eclogite facies event is lacking (O'Brien, 1991 a; Bosbach et al., 1991; Matthes and Seidel, 1977). The Hangendserie comprises a well statified sequence of banded amphibolites and hornblende gneisses, acid gneisses and some carbonates with eclogites, intimately interlayered with pelitic gneisses (Matthes et al., 1974) occurring very near the base (Stettner, 1960). The eclogites, which are broadly distinguished into a dark coloured kyanite-free type of oceanic MORB composition and a light coloured kyanite-bearing variety corresponding to high alumina basalt (Matthes et al., 1975; Stosch and Lugmair, 1990), record pressures in the range 20 – 25 kbar at around 650 °C for an initial high pressure stage and partial breakdown occurring at around 14 kbar, in the amphibolite facies (550 – 650 °C, 5 – 7 kbar), in the greenschist facies and even in the stability range of prehnite and pumpellyte (Franz et al., 1986; Klemd 1989; O'Brien 1993). A minimum intrusion age of 480 ± 23 Ma was determined for the protolith of a kyanite-free eclogite (seven point Sm/Nd WR isochron, Stosch and Lugmair, 1990) with eclogite facies metamorphism occurring around 380 – 395 Ma as deduced from U/Pb dating of almost concordant zircons (Gebauer and Grünenfelder, 1979) and Rb/Sr and Sm/Nd mineral isochrons (Stosch and Lugmair, 1990). Eclogite coarse mica fractions yielded K/Ar and Ar/Ar plateau ages around 390 Ma, whereas fine sieve fractions and hornblendes from the Hangendserie amphibolites gave ages around 380 Ma using the same methods (Kreuzer et al., 1989; Kreuzer and Seidel, 1989): a 300 Ma age component is attributed by Hammerschmidt and Franz (1992) to a regional prehnite-pumpellyite facies event.

Granulitgebirge

The north-east – south-west trending ovate outcrop of the Granulitgebirge lies immediately north-west of the Frankenberg Intermediate Massif. Acid granulites with occasional mafic lenses (pyriclasites) dominate the core of the area whereas garnet-bearing serpentinites are concentrated in the north-east part. An ophiolitic association (Werner, 1981) of serpentinites (garnet-free) along with metagabbros and diabases in the north-east and south-west of the Granulitgebirge was overthrust onto, and interfolded with, already retrograded granulites. Metapelites with a high temperature cordierite-K feldspar overprint sporadically overlie the granulites in ductile shear zones (Behr, 1978; J. Rötzler, 1992) and surrounding the whole complex is a belt of phyllitic schists, including proved Cambrian, and some graphitic cherts (Scheumann, 1925). The metamorphic grade in the mica schists increases towards the granulites (J. Rötzler, 1992). A four stage metamorphic development deduced for a kornerupine-bearing granulite in which kyanite was replaced by sapphirine includes an early granulite stage at 800 – 850 °C, 12 kbar, followed by initially higher temperatures at decreasing pressure to a second granulite stage at 800 °C, 6.5 kbar (Grew, 1986). The garnet peridotites are relics of an earlier, much higher pressure, event and the common amphibolite facies and lower grade overprints represent further metamorphic rejuvenations during uplift. Conditions of 730 °C, 7 kbar, and an isothermal uplift to about 4 kbar are deduced for relict parts of the cordierite-bearing schists and, for the schist mantle of the complex, a maximum of 670 °C, 3.5 kbar, is deduced (Frischbutter and Rötzler, 1990). Recent geochronological studies (Von Quadt and Gebauer, 1990) yielded ages of 377 ± 14 Ma (Sm/Nd, garnet-clinopyroxene-zircon-whole rock) and 338 ± 15 Ma (U/Pb, zircon) for a garnet pyroxenite lens inside a garnet peridotite, whereas two amphibolites yielded a probable 500 Ma protolith age and a metamorphic event at 352 ± 4 Ma (both U/Pb on zircon). The *ca.* 340 – 350 Ma ages were found by the same workers in the acid granulites (both Sm/Nd and U/Pb systems).

The Granulitgebirge has long been thought of as Precambrian basement thrust up to pierce its cover (e.g. Weber, 1986) and as a metamorphic core complex exhumed by extension (Franke, 1989). However, the increasing number of metamorphic ages comparable with those of similar rocks elsewhere in the Bohemian Massif, but younger than the fossils in the overlying series, tell another story. Considering also the presence of weakly metamorphosed metagabbros and the important graphitic cherts tectonically *above* the granulites and peridotites, an alternative possibility is that the whole sequence represents a tectonic window (probably opened by extension) into the inverted limb of a refolded, flat-lying, recumbent fold or a multi-layer nappe pile.

Erzgebirge

Traditionally the Erzgebirge is seen as a north-east – south-west trending, gently south-west plunging anticline. In the east predominant monotonous (metagreywackes) gneisses and migmatites of the Osterzgebirge

Formation, of supposed Precambrian age, record a low pressure metamorphism up to sillimanite (with muscovite) grade, whereas an overlying more variegated (containing additional calcareous, mafic, pelitic and quarzitic lenses) Preßnitz Formation, also presumed Precambrian, shows conditions of staurolite ± kyanite grade (Wienholz et al., 1979). Surrounding these two is the Lower Palaeozoic (presumed partly Cambrian) Keilberg Series, again of variegated lithology, which is commonly extended westwards into the Fichtelgebirge. Large deformed orthogneiss bodies are found in the central and southern parts of the Erzgebirge and post-orogenic granites occur in the east. Eclogites, granulites and pyroxenite-bearing garnet peridotites occur in a number of localities (cf. Rost and Grigel, 1969; Schmädicke et al., 1992), but apparently only appear in the lower most part of the Upper Preßnitz Series or associated with ortho-augengneiss bodies within the area of the south-western Keilberg Series (Klápová, 1990). Geochemically the eclogites resemble oceanic tholeiites, whereas non-eclogitic amphibolites in the area are calc-alkaline in composition (Werner and Kononkova, 1989; Klápová, 1990).

The eclogites contain accessory phengite, kyanite, zoisite or hornblende and so are comparable with the MM rather than the MZ types, but show a range in equilibration temperatures from around 650 °C in the westernmost examples to 850 °C in the Central Erzgebirge (Klápová, 1990; Schmädicke et al., 1992). Pseudomorphs after possible coesite found in the higher temperature eclogites testify to a possible former extremely high pressure (> 25 kbar) evolution compatible with the formation conditions of the accompanying garnet peridotite and pyroxenite. Peak conditions of 700–720 °C, 16–18 kbar, were deduced for quartzo-feldspathic granulites in this sequence (K. Rötzler, 1992). For the common gneisses of the Erzgebirge, an early medium pressure metamorphism (< 7 kbar) followed by a later low pressure (2–3 kbar) event have been deduced from phase relations and fluid inclusions (Krentz et al., 1990). The discrepancy in metamorphic grade between the eclogites and their host gneisses is explained by Werner and Kononkova (1989) as due to the eclogites being olistolith blocks deposited into the trough where the sedimentary precursors of the gneisses were accumulating. Without isotopic age determinations the relationship between the Erzgebirge eclogites and those of the rest of the massif is uncertain, but it would be surprising if they turned out to be anything other than Variscan in age. Early models emphasizing the mylonitic fabrics, possible nappes and large scale recumbent folds in this region (see review of Behr, 1983) were later discarded in favour of simple vertical tectonic block models.

Eclogites enclosed in peridotites bounded by acid granulites are known to occur beneath the Cretaceous cover of the České Středohoří, south of the Erzgebirge Fault, from their presence as xenoliths in Tertiary volcanics and borehole investigations (Fiala and Paděra, 1984). Gebauer (1991) deduced ages of 424 ± 4 and 342 ± 5 Ma for the core and rim, respectively, of a single zircon from a borehole eclogite. Acid granulites exposed in the valley of the Ohře River record an early 750–800 °C, 15–17 kbar, stage before deformation and lower pressure overprints (Kotková, 1992).

Moldanubian Zone

The Moldanubian Zone (MZ) extends to the margins of the Bohemian Massif in the south and west where it is covered by Alpine molasse; in the east it partly overrides the Moravo-Silesian Zone; towards the north-west is the Barrandian block; in north-east Bavaria, the SZ (contacts explained earlier); and towards the north-east the unit is covered by Mesozoic platform sediments or the overthrust Barrandian of the Železné Hory (Fig. 1). Important features of this Zone are the generally higher grade of metamorphism (widespread upper amphibolite facies) and the presence of numerous Variscan plutons such as the 160 km long north-east–south-west trending Moldanubian (or South Bohemian) Pluton (350–320 Ma, Scharbert, 1987).

Under the classification introduced here, the MZ is divided into the underlying Drosendorf and overlying, allochthonous, Gföhl units (Kober, 1938; Fuchs, 1971; Tollmann, 1982; Matte et al., 1990). In the following section the features of the Austrian and Czechoslovakian part of the Zone are outlined with a brief comparison of the neighbouring Bavarian sector. In Lower Austria, where the type localities occur, the lower part of the Drosendorf unit, the Ostrong unit, comprises a sequence of monotonous, partly migmatitic, cordierite- and K feldspar-bearing garnet-biotite-sillimanite gneisses with intercalated calcsilicates, orthogneisses and minor amphibolites. Above this, in thrust contact, the Drosendorf unit s.s. is characterized by a lower platy-textured granitic orthogneiss (Dobra gneiss) and an upper variegated sequence with biotite-plagioclase (+ garnet and sillimanite) paragneisses, amphibolites, marbles, calcsilicates, metaquartzites and graphitic schists. The uppermost, allochthonous Gföhl nappe is itself also a composite unit, the major constituents of which are the Gföhl gneiss and Granulite Complexes. A leucocratic, polydeformed metablastic to migmatitic granitic gneiss with intercalations of paragneiss and amphibolite forms the Gföhl gneiss. Granulites, overlying the Gföhl gneiss, have been interpretated as a metamorphosed pile of dominantly acid volcanics with minor sediments and mafic lenses (Fiala et al., 1987). However, an alternative origin as the result of dry melting of metasedimentary rocks at mantle pressures (followed by later deformation) is supported by some studies (Vrána, 1989). The granulites typically contain ribbon quartz, mesoperthitic K feldspar, antiperthitic plagioclase, garnet, kyanite, sillimanite, biotite and, depending on bulk composition, orthopyroxene or clinopyroxene. Mafic lenses are quartz-free garnet-pyroxene-plagioclase rocks (Scharbert, 1963). Intercalated in the granulites are serpentinized garnet peridotites, pyroxenites and eclogites (e.g. Dudek and

Fediuková, 1974; Carswell et al., 1989; Medaris and Carswell, 1990; Carswell, 1991). Additional components are variegated 'accompanying' series of disputed structural and stratigraphic position (see Fuchs, 1986), but designated by Weber and Duyster (1990) as the Meisling and Raabs units when underlying the Gföhl gneiss and granulites, respectively. The Meisling series comprises high temperature mylonitized amphibolites, orthogneiss, metasediments and serpentinites, whereas the Raabs series is typified by garnet- and clinopyroxene-bearing amphibolites within leucocratic orthogneiss, migmatitic paragneiss, metacarbonates and graphitic quartzites (Weber and Duyster, 1990; Thiele, 1976).

The areal extent of the Gföhl nappe is deduced from the location of the granulites, eclogites and garnet peridotites typical of its upper part. Granulite complexes are known from south Bohemia (e.g. Blanský Les, Prachatice, Křišt'anov and Lišov), Lower Austria (e.g. Dunkelsteinerwald, Blumau and St. Leonhard) around Kutná Hora and in south-east Moravia (e.g. Náměšt' and Strážek) (see Fiala et al., 1987), whereas eclogites and garnet peridotites occur with or without granulites within linear zones either side of the Moldanubian Pluton (e.g. Scharbert, 1963; Weiss, 1966; Dudek and Fediuková, 1974; Machart, 1984). Use of these criteria leads to the Gföhl nappe (Fig. 1) as delineated by Matte et al. (1990) as opposed to the slightly less extensive version of Tollmann (1982) utilized by Franke (1989). The picture is not so simple, however. In southern Bohemian, the sequence of units moving north-west away from the Moldanubian Pluton is: (1) two-mica paragneisses with minor quartzites and calcsilicates of the Kaplice unit; (2) a Monotonous unit of migmatitic biotite-sillimanite-K feldspar gneisses with minor garnet pyroxenites, kyanite-and/or zoisite-bearing eclogites, spinel peridotites and calcsilicates; (3) the Světlík orthogneiss with minor coronitic metagabbros; (4) the Česke Krumlov Varied Group with sillimanite-biotite paragneiss enclosing abundant marble, amphibolite and calcsilicate gneiss and minor orthogneiss and graphititic and quartzitic gneisses; and (5) the granulite complexes (Vrána, 1979; 1992; personal communication; Suk et al., 1984). Eclogites (sometimes with spinel peridotites) also occur in Monotonous units outside the granulite bodies elsewhere in Bohemia and Moravia, including locations within the outcrop area of the Moldanubian pluton (Dudek and Fediuková, 1974; Fediuková and Dudek, 1979; Machart, 1984).

Understanding the development of the granulites, eclogites and peridotites is a key factor in elucidating the overall tectonometamorphic history of the region. Typical of the prevalent acid granulites is a high temperature blastomylonitic fabric with ribbon textured quartz and a prominent stretching lineation (e.g. Scharbert, 1963; Weber and Duyster, 1990). However, this represents an amphibolite facies re-equilibration of a former granulite facies assemblage which is itself the product of overprinting of an earlier higher pressure granulite facies paragenesis (Carswell and O'Brien, 1991; 1993). Rare relict acid granulites yield peak conditions (garnet + K feldspar (mesoperthite) + quartz ±plagioclase (antiperthite) ± kyanite + rutile ± orthopyroxene ±clinopyroxene) around 1000 °C, 16 kbar, values consistent with the persistence of plagioclase in (mafic) garnet pyriclasites also within the acid granulite sequence (Carswell and O'Brien, 1993). The second granulite stage, accompanied by growth of biotite, plagioclase and sillimanite, occurred in the range 600–800 °C, 5–7 kbar, whereas the subsequent shearing and retrogression were at still lower grade. Petrakakis and Richter (1991) deduce conditions of *ca.* 750 °C, 8.5–9 kbar for 'accompanying series' mafic and pelitic gneisses using internally consistent thermodynamic data, but the narrow intersection range of equilibrium curves is inconsistent with the pairing of cores of strongly zoned garnets with matrix phases. It is highly probable that the Gföhl gneiss is just a migmatized and generally more retrograded version of the granulite – a suggestion substantiated by the presence of a heavily serpentinized garnet peridotite in the unit near Weitenegg (e.g. Rost and Grigel, 1969; see also Matějovská, 1975, and discussion in Fuchs and Scharbert, 1979).

Although the garnet peridotites within the Gföhl nappe are serpentinized, detailed studies of breakdown textures in better preserved samples (Medaris and Carswell, 1990; Carswell, 1991) have enabled a complex, multistage igneous and metamorphic evolution to be established. In summary, an early high temperature igneous protolith with aluminous pyroxenes and spinel is overprinted by a high pressure garnet-bearing and low aluminium pyroxene-bearing paragenesis. Decompression then led to kelyphitization of garnet producing spinel and aluminous pyroxenes and was followed by an amphibolite stage and later serpentinization. Pressure–temperature conditions of 1105 ± 77 °C, 33.9 ± 4.1 kbar for the Austrian garnet peridotite stage indicate a significant pressure increase from the 1100–1200 °C, 10–20 kbar implied by the igneous aluminous pyroxenes and spinel association (Carswell, 1991). Breakdown reactions in the peridotite and enclosed lenses of pyroxenite and rare eclogite indicate recrystallization at eclogite facies (855 ± 63 °C, 20.1 ± 1.8 kbar), granulite facies (775–800 °C, 12–15 kbar) and amphibolite facies (650–750 °C, 4–6 kbar) (Scharbert and Carswell, 1983; Carswell et al., 1989; Carswell, 1991). Even higher pressures (40–50 kbar) have been calculated for some of the Czechoslovakian localities (Medaris and Carswell, 1990). A contrasting evolution is presented for the high temperature Mohelno ultramafic locality where garnet only occurs in a narrow zone at the margin of the body (Medaris et al., 1990). This is interpreted as a result of cooling of the original peridotite by emplacement in the crust during crust–mantle imbrication, but without further subduction (Medaris and Carswell, 1990; Medaris et al., 1990).

For eclogites in Bohemia and Moravia pressure–temperature conditions of 820–1060 °C, 15–22 kbar have been estimated (Beard et al., 1989; Dudek and Fediuková, 1974; Medaris et al., 1991). Considering rocks of broadly the same bulk composition, it is recognizable that temperatures are on average lower in the belt to the north-west than in that south-east of the Moldanubian Pluton (cf. O'Brien et al., 1990). Also, prograde zoning and amphibole inclusions in garnet and amphibole-plagioclase rather than orthopyroxene-spinel breakdown after garnet indicate an overall lower temperature evolution (e.g. Borek eclogite of Kutná Hora complex; Messiga and Bettini, 1990) in the north-west zone, although orthopyroxene coronas on quartz are recognized in some eclogites in the Monotonous group of southern Bohemia (Vrána, personal communication).

Below the Gföhl nappe, cordierite-K feldspar bearing gneisses of the Ostrong unit formed in the range 630 – 670 °C, 3 – 4 kbar (Zaydan and Scharbert, 1983) whereas in the overlying variegated (Drosendorf s.s.) unit, kyanite relicts in garnet indicate an early medium pressure (720 – 760 °C, 7 – 9 kbar) phase before an overprint at lower grade conditions (620 °C, 2 – 4 kbar) (Petrakakis, 1986). Corona gabbros with orthopyroxene, magnesio-hornblende + spinel and garnet between olivine and plagioclase are also known from the variegated sequence (Koller, 1990; Richter et al., 1991) but their pressure – temperature evolution is as yet undetermined. A similar coronitic metagabbro is reported by Holub and Munshi (1984) from the Svatý Kříž massif, about 25 km south-east of Kutná Hora where it is possibly part of the Gföhl unit.

With respect to geochronology, Arnold and Scharbert (1973) report Rb/Sr whole rock isochrons of 470 and 430 Ma for Austrian granulites, but more recent U/Pb dating of zircons from Bohemian and Moravian granulites indicate an age of around 345 Ma for the granulite event, followed by the amphibolite event, and its associated shearing, within less than 10 Ma as evidenced by zircon data from the Gföhl gneiss and monazites from both granulite and Gföhl gneiss (Van Breemen et al., 1982; Kröner et al., 1988). Important to note is that the 345 Ma age from the Lišov granulite (Van Breemen et al., 1982) is for the prevalent medium pressure stage in this unit and not for the scarcely recognizable earlier high pressure event. Different samples of garnet pyroxenite from within peridotites of the Dunkelsteiner Wald yielded garnet-clinopyroxene-whole rock Nd/Sm isochrons of 370 ± 15 Ma and 344 ± 10 Ma, respectively (Carswell and Jamtveit, 1990): values around the same as the two groups distinguished by Beard et al. (1991) from 11 samples of peridotite, pyroxenite and eclogite from the Gföhl gneiss and Kutná Hora-Svratka Complex in Czechoslovakia. Brueckner et al. (1989) also obtained 374 Ma for a garnet pyroxenite, whereas Beard et al. (1989) report an age as low as 324 Ma for an eclogite (Sm/Nd garnet-clinopyroxene). In the variegated upper part of the Drosendorf unit Dallmeyer et al. (1990) found hornblende Ar/Ar ages of 330 – 340 Ma, which they attribute to the cooling of the rocks below about 500 °C. Part of the variegated group could be late Proterozoic to Palaeozoic in age according to the palaeontological finds of Andrusov and Čorna (1976) within the units beneath the south Bohemian granulites.

The structural history of this region has been, and remains, a matter of intense discussion and disagreement. Within the MZ itself major thrusts separate the Ostrong, Drosendorf s.s. and Gföhl units. In addition, since the time of Suess (1897), thrusting of the MZ over the adjacent Moravian Zone in an easterly or south-easterly direction has been a part of most tectonic models (e.g. Fuchs, 1971; Tollmann, 1982; Weber and Duyster, 1990), but this appears to be only the last in a series of many deformation events, all of which post-date the early metamorphic stages of the granulites and peridotites. In the region of the Náměšt' granulites, Urban (1990) distinguishes a first deformation phase of NNE directed nappe piling, at upper amphibolite facies, during which granulites and peridotites came together. The north to NNE trending stretching lineation of this D1 phase was supplemented by a second of north-east – south-west orientation during a second deformation stage at low amphibolite to greenschist facies conditions and only a third stage reflected south-east directed movement. Neubauer (1991) reports a comparable NNE shearing and stacking followed by east to ESE shearing in the Austrian part of the MZ. In the variegated sequence of south Bohemia, the major deformation records north-west to south-east thrusting and is interpreted to be contemporaneous with convergent amphibolite facies metamorphism between rocks of the varied and overlying granulite units (Vrána, 1979; Rajlich et al., 1986).

The Bavarian sector of the MZ is composed predominantly of monotonous paragneisses with the only significant exposures of a variegated group, i.e. para- and orthogneiss with abundant interlayered amphibolite, calcsilicate rocks and graphitic schists, occurring near the south-west margin of the Barrandian block (Künisches Gebirge) and close to Passau. These rocks are thus similar to those of the Drosendorf unit as defined earlier. In the northern part of the Bavarian Forest Blümel and Schreyer (1977) have traced a regional low pressure metamorphic zonation from a chlorite isograd in the variegated sequence of the Künisches Gebirge via andalusite, sillimanite, sillimanite + K feldspar and cordierite + K feldspar zones, eventually to rocks with garnet and orthopyroxene in the highest grade parts within the monotonous units. The north-west – south-east trending isograds are truncated by the faults around the Neukirchen-Kdyně complex. The cordierite-K feldspar zone (4.2 ± 0.4 kbar, 690 ± 50 °C, Blümel, 1983), with its associated migmatization, is widespread in the Bavarian MZ although the biotite-sillimanite association, stable to higher temperatures in more Fe-rich rocks, is also extremely common (Fischer, 1968; Blümel and Schreyer, 1977).

High pressure rocks, occurring in a restricted number of small outcrops clustered around the Oberviechtach granite, are treated as part of an outlying klippe related to the ZEV, MM and MLC high-pressure units. However, scarce eclogites and pyroxenites are also known from the paragneiss series of south-west Bohemia (Vrána, personal communication). The characteristics of the high pressure relicts are best observed in the quarry at Winklarn, 6 km south-east of Oberviechtach, where interlayered and interfolded eclogites [of MORB-type geochemistry (O'Brien, 1989 c; Okrusch et al., 1991)], garnet pyroxenites, garnet websterites and pelitic gneisses are in fault contact against a serpentinized peridotite (O'Brien, quoted in Blümel, 1990). The complex multistage metamorphic evolution of different rocks at this locality is well represented within the retrograded eclogites, where an initial high pressure stage (minimum conditions of 700 °C, 15 kbar) is overprinted by high pressure granulite ($\cong$800 °C, 12 kbar), medium pressure granulite (> 800 °C, 8 – 10 kbar) a low pressure pyroxene-hornfels stage with Fe-rich olivine + spinel and later amphibolite and even greenschist facies mineral growth (O'Brien, 1989 a; 1989 b; 1991 c). A pressure of *ca.* 28 kbar has been calculated from the garnet-orthopyroxenel pairing of the websterite (O'Brien and Schmidt, 1991), but no garnet has been found in the peridotite or in any of the other scattered serpentinites of north-east Bavaria (Klinkhammer and Rost, 1975; Von Gehlen and Schmitt, 1989). The high temperature breakdown in the mafic rocks has more in common with that seen in the Austrian and Czechoslovakian eclogites and mafic granulites (e.g. Carswell et al., 1989; Messiga and Bettini, 1990) but unusual garnet + gedrite + orthopyroxene-bearing rocks interlayered with the eclogites show marked similarities to rocks of the western Barrandian block (Vejnar, 1974). Pelitic rocks interlayered with eclogites are strongly overprinted by a low pressure, cordierite-producing, event but retain kyanite relicts and garnet zoning (high Ca and Mg cores) indicative of an early higher pressure evolution (O'Brien, 1989c; 1991a). Cordierite-bearing metatexites *outside* the eclogite body, although of broadly similar chemistry and also containing relict kyanite and sometimes staurolite, have large garnets affected by the late low pressure event with distinct core and overgrowth compositions indicative of an overall lower pressure history.

Ages of 422 ± 8 and 423 ± 8 Ma, respectively, for an eclogite and acid orthogneiss from Winklarn (Nd/Sm, garnets-whole rock-rutile or zircon, Von Quadt and Gebauer, 1988) probably reflect the high pressure event whereas the 356 ± 10 Ma from Miethig (Sm/Nd, garnet-whole rock, cited in Köhler et al., 1989) possibly represents one of the overprint stages. The regional low pressure metamorphism in the Bavarian MZ occurred around 320 Ma as deduced from U/Pb dating of zircon, monazite and xenotime and mineral and small area Rb/Sr isochrons (e.g. Grauert et al., 1974; Gebauer et al., 1989). However, older ages were derived from Rb/Sr isochrons from larger areas (450 – 550 Ma) interpreted as the age of sedimentation or of a 'Caledonian' thermal event (e.g. Grauert et al., 1974; Köhler and Müller-Sohnius, 1980; 1985; Gebauer et al., 1989). A 450 Ma *metamorphic* event conflicts with the discovery of apparent Upper Silurian spores in the paragneisses of the Künisches Gebirge (Pflug and Reitz, 1987).

Sudetes

To paraphrase Aleksandrowski (1990): the Sudetic region at the north-east margin of the Bohemian Massif has not been as yet sufficiently understood in terms of its structural and facies links with the adjacent areas. In the following section we compare the main rock groups with those of the rest of the massif and attempt to subdivide the region into zones of the scheme already presented. The Tertiary horst of the Sudetes forms a *ca.* 280 km long by 75 km wide belt between the north-west – south-east trending Elbe and Sudetic Marginal Faults (reactivated Variscan fractures) and comprises the Lausitz, Izera-Karkonosce, Kaczawa, Góry Sowie, Śnieżnik and Jeseník blocks: sporadic basement also appears beneath Cainozoic cover in the Fore-Sudetic block between the Central Sudetic and Odra Faults (Fig. 1). Kossmat (1927) considered this region as an extension of the Saxothuringian Zone.

Orlica-Śnieżnik Dome

The essentially V-shaped exposed crystalline of the Orlica-Śnieżnik Dome, cored by the Permo-Mesozoic filled Nysa graben, splits into the eastern Ladek-Śnieżnik and western Orlickie-Bystrzyckie massifs. The eastern margin is faulted against the MSZ (see earlier), to the north, after the intervening Variscan Kłodzko-Złoty granodiorite, are the epizonal to non-metamorphic Palaeozoic basins of Kłodzko and Bardzkie, and in the west and south, where Cretaceous cover is removed, are the epizonal Nové Město and Zabřeh units (Don et al., 1990). The crystalline sector consists of three main parts: (1) the monotonous Młynowiec formation of plagioclase gneiss with minor mica schists and amphibolites overlain by the variegated Stronie series comprising staurolite- and garnet-mica schists (occasionally kyanite or chloritoid bearing), quartzite, marble, amphibolite and graphitic schist; (2) the Śnieżnik ortho-augengneiss; and (3) the Gierałtów gneisses mostly of fine grained, laminated, often migmatitic, rocks of K-rich leucocratic composition containing lenses of granulite and eclogite (Don et al., 1990).

Eclogites, consisting of both simple bimineralic garnet-omphacite types as well as those with accessory kyanite, zoisite, phengite and hornblende, show a complex multistage evolution, from the evidence of inclusion suites and breakdown reactions, including a precursor greenschist facies and two eclogite facies stages (Smulikowski and Smulikowski, 1985). Acid granulites (quartz, two feldspars, garnet, kyanite and rutile) occur in the largest segment of the Gierałtów gneiss (the Gierałtów Massif which stretches across the border into Czechoslovakia) and are accompanied by intermediate omphacite bearing granulites and true plagioclase-free eclogites (Pouba et al., 1985; Bakun-Czubarow, 1991). Equilibration conditions for the eclogites *outside* the granulite area are 620 – 740 °C, 13.5 – 16 kbar, whereas those *within* the granulites are noticably at higher temperatures (800 – 900 °C, 15 – 18 kbar; Bakun-Czubarow, 1989; 1991).

Isotopic investigations by Brueckner et al. (1989) (Nd/Sm, garnet-clinopyroxene-whole rock) yielded an age of 352 Ma in an eclogite of the Gierałtów Massif and ages of 341 and 327 Ma in the lower temperature eclogites, the latter two values being remarkably low considering the apparent K/Ar cooling ages of *ca.* 380 Ma from micas of the same rock series (Bakun-Czubarow, 1968). For the Stronie series a protolith age of around the Pre-Cambrian – Cambrian boundary is evident from the micropalaeontological findings of Gunia (1984), whereas Rb/Sr whole rock and mica ages of 385 ± 35 and 335 ± 5 Ma are interpreted as intrusion and metamorphism ages, respectively, in the Śnieżnik gneiss (Borkowska et al., 1990). Don et al., (1990) suspect that the 'Śnieżnik gneiss' samples of Van Breemen et al. (1982), for which Rb/Sr whole rock data pointed to a *ca.* 490 Ma homogenization event and a maximum age of 600 Ma, were in fact coarser variants of the Gierałtów gneiss, a gneiss body from which Borkowska et al. (1990) also obtained an Ordovician age (464 ± 35 Ma, Rb/Sr, whole rock).

Numerous folding phases are reported in the Orlica-Śnieżnik area but the overall structural evolution is a contentious subject. Don (in Don et al. 1990) interprets the Młynowiec-Stronie series to have been intruded by the Śnieżnik gneiss (evidence from contact metamorphism) with the two then sharing a strong deformation before the Gierałtów gneiss (and enclosed eclogites and granulites) was introduced during an amphibolite facies retrogression of the latter series. The structurally simpler Gierałtów gneisses, now apparently the cores of anticlines, share the post-coupling history of the whole area. Don et al. (1990) determined the coupling to have occurred before the Mid-Devonian whereas Dumicz (in Don et al., 1990) believes all the deformation to have begun in Early to Mid-Devonian times. The mix of rock types, especially the two groups of eclogites, bears a striking resemblance to that seen in the Erzgebirge.

In the neighbouring units the following features are seen. The adjacent Kłodzko unit contains a mix of metasediments (phyllite, chlorite schist, quartzite, limestone) and metavolcanics and intrusions (amphibolite, metagabbro, metarhyolite) of at least Late Silurian age, metamorphosed to greenschist/low amphibolite grade (before deposition of an unmetamorphosed Fammenian limestone) and partly retrogressed during a shearing event (see review of Wojciechowska, 1990). The unit bears a strong resemblance to the allochthonous 'prasinite-phyllite' series of the MM and ZEV. In the sedimentary basin sequence of the Bardzkie Mountains a gneissic basement is covered from the Frasnian to early Namurian by limestones and some sandstones including gabbro (lower part) and gneiss (from the mid-Tournasian) debris with the sequence continuing in the Namurian with a thick greywacke deposit containing numerous olistolith blocks (dimensions up to hundreds of metres) for which an Ordovician to Tournasian deep water (graptolite bearing shales and turbidites) environment has been deduced (Haydukiewicz, 1990). The association of allochthonous deep basin sediments in shelf deposits is reminiscent of the Bavarian versus Thuringian facies Palaeozoic of the north-east Bavarian SZ. From the Nové Město unit, predominantly metabasites of oceanic tholeiitic affinity and phyllitic metapelites, a regional metamorphic zonation from low grade chlorite zone up to garnet zone against the faulted contact with the Stronie series has been mapped (Domečka and Opletal, 1980).

Góry Sowie

The triangular Góry Sowie crystalline block, to the north of the Orlicka-Śnieżnik unit, is bounded on all sides by faults and is split into two parts by the north-west – south-east trending Sudetic Marginal Fault (Fig. 1): the mountainous part is found south-west of the fault. The northern boundary is the ophiolitic mafic/ultramafic Śleża complex with a crystallization age of *ca.* 350 Ma (Pin et al., 1988) and the Devono-Carboniferous of the Świebodzice depression, to the east are the mylonites and schists of the Niemcza zone (equivalent to the MSZ), in the south are the Nowa Ruda (351 Ma, Pin et al., 1988) and Braszowice ophiolites and the Bardzkie basin and to the west are Permo-Carboniferous sediments of the Intra-Sudetic Depression (see overview of Don, 1990). The unit comprises a dominant monotonous psammitic-pelitic paragneiss sequence, usually K feldspar-poor quartz + oligoclase + biotite ± sillimanite ± cordierite migmatites with garnet and kyanite relicts, and minor lenses of amphibolite, marble and graphitic rocks (Polański, 1955; Grocholski, 1967). Granulites occur in three locations, all south-west of the Sudetic Marginal Fault, where they are accompanied by garnet peridotites and eclogites (Żelaźniewicz, 1985; Smulikowski and Bakun-Czubarow, 1969). Bodies of coronitic metagabbros with rims of orthopyroxene, hornblende + spinel and garnet between olivine and plagioclase are reported by Morawski (1973); alteration to amphibolite is common. The granulites, recording peak conditions of 14 – 15 kbar, 750 – 800 °C (Pin and Vielzeuf, 1988), are mostly of felsic type with quartz, oligoclase, K feldspar, garnet and kyanite and occur in granoblastic as well as strongly foliated variants with the latter type associated with ductile shearing and retrogression (Żelaźniewicz, 1985). In the serpentinized lherzolites garnet is seen to overgrow spinel, is zoned, and shows kelyphitic breakdown (Bakun-Czubarow, 1983). Calculated equilibration conditions for the garnet peridotite stage (mineral cores) of 1 030 °C, 27 kbar, and for rims of 800 °C, 16 kbar were tied to ages of 403 Ma and 386 Ma, respectively, by Brueckner and Bakun-Czubarow (1991). Microflora in the common biotite-placioclase gneisses indicate a late Proterozoic maximum age (Gunia, 1981) whereas a concordant monazite U/Pb age of 381 ± 2 Ma and Rb/Sr biotite ages of *ca.* 370 – 360 Ma for the same rocks (Van Breemen et al., 1988) are consistent with the data from the ultramafic rocks. A complex structural history (outlined by Żelaźniewicz, 1990) interprets the granulites and peridotites to have been upthrust and *retrograded* concurrent with a *prograde*, post-D_1, amphibolite facies event in the host gneisses and then later to have shared four further deformation events. Cordierite, just developed at the eastern and north-western edges of the Góry Sowie block, is interpreted as occurring very late in the evolution (Dziedzic, 1985; Żelaźniewicz, 1990). The crystalline basement was exposed by the Carboniferous as evidenced by overlying late Visean Culm (Żakowa, 1963). The Góry Sowie block shows features comparable with those found in the Granulitgebirge: a comparison with the MM was published long ago (e.g. Bederke, 1927).

Kaczawa Complex

North-west of the Góry Sowie is the Kaczawa complex, extensively covered by post-orogenic (from Late Carboniferous) sediments and broken into a series of half-horst/half-graben structures between the Sudetic Marginal and Intra Sudetic Faults. The predominantly greenschist facies Cambrian to Upper Devonian pelagic sediments, metavolcanics and intrusions have been interpreted as an accretionary prism (Baranowski et al., 1990). Within the metabasites, alkali pillow basalts, lavas and sills of continental or oceanic island character, relicts of an early glaucophane bearing assemblage overprinted by the greenschist facies event have been reported (Baranowski et al., 1990; Kryza et al., 1990).

Izera-Karkonosce Block

Beyond the Main Intrasudetic Fault to the south-west of the Kaczawa complex is the Izera-Karkonosce block, dominated by the central dumb-bell shaped Variscan Karkonosce granite. A metamorphic (up to amphibolite facies) complex of granitic to granodioritic gneisses with minor pelitic, quarzitic and basic lenses occurs north (Izera Mountains) and south (Krkonoše crystalline complex) of the granite and in the south and east is overlain by a distinctive Lower Palaeozoic (palaeontologically proved) group comprising a lower volcaniclastic pelite-amphibolite-marble series with a graphitic quartzite at its base and an upper bimodal volcanic pile of island arc affinity from which blue amphiboles have been reported (Guiraud and Burg, 1984; Narebski et al., 1986; Mierzejewski and Oberc-Dziedzic, 1990) Upper Devonian – Lower Carboniferous low grade sediments are found at the western edge of the block (see Mierzejewski and Oberc-Dziedzic, 11990).

Lausitz Block

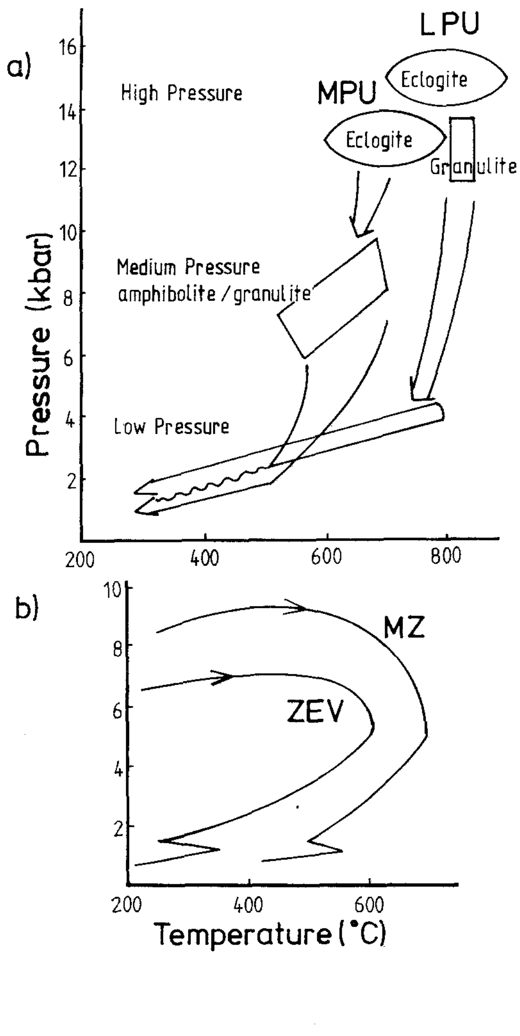
The Lausitz block consists predominantly of large granodiorites and granites of Upper Palaeozoic, Lower Palaeozoic and possibly also Late Precambrian age and a Cambrian – Carboniferous volcano-sedimentary sequence above greywacke units of presumed Precambrian age: contact metamorphic features are common in the sedimentary series (Bankwitz et al., 1988). A 'Lausitz-like' Precambrian greywacke series cut by a granodiorite is found poking through the Permian and Cretaceous cover of the Elbe Zone at the margin of the Erzgebirge SSE of Dresden, where it is associated with two fault-separated Palaeozoic series resembling the Thuringian and Bavarian Facies of the SZ further west (Linnemann, 1990).

Discussion

To deduce the geological evolution of the Bohemian Massif we must sift through evidence gathered from different scientific disciplines derived by a variety of techniques and on scales from the atomic interaction in crystal lattices to satellite imagery. The massif must be treated as part of the more extensive Variscan Orogenic Belt which, although by no means universally accepted, formed by an ocean closure – collision – wrench faulting tectonic scenario during the construction of Pangea (e.g. (Ziegler, 1984; Neugebauer, 1988; Matte, 1991; Franke, 1989; Matte et al., 1990). Palaeontological evidence supports a large ocean between Gondwana and Laurasia until the late Ordovician (Cocks and Fortey, 1982). The possible nature of the margin of Gondwana during its northward movement due to closure, by subduction, of this oceanic realm may be inferred from the analogous present day Western Pacific, where Australia is heading for a collision with Asia. For example, around the North Island of New Zealand, oblique subduction is causing stretching associated with voluminous acid magmatism on land, whereas along strike is an oceanic rift (Walcott, 1987). In the Phillipines numerous transform faults have offset and repeated subduction zones, arc segments and spreading ridges (cf. Hall and Nichols, 1990). Exposure of garnet peridotites and eclogites along fault zones in Indonesia and New Guinea (e.g. Helmers et al., 1990) is extremely interesting as they have been formed and exhumed before the major continent – continent collision. A significant fact to be recognized is that multiple rift basins, volcanic arcs or shallow water, slope and trench depositional sites of the same age may have existed in the same region between the approaching continental blocks. Such duplicity of environments must be considered when broad correlations within the later collision belt are made. For example, it would be ridiculous to closely link the hypothetical diet cola can zone of the Bondi Beach and Long Beach Sandstones in a future Pacific-absent megacontinent. Nevertheless, comparisons and correlations must be made to ascertain the gross geometry of the Bohemian Massif, i.e. the fundamental crustal units which acted coherently, the age of their consolidation, the position of their boundaries and the ages and effects of fault/thrust/wrench movement along them. The location of possible former oceanic realms (ophiolite-lined sutures) and the deduction of the age and duration of the passive versus active nature of the margins of these oceans are important guides to the large scale progression of the orogeny. The final closure of oceanic or rift basins is also an important time marker as the interaction of thicker continental blocks will have a character, and possibly also direction, very different from that between the preceding thinned crustal segments. In the following discussion, the metamorphic features of rocks of the Bohemian Massif will be summarized and combined with the nature of protoliths and structural and geochronological data in an attempt to delineate some fundamental building blocks and their interaction over time.

When we look at recent attempts to quantify the metamorphic pressure – temperature – time paths for the Bohemian Massif rocks we see the major pitfall: interpreting pressure – temperature – time paths for rock units where the units are composites of rocks with different histories. Blümel (1986; see also 1990) distinguishes a medium pressure (MPU) and a low pressure (LPU) unit (Fig. 2), which have the same shape of pressure – temperature path but at different temperatures. The Variscan low pressure event characterizing the LPU is apparently not seen in the MPU, but surprisingly both have eclogite stages. The eclogites in the Oberpfalz are seen to be an integral part of the Moldanubian LPU of north-east Bavaria, with evidence having been presented

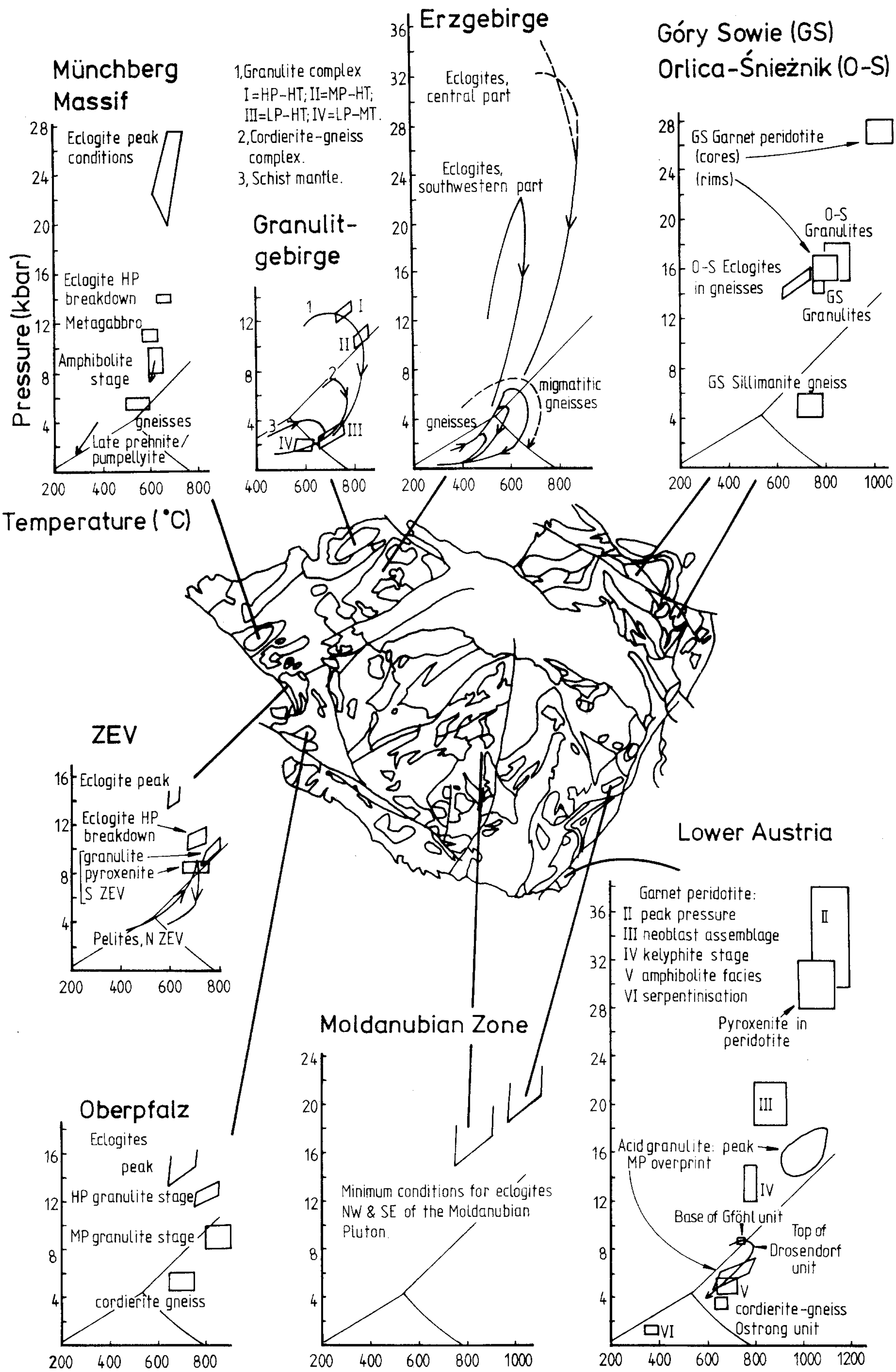
Fig. 2 a, b. Previously published pressure – temperature paths for the north-west Bohemian Massif. **a** Blümel, 1986; **b** Stöckhert, 1989



to show that relicts of a higher pressure history – namely kyanite relicts in plagioclase (in metapelites) – are sporadically preserved throughout the region. True polymetamorphism in the LPU does not tally with the simple monophase progressive evolution of the Künisches Gebirge mica schists. Further studies in the area (O'Brien, 1989 b; 1989 c; 1991 a; and outlined earlier) show that kyanite bearing pelites directly *interlayered* with eclogites have distinct garnet compositions (high Ca-Mg) comparable with a higher pressure evolution, whereas others *outside* the eclogite bodies have only evidence for a medium pressure former stage. Although kyanite relicts in plagioclase do exist and provide evidence for a medium pressure history at a significant temperature (minimum 650 °C at 7 kbar), others (for example, Fig. 7-3 in Weber, 1985) could also be interpreted as former inclusions in garnet now sitting metastably in plagioclase produced by garnet breakdown during a temperature increase. This difference in temperature is an important distinction in comparison of pressure – temperature paths. A contrasting model by Stöckhert (1989) saw the ZEV and adjacent MZ as different levels of essentially the same unit such that their pressure – temperature paths were perfectly matching in form, though at different temperatures (Fig. 2). The high pressure relicts found in the ZEV since then (O'Brien et al., 1993) and their incompatible history compared with accompanying paragneisses negate this model unless both MZ and ZEV high pressure rocks are allochthonous.

From the multiple rock descriptions given here it is clear that the rocks showing the highest pressures of metamorphism – the eclogites, granulites and garnet peridotites – are widely distributed but form rather small proportions of their host units. The high pressure rocks are always found associated with retrograded high pressure rocks as well as rocks showing no apparent signs of having ever endured high pressures – the arbitrary limit being set at 10 kbar, corresponding to a normal maximum crustal pressure. In the more external parts of the belt we commonly find only thin nappes with the high pressure rocks near the top of the pile and rocks of decreasing grade underneath, including units whose palaeontologically proved ages are younger than the metamorphic ages of overlying sequences. An important feature pointed out by O'Brien (1989 a) and expanded upon later (O'Brien et al., 1990) is the temperature gradient which existed across the Bohemian Massif when considering the high pressure rocks alone (Fig. 3). Thus in

Fig. 3. Assembled pressure – temperature data from various units with high pressure relicts: Münchberg Massif (Franz et al., 1986; Klemd, 1989; O'Brien, 1993); ZEV (O'Brien et al., 1992; Kleemann, 1991; Reinhardt, 1990); Oberpfalz (O'Brien, 1989; unpublished data); Moldanubian Zone (Dudek and Fediuková, 1974); Lower Austria (Zaydan and Scharbert, 1983; Petrakakis, 1986; Carswell, 1991; Carswell and O'Brien, 1993); Orlica-Śnieżnik/Góry Sowie (Bakun-Czubarow, 1983; 1989; 1991; Pin and Vielzeuf, 1988); Erzgebirge (Krentz et al., 1990; Schmädicke et al., 1992); Granulitgebirge (Grew, 1986; Frischbutter and Rötzler, 1990)


Münchberg Massif
Eclogite peak conditions
Eclogite HP breakdown
Metagabbro
Amphibolite stage
gneisses
Late prehnite/ pumpellyite
Pressure (kbar)
Temperature (°C)
1, Granulite complex I=HP-HT; II=MP-HT; III=LP-HT; IV=LP-MT.
2, Cordierite-gneiss complex.
3, Schist mantle.
Granulitgebirge
Erzgebirge
Eclogites, central part
Eclogites, southwestern part
migmatitic gneisses
gneisses
Góry Sowie (GS) Orlica-Śnieżnik (O-S)
GS Garnet peridotite (cores) (rims)
O-S Granulites
O-S Eclogites in gneisses
GS Granulites
GS Sillimanite gneiss
ZEV
Eclogite peak
Eclogite HP breakdown
granulite
pyroxenite
S ZEV
Pelites, N ZEV
Lower Austria
Garnet peridotite:
II peak pressure
III neoblast assemblage
IV kelyphite stage
V amphibolite facies
VI serpentinisation
Pyroxenite in peridotite
Acid granulite: peak
MP overprint
Base of Gföhl unit
Top of Drosendorf unit
cordierite-gneiss
Ostrong unit
Moldanubian Zone
Minimum conditions for eclogites NW & SE of the Moldanubian Pluton.
Oberpfalz
Eclogites
peak
HP granulite stage
MP granulite stage
cordierite gneiss

the north-west, in the MM and part of the Erzgebirge, eclogites have the lowest temperatures. The temperatures at eclogite facies and, just as importantly, during the breakdown stages, increase towards the south-east. A comparable regional temperature variation has been reported from the Norwegian Western Gneiss Region (Krogh, 1977) and in the Variscan belt in France (Bouchardon et al., 1989). Some regions, however, have sequences with different groups of high pressure rocks showing different temperature evolutions (e.g. Erzgebirge, Orlica-Śnieżnik) and it is clear that rocks with different pressure evolutions are also now side by side (e.g. granulites and garnet peridotites) even in the highest pressure massifs (see Fig. 3). How can these features be explained?

The most important indicator of the metamorphic path that a unit has taken is the rocks themselves. Studies of the eclogites, pyroxenites and peridotites have emphasized the multistage evolution of their complex mineral assemblages (e.g. O'Brien, 1989a; 1991a; 1991b; 1991c; 1993: O'Brien et al., 1990; 1992; O'Brien and Schmidt, 1991; Carswell and O'Brien, 1993; Carswell et al., 1989; Medaris and Carswell, 1990). The rocks appear to re-equilibrate, fully or in part, at a number of discrete positions in pressure – temperature space which also show a regional thermal pattern such that the loci of pressure – temperature points define a series of *piezothermic arrays* (Richardson and England, 1979). Early theoretical models of the pressure – temperature evolution of thickened crustal sections (e.g. England and Richardson, 1977; England and Thompson, 1984) predict a metamorphic peak temperature at well below the peak pressure and a simple clockwise loop for a single overthrust scenario. The fact that multiple mineral generations are commonly present tells us that the reaction and tectonic histories are not so simple. Instead of drawing a single smooth curve through the calculated pressure – temperature domains from a single sample, it has been suggested (O'Brien, 1991a; 1991b; 1993) that the pressure – temperature paths were kinked or inflected. Each recognizable step in the pressure – temperature evolution of a rock must be related to events that activated and then deactivated the relevant reactions. This may be a short-lived thermal pulse caused by magmatic intrusion, juxtaposition by faulting or thrusting of crustal levels with different ambient temperatures, or the slowing of 'refrigerating' underthrusting as found in a subduction zone. Reaction kinetics may play an important part. The lack of a catalyst, for example a fluid phase, could retard potential reaction and allow phases to persist metastably. Thus when a catalyst became available again the rock, now possibly at a lower pressure due to continued uplift and with an even greater free energy, would react quickly. The preservation of delicate intergrowths tells us that our key samples were not deformed, but deformation-enhanced reaction outside or at the margins of the high pressure bodies, where recrystallization – commonly to amphibolite – may be complete, could have consumed available fluids and thus shielded interiors from reaction while reducing the overall volume of material preserving the older history.

The multiple inflected paths found in the highest pressure part of this region are more closely modeled by multiple thrusting events (e.g. Gillet et al., 1989; Mercier et al., 1991a; 1991b). Models presented for the Variscan eclogite belt in the Armorican and Central Massifs in France predict a major underthrusting, of variable areal extent, beneath the eclogite bearing unit thus causing cooling (Mercier et al., 1991a; 1991b). The result is that the part of the region closest to the new underlying unit will be cooled more quickly than that more external to the 'refrigerator'. An additional feature of this tectonic scenario is that each new underthrusting is likely to introduce a rock unit formerly at lower grade into the metamorphic pile where it will undergo a *prograde* metamorphism, possibly with dehydration reactions, whereas the 'refrigerated' pile lying above may suffer a *retrograde* event, possibly catalysed by the fluids derived from below. The result of this type of multi-thrusting is a composite thrust sheet containing rocks of different metamorphic age and preserving evidence for a range of metamorphic pressures: exactly the pattern which we see in the best studied nappes of the Bohemian Massif.

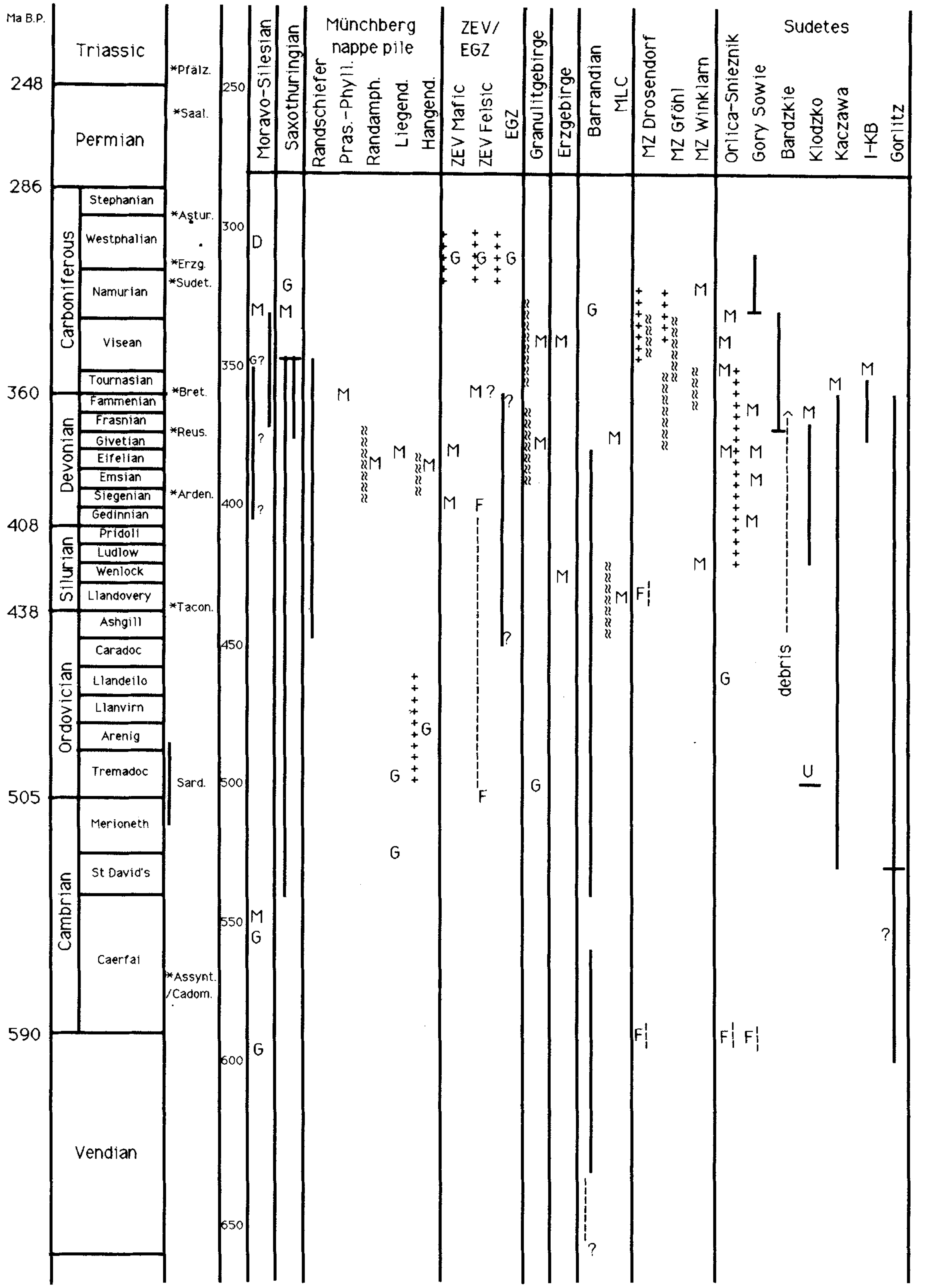
The most widely evident metamorphism in the Bohemian Massif is of low pressure, high temperature type with abundant migmatization. This event has been closely followed in time by the intrusion of peraluminous granites and related contact metamorphism. A possible cause was fast exhumation, by extension faulting, exceeding the rate of crustal thermal re-equilibration and resulting in isothermal decompression in exhumed rocks concurrent with isobaric heating in hanging wall rocks. Alternatively, imbrication and thrust stacking of slices of hot, previously thinned crust over young sediments would give rise to considerable melting and granite formation at depth as fluids released from the sediments reduced the melting temperature of the overlying units. This is essentially the model of Brown and Treloar (1991) for the Brittany migmatite belt and also that for the proposed origin of Himalayan leucogranites (France-Lanord and Le Fort, 1988). Such voluminous granites, having risen and reached their equilibrium depth, could cause a regional low pressure metamorphism. Subsequent addition of another overlying thrust sheet could possibly reactivate upward granite movement to produce intrusive contact metamorphism in rocks with an earlier regional low pressure, high temperature metamorphism. This scenario is consistent with emplacement of the thin nappe pile during the late stages, or after, regional low pressure metamorphism but before the arrival of granites at the thrust-plane level.

Isotope studies yielding information on protoliths and intrusive or metamorphic events have become an important tool in the study of orogenic belts. However, in a polymetamorphic region or where mineral reactions are multistage and there is obvious disequilibrium, geochronological results become difficult to interpret. The ages of metamorphic events cannot be taken in isolation, however. Major temperature and pressure changes below the earth's surface are usually driven by tectonic events which will also be reflected in depositional basins as volcanic episodes, stratigraphic breaks or deformation features. Looking at the Variscides as a whole, the numerous minor 'orogenic' or deformation phases deduced before the days of isotopic dating [Sardian (500 ± 15 Ma); Taconian ($\cong 435$ Ma); Ardennian/Ligerian ($\cong 395$ Ma); Reussian ($\cong 375$ Ma); Bretonian (360 ± 5 Ma); Sudetian ($\cong 325$ Ma); Erzgebirgian ($\cong 320$ Ma) and Asturian ($\cong 295$ Ma)] fit rather well with the clusters of ages since determined for metamorphic and magmatic rocks (Fig. 4). Thus the multi-stage thrusting model used to explain the sequence of metamorphic overprints at decreasing pressure seems to have some basis. The clusters of metamorphic ages in particular units taken in conjunction with proved sedimentary ages in surrounding series provide some of the strongest evidence for separate evolutions of the high pressure and low pressure series until the late stages of orogeny.

For structural geology to aid us in our interpretation we need to find structures in the rocks and relate them to metamorphic events. Numerous studies have been carried out throughout the Bohemian Massif but the common failing is that structures in rocks deformed above the amphibolite grade do not seem to be preserved. For the highest pressure rocks, the amphibolite stage is two or three steps down the evolutionary ladder and so information relating to the earlier, generally higher temperature, events is overprinted. Multiple deformation events generally make recognition of former stages increasingly difficult. The interpretation of geological structures must therefore be made in the light of the importance of the structure relative to the *overall* possible history. For example, in the surroundings of the Intermediate Massifs, the compatible structural histories of the so-called allochthonous and autochthonous units led Cloos (1927) to counter the nappe models and favour an *in situ* evolution: the possibility that earlier emplacement related structures had been obliterated was not considered. Likewise, in the south-east of the Bohemian Massif, thrusting of the margin of the MZ over the MSZ has been shown to be part of a multiphase event with a change in principal direction, all of which related to the amphibolite facies and younger stages in the overlying unit. Late structures can also make the distribution of units confusing. The presence of a thin composite nappe unit with a thrust contact between its crystalline and low grade part and also a thrust contact with its (par)-autochthonous host will, when folded and preserved in synclines and limbs of anticlines, appear to be related to 'major' fault zones.

The most intensive integrated studies within the Bohemian Massif have taken place in the western part of the Bohemian Massif around the Continental Deep Drilling (KTB) site (located in the ZEV). Overviews of geochronology (Hansen et al., 1989; Kreuzer et al., 1989; Hansen, 1990), metamorphism (Blümel, 1983; 1986; 1990; O'Brien, 1991a) and tectonic development (Franke, 1984; 1989; KTB, 1986; Weber and Vollbrecht, 1989; Hirschmann et al., 1990) provide much information, but the lack of an accepted definition for the various large scale units has clouded the picture. The MM is happily accepted as allochthonous, the ZEV also (although to a lesser extent), but the scare high grade relicts in the Oberpfalz (Opf in Fig. 1) have mostly been treated as part of the MZ. Age dating of the rocks with high pressure relicts reveals that they were metamorphosed before 380 Ma, with the latter date representing a major cooling event as evident from different isotopic systems; values around 360 Ma are found from rocks within the lower level nappes (Erbendorf Greenschist Zone, prasinite-phyllite series). In the MZ and SZ the low pressure metamorphism is dated around 320 – 330 Ma and was followed by granite intrusion. The low pressure event, not recorded in the MM, is vaguely represented in the eastern ZEV (Kreuzer et al., 1989) and is well documented by monazite in an acid granulite from Winklarn (Opf in the MZ) in which Nd/Sm mineral isochrons define a 423 Ma age for the earlier higher pressure event (Von Quadt and Gebauer, 1988). Assuming that the Winklarn rocks are also allochthonous and part of the nappe, petrological studies indicate an increase in the degree of lower pressure overprint in the nappe from north-west to south-east, a feature not unexpected considering the increase in metamorphic grade in the underlying SZ/MZ *and* the increase in the temperature of breakdown reactions of eclogites in the same direction. No individual pressure – temperature path exists for the different units, rather they are nested pressure – temperature loops with piezothermic arrays for each specific metamorphic stage. This is shown schematically in Fig. 5 (cf. O'Brien, 1991a) whereby units with a high pressure early stage (M1), A, B and C, with their variation in peak temperature (corresponding to the eclogite bearing units of the Bohemian Massif), are juxtaposed at lower pressure (M2, caused by a second slight burial/subduction) with unit D (analogous to the pelitic gneisses of the ZEV and the Liegendserie of the MM). Finally, the composite nappe is emplaced on unit E (comparable with the SZ and MZ in the lower and higher temperature sectors, respectively) in a third event, M3, also caused by a renewed burial. Ages recorded for each point defining a single array will decrease slightly at the higher temperature end as reactions take longer to 'close' isotopically. Assuming a link between the high pressure rocks of the Gföhl Nappe in the south-east of the Massif and those in the north-west then the younger ages of the former are consistent with the higher temperature evolution in that segment.

Such a link between the north-west and south-east of the Massif is not yet widely accepted. Confusing in southern Bohemia and Moravia is the presence of the majority of 'common eclogites' (according to the classification of Dudek and Fediuková, 1974) i.e. those corresponding closest to the eclogites in the north-west of the Massif, in Monotonous series *outside* the granulite massifs. This means that more than one unit with high pressure rocks exists. A tectonic juxtaposition of such



M or ≈≈≈: metamorphic events G or ++++; intrusion age of granite or gabbro

——— ; sedimentation, broken when uncertain

F; age from fossils D; deformation without metamorphism

◀ **Fig. 4.** Assembled data on sedimentation, intrusion and metamorphic ages in the various units of the Bohemian Massif. Sources are given in the text

eclogite + granulite bearing and 'common eclogite' bearing units could explain the discrepancy in temperature between certain garnet-clinopyroxene rocks in the Erzgebirge and Orlica-Śnieżnik areas.

Some later models (e.g. Franke, 1989; Matte et al., 1990; Matte, 1991) see the high pressure rocks of the north-west of the Massif as part of a thrust sheet derived from the Barrandian block or at its margin with the Saxothuringian. In the south-east, the Gföhl Nappe was interpreted to be rooted at the southern margin of the Barrandian block and thrust in a south-easterly direction. The Barrandian block is thus supposedly underthrust from both sides but with garnet peridotites, exhumed from a depth of around 100 km, now less than 100 km apart on either flank (České Středohoří and Kutná Hora). However, in the case of the Gföhl unit, the thermal pattern preserved in the mafic and ultramafic rocks is more in line with at least initial north-west directed overthrusting *during high pressure conditions*.

The model of Hirschmann et al. (1990) interprets the Barrandian, Bavarian MZ and (par)autochthonous SZ as different structural levels of the same crustal block affected by differential tilting along major faults. These have been overthrust by a composite nappe pile with high pressure relicts near the top and some marginal basin 'ophiolite' and telescoped trench and slope sediments at the bottom. The accretion of the lowest nappe units is comparable with part of the model of Behr et al. (1980; 1984). The nappe units originated either as part of a suture zone between the Saxothuringian and Barrandian block or from a no longer identifiable suture (see also Weber and Vollbrecht, 1989). Emplacement of the Münchberg and ZEV nappes involved west to south-west directed movements at amphibolite facies followed by later north-west and then south-east directed motion at lower grades (Kleemann et al., 1989; Franke et al., 1992). Again the problem is that the recognizable structures are a long way down the evolutionary path of the high pressure rocks which would, according to their preserved thermal pattern, require initial underthrusting from the north-west.

It is interesting to note that if the *ca.* 100 km dextral displacements along the major shear zones of the Massif – essentially the boundaries of the SZ, MZ, M-SZ, Barrandian block and Sudetes – are considered (cf. Rajlich, 1990b), then the high pressure units, excluding those in the Sudetes, are draped around the southern part of the Barrandian block. The situation in the Sudetes is not clear. Although the metamorphic effects of hypothetical nappe emplacement over the top of the Barrandian would be slight (cf. the situation around the MM), the less intense deformation relative to that in the SZ and MZ speaks against this possibility. A geometrical solution is to have the high pressure rocks of the Sudetes as an

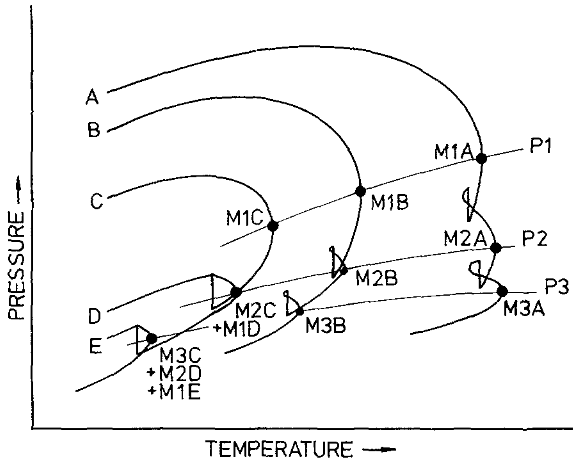


Fig. 5. Schematic pressure–temperature grid for a multi-stage thrusting evolution. Detailed explanation in the text. Paths A, B and C are for different parts of the same unit, D and E are paths for units accreted during later thrusting. P's are piezothermic arrays, M's are metamorphic events

extension of the SZ, thus extending the granulite-eclogite-peridotite belt of the Erzgebirge and Granulitgebirge (e.g. Aleksandrowski, 1990). This model would also require a greater offset along the Barrandian – SZ boundary fault to keep the Barrandian free from major overthrusting, as well as along the Elbe Lineament. Significantly, the high pressure rocks would thus be derived from one side and not both sides of the Barrandian block. It is clear that a knowledge of the timing of movement(s) along the major shear zones is vital to our understanding of the overall tectonometamorphic evolution. They may, in fact, be juxtaposing different structural levels of the same fundamental units thus creating 'apparent terranes'.

The distinction of Zwart (1967) between 'Hercynotype' orogens characterized by low pressure andalusite-cordierite type metamorphism in thin zones, abundant granites, scarce ophiolites, scarce nappes and of broad extent and 'Alpinotype' orogens with their high pressure minerals (glaucophane, sodic pyroxene, lawsonite and kyanite) in thick metamorphic zones, abundant ophiolites, dominant nappes, scarce granites and migmatites and of narrow (belt-like) extent led many workers to consider the Variscan belt in Europe to be fundamentally different from its neighbouring Caledonian and Alpine chains. The high pressure rocks of the Variscides were thought to be part of an older Precambrian orogeny. From the increasing database of geochronological data the high pressure rocks can be seen to be of Palaeozoic age but, more specifically, of *early* Variscan age, i.e. > 370 – 380 Ma. Remnants of ophiolite are clearly found in many parts of the Bohemian Massif as well as elsewhere in Variscan Europe. Some of these are shown to be younger than the metamorphic rocks which now overlie them, a feature indicative of nappe tectonics. If we just consider the broad groups of high pressure polymetamorphic rocks and medium to low pressure series and their separate clearly defined age characteristics, then the nappes defined within central Europe are extensive. Moving into the external parts of the Variscides, to the Rhenohercynian Zone, the pattern of thin skinned nappes continues and overall the south-easterly dipping pattern of major seismic reflectors confirms this on a crustal scale. This is more characteristic of an Himalayan-type collision.

What we are seeing is thus evidence for an early collision leading to the features typical of the 'Alpinotype' orogeny followed by a later continent – continent collision whereby the products of the first phase, now in erosionally thinned or otherwise exhumed units, are involved in major 'thin-skinned' tectonic events and emplaced hundreds of kilometres away from their original 'narrow collision belt'. During this stage, continental trench, slope and shelf deposits may have become incorporated into the base of the advancing nappe pile. Graphitic shales and cherts, superb lubricators, appear often in the lower units of these nappes and are similar to those in the basal unit known from the Scandinavian Caledonides where there are also eclogites in far travelled nappes (e.g. Gee, 1978).

Finally, although the presentation of a satisfactory *coherent* geological model for the development of the Bohemian Massif has not been possible, undoubtedly the metamorphic *style* of the Variscan Orogeny has been ascertained. Important to recognize is that only a minority of the present day rocks preserve records of older parts of the Variscan event, but these are the important limits and constraints with which any future models must be consistent.

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