J. metamorphic Geol., 2003, **21,** 3–20

High-pressure granulites: formation, recovery of peak conditions and implications for tectonics

P. J. O'BRIEN AND J. RÖTZLER
Institut für Geowissenschaften, Universität Potsdam, Postfach 601553, D-14415 Potsdam, Germany
(obrien@geo.uni-potsdam.de)

ABSTRACT High-pressure granulites are characterised by the key associations garnet-clinopyroxene-plagioclase-quartz (in basic rocks) and kyanite-K-feldspar (metapelites and felsic rocks) and are typically orthopyroxene-free in both basic and felsic bulk compositions. In regional metamorphic areas, two essential varieties exist: a high- to ultrahigh-temperature group and a group representing overprinted eclogites. The high- to ultrahigh-temperature type formerly contained high-temperature ternary feldspar (now mesoperthite) coexisting with kyanite, is associated with garnet peridotites, and formed at conditions above 900 °C and 1.5 GPa. Clinopyroxene in subordinate basic rocks is Al-rich and textural evidence points to a high-pressure–high-temperature melting history. The second variety contains symplectite-like or poikilitic clinopyroxene-plagioclase intergrowths indicating former plagioclase-free, i.e. eclogite facies assemblages. This type of rock formed at conditions straddling the high-pressure amphibolite/high-pressure granulite field at around 700–850 °C, 1.0–1.4 GPa. Importantly, in the majority of high-pressure granulites, orthopyroxene is secondary and is a product of reactions at pressures lower than the peak recorded pressure. In contrast to low- and medium-pressure granulites, which form at conditions attainable in the mid to lower levels of normal continental crust, high-pressure granulites (of nonxenolith origin) mostly represent rocks formed as a result of short-lived tectonic events that led to crustal thickening or subduction of the crust into the mantle. Short times at high-temperature conditions are reflected in the preservation of prograde zoning in garnet and pyroxene. High-pressure granulites of both regional types, although rare, are known from both old and young metamorphic terranes (e.g. *c.* 45 Ma, Namche Barwa, E Himalaya; 400–340 Ma, European Variscides; 1.8 Ga Hengshan, China; 1.9 Ga, Snowbird, Saskatchewan and 2.5 Ga Jianping, China). This spread of ages supports proposals suggesting that thermal and tectonic processes in the lithosphere have not changed significantly since at least the end of the Archean.

Key words: disequilibrium; geothermobarometry; high-pressure granulite; mesoperthite; reaction-texture.

INTRODUCTION

Granulites from the type locality of the Saxonian Granulitgebirge, Germany (Weiss, 1803) are mainly light-coloured rocks, of broadly granitic composition, showing quartz + feldspar-dominated parageneses with minor kyanite and garnet, and characteristically showing a strong platy or mylonitic fabric (e.g. Scheumann, 1961; Pin & Vielzeuf, 1983, 1988; Fiala *et al.*, 1987). However, modern usage of the term granulite for any rock of the granulite facies (e.g. Eskola, 1952), rather than just for this specific rock from Saxony, has resulted in heated discussion (see Behr *et al.*, 1971; Mehnert, 1972). It is significant that Winkler (1979), in the fifth edition of his textbook 'Petrogenesis of Metamorphic Rocks', saw the Saxonian rocks as nondiagnostic for his newly defined 'regional hypersthene zone' and ironically it is exactly this Saxony granulite-type that has taken on greater importance as the high pressure and temperatures of its formation have become understood.

The granulite facies is subdivided into high-, medium- and low-pressure granulite fields on the basis of experimental studies in basalts (Green & Ringwood, 1967; Ito & Kennedy, 1971; Hansen, 1981). The HP-granulite field lies above the 'garnet-in' reaction in quartz tholeiite whereas the 'garnet-in' reaction in undersaturated basalts divides the fields of medium- and low-pressure granulites (Fig. 1). Important reactions controlling garnet and pyroxene presence as well as their compositions are (abbreviations after Kretz, 1983):

$$\mathrm{Opx + Pl = Grt + Qtz;} \qquad \mathrm{(R1)}$$

$$\mathrm{Opx + Pl = Grt + Cpx + Qtz;} \qquad \mathrm{(R2)}$$

$$\mathrm{Cpx + Pl = Grt + Qtz} \qquad \mathrm{(R3)}$$

and

$$\mathrm{An(in\ Pl) = CaTs(in\ Cpx) + Qz} \qquad \mathrm{(R4)}$$

In mafic rocks these reactions thus delineate, from high to low pressure, the fields of granulites containing

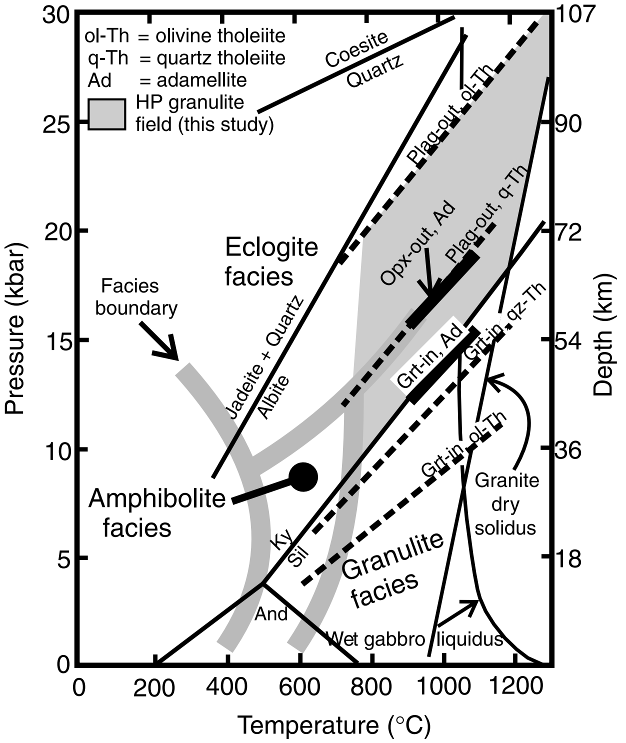

Fig. 1. *P–T* grid with granulite, amphibolite and eclogite facies domains (from Spear, 1993). Garnet and pyroxene stability curves for mafic rocks of different composition (Green & Ringwood, 1967; Ito & Kennedy, 1971; Hansen, 1981) define the standard subdivision for high-, medium- and low-pressure granulites. Opx-out and Grt-in in adamellite composition is from Green & Lambert (1965). The dry granite solidus is from Johannes & Holtz (1996). In this study, only rocks plotting in the kyanite field (shaded area) are considered as high pressure granulites.

Grt + Cpx, Grt + Cpx + Opx and Cpx + Opx. The scheme for basic rocks suggested by De Waard (1965) is slightly different with low-, medium- and high-pressure zones defined by Ol + Pl stable, Opx + Pl stable (Ol + Pl not stable) and Cpx + Pl + Grt + Qz stable (Opx + Pl not stable). At higher pressures, plagioclase disappears in basic rocks by reactions such as

$$\mathrm{Ab(in\ Pl)} = \mathrm{Jd(in\ Cpx)} + \mathrm{Qz} \tag{R5}$$

and

$$\mathrm{An(in\ Pl)} = \mathrm{Grs(in\ Grt)} + \mathrm{Ky} + \mathrm{Qz} \tag{R6}$$

as the eclogite facies is reached and generally the disappearance of orthopyroxene is taken to mark the transition to the lower temperature amphibolite facies.

In this study, HP granulites are considered only from the restricted *P–T* realm for Grt + Cpx-bearing rocks of quartz tholeiitic and high-Al basaltic compositions (Wood, 1987) that falls also within the kyanite stability field (Fig. 1). Experimental studies of partial melting of amphibolites at high *P–T* conditions have produced such orthopyroxene-free HP granulites (e.g. Rushmer, 1993) but note that the HP assemblage Grt + Cpx + Pl ± Hbl ± Qz in mafic rocks may also occur in the amphibolite facies (see review of Pattison, 2003). However, the Al-content of granulite clinopyroxene is controlled by two reactions, namely a pressure-dependent (R5) and a temperature-dependent (R4) reaction, and thus, if chemical analyses are available, it is generally possible to distinguish Ca-Tschermaks-rich granulite facies pyroxene from those of lower grade (cf. Lovering & White, 1969). In metapelitic and metagranitic rocks, the important association for high-pressure granulites is Grt + Ky + Kfs as controlled by reactions such as:

$$\mathrm{Mu} + \mathrm{Qz} = \mathrm{Kfs} + \mathrm{Ky} + \mathrm{melt}, \tag{R7}$$

$$\mathrm{Bt} + \mathrm{Ky} + \mathrm{Qz} = \mathrm{Grt} + \mathrm{Kfs} + \mathrm{melt} \tag{R8}$$

and

$$\mathrm{Bt} + \mathrm{Qz} = \mathrm{Opx} + \mathrm{Grt} + \mathrm{Kfs} + \mathrm{melt} \tag{R9}.$$

Experimental studies at high pressure conditions on a granitic (adamellite) composition (Green & Lambert, 1965) showed the disappearance of orthopyroxene at around the same conditions as the 'plagioclase-out' reaction for quartz tholeiite and the beginning of a large field for Grt + Cpx-bearing assemblages from about 16–2.0 GPa at 950–1100 °C. Importantly, on the basis of phase relations from the adamellite study, the Grt-bearing, Opx-free Saxonian 'type locality' granulites plot in the eclogite facies field as defined for tholeiitic bulk compositions (see also Winkler, 1979).

Rocks of pelitic bulk composition are also found in some granulite terranes. At the conditions outlined for the mafic and felsic granulites (Fig. 1) pelitic granulites should be kyanite- and K-feldspar-bearing and, at higher temperatures, should show evidence for dehydration melting of biotite. Experimental and phase equilibrium studies in pelitic systems (e.g. Le Breton & Thompson, 1988; Vielzeuf & Holloway, 1988; Carrington & Harley, 1995; Patiño Douce & Beard, 1995; Harley, 1998; Spear *et al.*, 1999; Indares & Dunning, 2001) show that biotite can exist to about 900 °C in the kyanite field where it is replaced by orthopyroxene as melting occurs. At lower pressures, in the sillimanite field, this marks the beginning of ultrahigh-temperature (UHT) Opx + Sil-bearing assemblages (Harley, 1998) but there is no reason to restrict the term 'UHT-granulite' just to rocks formed at normal crustal pressures. If crust is over-thickened, as in the present-day Himalaya, or if crust is subducted into the mantle, then HP–HT conditions may be attained in these rocks as well.

Although garnet peridotites are generally regarded as mantle rocks found sometimes as xenoliths in kimberlite or alkali basalt, it is remarkable how many large bodies have been identified in HP granulite terranes. In ultrabasic rock compositions the presence of garnet, important for reliable geothermobarometry, indicates higher pressures than the occurrence of spinel but the transition is compositionally dependent (see Harley & Carswell, 1990), a rather wide transition zone occurs, and so no definite granulite–eclogite boundary exists.

The highest-pressure granulites, i.e. orthopyroxene-free varieties of felsic or mafic composition, have been largely ignored in the literature in contrast to other granulite types. For example, of the over 90 granulite terranes assessed in the excellent review of granulites by Harley (1989), only 10% exhibited peak conditions above 1.0 GPa and of these only two were kyanite-bearing. In addition, in an attempt to emphasise the importance of magmatic intrusion as the heat source for granulite formation along anticlockwise *P–T* paths, Bohlen (1987) questioned the regional tectonic importance of 'scarce' higher pressure granulites. In the last decade, several publications on the topic of HP granulites and their formation have appeared in the international literature and the time has come for a review of the newly available data and a re-assessment of the importance of this rare rock type.

In the following, the key petrological features of the documented HP granulites will be addressed as well as their contribution to the understanding of lithospheric processes. It is important to note that pressure-temperature-time (*P–T*–t) paths of HP granulites will cross through the *P–T* realm covered by the reactions listed above, during exhumation and cooling, as will be recorded in the form of compositional zoning, reaction coronas, symplectites, kelyphites and overgrowths of multiple generations of these phases. It is the correct deciphering of these reaction textures that enables the petrologist to deduce the trajectory and velocity of the *P–T*–t path and thus the tectonometamorphic evolution of the granulite-bearing terrane.

HP GRANULITE TYPES

In general, two distinct varieties of HP granulite are recognised in regional metamorphism. The first variety forms at high- and ultrahigh-temperature conditions (often over 1000 °C) and is typified by the type granulite found in the Saxonian Granulite Massif in Germany. A second variety of HP granulite encompasses rocks that entered the *P–T* field of the granulite facies via the eclogite facies, or at pressures approaching those of the eclogite field, and thus represent parts of subducted complexes that were not rapidly exhumed and underwent reactions as a result of partial re-equilibration of perturbed geotherms. HP granulite facies assemblages are also recorded in some suites of presumed lower crustal or upper mantle xenoliths in volcanic rocks. In the following, each of these particular types will be described and their importance for understanding the tectono-thermal evolution of metamorphic belts will be outlined. A list of locations, rock type, peak conditions of metamorphism and age of peak metamorphism can be found in Table 1.

HIGH- (ULTRAHIGH-) TEMPERATURE TYPES

An association of HP granulite facies rocks of regional extent is found within the various basement blocks of the European Variscides (see O'Brien, 2000) in Germany, Poland, the Czech Republic, Austria and France (Fig. 2).

In the Saxonian Granulitgebirge type locality (Fig. 2), high grade rocks form a 45-km-long dome-like body, separated by a shear zone from overlying lower grade series. The complex consists mainly of fine-grained quartzo-feldspathic granulites and their alteration products along with minor layers, from a few centimetres up to a few metres thick, of pyroxene-bearing granulites of intermediate to basic composition. In addition, bodies of serpentinised garnet peridotite, up to a few tens of metres in size and enclosing mafic granulite lenses, are found concordant with the main foliation in the felsic granulite. The typical felsic ('Weiss-stein') granulites display a protomylonitic quartzo-feldspathic microstructure (Fig. 3a), are of granitic-granodioritic composition, are notably chemically relatively undepleted, and display a HP mineralogy of hypersolvus ternary feldspar (now mesoperthite) + quartz along with variable amounts of garnet, kyanite and rutile (Rötzler, 1992; Rötzler & Romer, 2001). Garnet in many samples contains mesoperthite or kyanite inclusions and garnet is sometimes surrounded by kyanite (Fig. 3b,c). During retrogression combined with strong deformation, biotite formed from garnet, mesoperthite was recrystallized to aggregates of two feldspars + quartz and kyanite was transformed to sillimanite or, in some cases, to aggregates of hercynitic spinel ± peraluminous sapphirine ± corundum set in calcic plagioclase (Fig. 3d,e). In places, secondary garnet has grown in the spinel-bearing domain and can be distinguished from primary garnet by its lower Ca and Mg/Mg + Fe contents, inclusions of spinel and a corona of plagioclase separating it from mesoperthite (Fig. 3f).

Determination of peak *P–T* conditions in these rocks requires reintegration of mesoperthite to yield original hypersolvus feldspar compositions which will then yield minimum temperatures by two-feldspar solvus geothermometry. Consistent ultra-high temperatures over 1000 °C were deduced by this method (Fig. 4), which, in conjunction with the coexistence of kyanite, requires pressures of at least 1.5 GPa (Rötzler & Romer, 2001).

Pyroxene-bearing granulites of basic to intermediate composition show a much wider variation in modal mineralogy than the felsic types and also allow for a more robust *P–T* determination. Mafic layers in garnet peridotite are quartz-free, plagioclase-poor garnet clinopyroxenites with Mg-rich garnet and pyroxene sometimes even of omphacitic composition (Fig. 5a). Breakdown of garnet produced kelyphites of Opx + Spl + Pl whereas symplectitic secondary clinopyroxene (Fig. 5a) contains lower Na and Al. Within the mafic

Table 1. HP granulite locations. Formation conditions and ages are from the given authors.Granulite types: F = felsic, I = intermediate, M = mafic. Other rock types: CS = calc-silicate rock, E = eclogite, GP = garnet peridotite, OG = omphacite granulite, Pel = pelite, semi pelite; UM = Ultramafic. 1: Rötzler (1992); 2: Rötzler & Romer (2001); 3: von Quadt (1993); 4: Kröner *et al.* (1998); 5: Willner *et al.* (1997); 6: Kröner & Willner (1998); 7: Nasdala & Massonne 2000; 8: Massonne (2001); 9: Kryza *et al.* (1996); 10: O'Brien *et al.* (1997); 11: Bakun-Czubarow, 1992, 12: Klemd & Bröcker (1999); 13: Pouba *et al.* (1985); 14: Kotková *et al.* (1996); 15: Fiala *et al.* (1987); 16: Vrána (1989); 17: O'Brien (1999); 18: Kröner *et al.* (2000); 19: Medaris *et al.* (1995a), 995b); 20: Scharbert & Carswell (1983); 21: Carswell & O'Brien (1993); 22: Becker (1997); 23: Cooke *et al.* (2000); 24: Gayk *et al.* (1995); 25: Kleemann (1991); 26: Kalt *et al.* 2000; 27: Pin & Vielzeuf (1983), (1988); 28: Latouche *et al.* (1992); 29: Gayk & Kleinschrodt 2000; 30: Schaltegger *et al.* (1999); 31: Costa *et al.* (1993); 32: Dufour *et al.* (1985); 33: Gardien *et al.* (1990); 34: Ballèvre *et al.* (1994); 35: Marques *et al.* (1996); 36: Galán & Marcos 2000; 37: Santos Zalduegui *et al.* (1996); 38: Libourel (1988); 39: Snoeyenbos *et al.* (1995); Baldwin *et al.* 2003; 40: Liu & Zhong (1997); 41: Ding & Zhong (1999); 42: Liu *et al.* (1996); 43: Sanders *et al.* (1987); 44: Wood (1977); 45: Baba (1998); 46: Cartwright & Barnicoat (1989); 47: Friend & Kinney (1995); 48: Sklyarov *et al.* (1998); Boven *et al.* (1999); 49: Möller *et al.* (1995); 50: Appel *et al.* (1998); Coolen (1980); 51: Treloar *et al.* (1990); Dirks & Sithole (1999); 52: Attoh (1998ab); 53: Campos Neto & Caby (1999), (2000); Del Lama *et al.* 2000; 54: Zhao *et al.* (2001); 55: Guo *et al.* (2002); 56: Wei *et al.* (2001); 57: Indares (1993), (1995), (1997) 58: Indares (1993), (1995), (1997); 59: Indares (1997); Indares & Dunning (2001); 60: Möller (1998), (1999); 61: Mukhopadhyay & Bose (1994); 62: Johansson & Möller (1986); Möller (1988); 63: Elvevold & Gilotti 2000; 64: Bradshaw (1989); Ireland & Gibson (1998); Clarke *et al.* (2000); 65: Jan & Karim (1995); Yamamoto & Yoshino (1998); Yoshino *et al.* (1998); 66: Faryad (1999); 67: Ellis & Maboko (1992); Scrimgeour & Close (1999); 68: Kempton *et al.* (1995); Hölttä *et al.* 2000; 69: Collerson *et al.* (1988); Davis *et al.* (1995); 70: Rogers (1977); Griffin *et al.* (1979); Pearson *et al.* (1995); 71: Stosch *et al.* (1995); 72: Griffin *et al.* (1990); 73: Lovering & White (1969); 74: Weber *et al.* 2002; 75: Godard *et al.* (1996).

Location	Rock types	*P* (GPa) *T* (°C) peak	Age (Ma)	Comment	Reference
Bohemian Massif					
(1) Granulitgebirge, Saxony, Germany	*F* + I + M + GP + OG	< 2.2, > 1000	338 ± 4–340 ± 4		1,2,3,4
(2) Erzgebirge, Germany	*F* + E + GP	< 2.2, < 830	339 ± 1–342 ± 1	coesite, diamond, no sillimanite	5,6,7,8
(3) N. Bohemia, Czech Republic	*F* + I + GP	1.5–1.7, > 800	342 ± 5	no MP-HT stage	14
(4) Sudetes: Góry Sowie	*F* + I + GP	1.5–2.0, 900–1000	402 ± 1		9,10
(5) Sudetes: Snieznik (P)/Jesenicky(CZ)	*F* + M + OG	1.6–2.2, 800–1000	340–350	coesite?	9,11,12,13
(6) S. Bohemia, Czech Republic	*F* + I + M + GP	> 1.5, > 900	339.8 ± 2.6		15,16,17,18
(7) Moravia/Kutná Hora-Svratka (CZ)	*F* + M + GP + E	1.4–2.0, 750–1050	337 ± 6–347 ± 9		19
(8) Lower Austria	*F* + I + M + GP	1.4–1.6, 950–1050	340–344		20,21,22,23
(9) (a) Hinterröhrenhof (NE Bavaria)	*F* + UM	1.8, > 925	?		24
(b) Michldorf, NE Bavaria, Germany	*F*	1.0–1.2, 800 ± 50	488 ± 8		25
10: Schwarzwald, Germany	*F* + I + GP	> 1.5, 950–1000	335–340		26
11: Vosges, France	*F* + GP	1.1–1.2, 700–800	335–340		27,28,29,30
12: Massif Central, France	*F* + M + GP	1.0–1.2, 700–750	340–350		27,31,32,33
13: Armorican Massif	*F* + M + OG	< 2.0, 950	380–345	no MP-HT stage	27,34
14: Iberia: Bragança-Morais	M + UM + GP	1.3–1.4, 800–850	500–1050 or 390–440	after eclogite	35
15: Iberia: W Galicia	M + UM	1.3–1.5, 850	390–406	after eclogite	27,36,37
16: Corsica Santa Lucia	*F* + M + UM	1.2–1.5, 800	> 330		27,38
50: Alps, Variscan basement, Ultental	*F* + M + Pel + GP	< 1.55, < 850	> 300	eclogite relics	75
HP-HT type, non Variscan					
17: Snowbird, W Canadian Shield	*F* + M + CS	> 1.5, > 1000	1900		39
18: Namche Barwa, China	*F*	1.8, 890	45–69		40,41
19: E Qinling	*F* + M	1.3–1.6, 800–900	1000–1200		42
20: NW Ireland, Ox Inlier	*F* + M + CS + Pel	1.4, 850–900	> 605	after eclogite?	43
21: NW Scotland, Lewisian (a) S Harris	*F* + M + UM + Pel	1.3–1.4, 800 ± 50	> 1870		44,45
(b) Scourie area	*F* + M	> 1.1, 1000 ± 50	> 2490	UHT, or P underestimated?	46,47
Moderate T and overprinted eclogite					
22: Tanzania:Ubendian	M + UM	< 1.5, < 800	> 1850–1950	after eclogite	48
23: Tanzania:Usagaran	M + Pel	< 18, 750–800	2010 ± 12	after eclogite	49
24: Tanzania: Uluguru, Pare, Furua, Usambara, Ukaguru Mts	M + I + Pel	0.95–1.1, 810 ± 40	650–620		50
25: Zimbabwe, Zambezi belt	M	< 1.5, 725–800	< 830	after eclogite	51
26: Dahomeyides, Ghana/Togo	M	1.2–1.4, 800–900	*c.* 600	after eclogite	52
27: SE Brazil: Guaxupé Complex, Varginha Shear Zone	*F* + I + M	1.2–1.4, 900–1000	630–660		53
28: N China Craton: Hengshan	M	1.3–1.5, 800 ± 30	1800	after eclogite?	54
29: N China Craton: Sanggan area	M	1.1–1.5, 750–870	1800		55
30: N China Craton: Jianping	M	1.0–1.2, 785–820	2500		56
31: Grenville belt Canada: (a) Gagnon terrane;	a: Pel + E	a: 1.3–1.6, 700–800 Pel	1000–1050		a: 57
(b) Molsen Lake;	b: M + E	b: 1.6–1.8, 800–850 E	1000–1050	after eclogite	b: 58
(c) Manicouagan Imbricate Zone	c: M + Pel	c: 1.4–1.6, > 850 Pel	1000–1050		c: 59
32: Grenville belt, SW Sweden	M	0.95–1.2, 700–800	1000?	after eclogite	60
33: India, nr. Kanjamalai, Tamil Nadu	M	1.4 ± 0.2, 900 ± 50			61
34: Caledonides, Roan, Norway	M + Pel	1.45 ± 0.2, 870 ± 50	400–420	after eclogite	62
35: Caledonides, NE Greenland	M	> 1.6, > 750	400–440	after eclogite	63
36: New Zealand, Fjordland	M + I	1.4, > 750	< 126	garnet in veins	64
37: Pakistan, Jijal Complex	M	0.8–1.1, 800	*c.* 100	garnet in vein	65
38: Afghanistan, Badakhshan block	M	1.2–1.3, 750	> 2400?	also whiteschist	66
39: Australia, Musgrave Block	M	1.2, 850–900	560–520	later cooled to eclogite field	67

Table 1. (*Cont'd*).

Location	Rock types	P (GPa) T (°C) peak	Age (Ma)	Comment	Reference
Xenolith types					
40: Baltic Shield (a) Kola; (b) E Finland	M + UM	1.2–1.5, 750–950	1700–2600	a: sometimes Plag-free	68
41: N Montana, S Alberta	M + Pel	< 1.6, 800	1800		69
42: Namaqua-Natal Belt, off Kaapvaal Craton	M	< 1.2, < 850	< 1150?	on-craton trend + E: 100 °C colder	70
43: Mongolia	M	< 1.25–1.55, 850		kelyphite after garnet	71
44: E Australia	M	1.0–2.2, 800–1050	< 200	both mantle and crust	72
45: Australia, Delegate Pipes	M	1.5, 1000?	380–400		73
46: SW Colombia	M + *F*	1.0–1.4, 720–850	?		74

rocks, more quartz-rich varieties show well-developed coronas of secondary orthopyroxene (with plagioclase) developed between garnet and quartz (Fig. 5b) and rocks of more intermediate composition commonly contain antiperthite as well as primary titanite. In both cases, clinopyroxene is the sole initial pyroxene, showing high Ca-Tschermaks and/or jadeite content, and is commonly rimmed or partially replaced by orthopyroxene (Fig. 5b,c): titanite is often pseudomorphed by symplectites of ilmenite + clinopyroxene. Peak *P–T* conditions, deduced by Grt-Cpx, Grt-Cpx-Pl-Qz and two-feldspar equilibria, confirm the high *P–T*-values of > 1000 °C, < 2.2 GPa as deduced for the volumetrically more dominant felsic granulites (Rötzler & Romer, 2001) and support the eclogite-like nature of the rocks as suggested long ago by Eigenfeld (1963).

The HP granulite facies metamorphism in the Granulitgebirge took place at *c.* 340 Ma (von Quadt, 1993; Kröner *et al.*, 1998; Romer & Rötzler, 2001) and was followed by rapid exhumation (10–20 mm a^{-1}) and cooling (25–50 °C Ma^{-1}) to mid-crustal levels. The emplacement of hot granulite by a 'core-complex-like' extensional mechanism caused low-pressure metamorphism with a high temperature gradient in the schist cover mantle that was completed by 333 Ma as documented by late cross-cutting granites (Reinhardt & Kleemann, 1994; Kroner, 1995; Kröner *et al.*, 1998). The rapid exhumation of these rocks is certainly an important factor in the degree of preservation of high-grade features as will be discussed later.

Granulites with essentially the same features as described from the Granulitgebirge—predominance of felsic types (often described as leptynites), strong mylonitic fabric, association with garnet peridotites, presence of mesoperthite + kyanite, absence of primary orthopyroxene in felsic and mafic types, high determined *P–T*-values and Upper Palaeozoic metamorphic age—are known from throughout Variscan Europe (Czech Republic, Lower Austria, Polish Sudetes, German Erzgebirge, Black Forest, Vosges, Massif Central and Armorican Massif: see Fig. 2 and Table 1) and have been the subject of intensive petrological and geochronological investigation in the last decade. In some of these bodies, less deformed portions allow recognition of important textural information. For example, in mafic bodies from Zrcadlová hut (Blanský les Massif, S. Bohemia), overgrowths of garnet on idiomorphic K-feldspar, and the poikilitic texture of garnet and clinopyroxene with large enclosed K-feldspar (now antiperthite) grains (Fig. 5b,d) points to a HP–HT migmatitic origin for the rocks. The same poikilitic texture is known for large primary garnet in felsic granulites (Fig. 3b) and

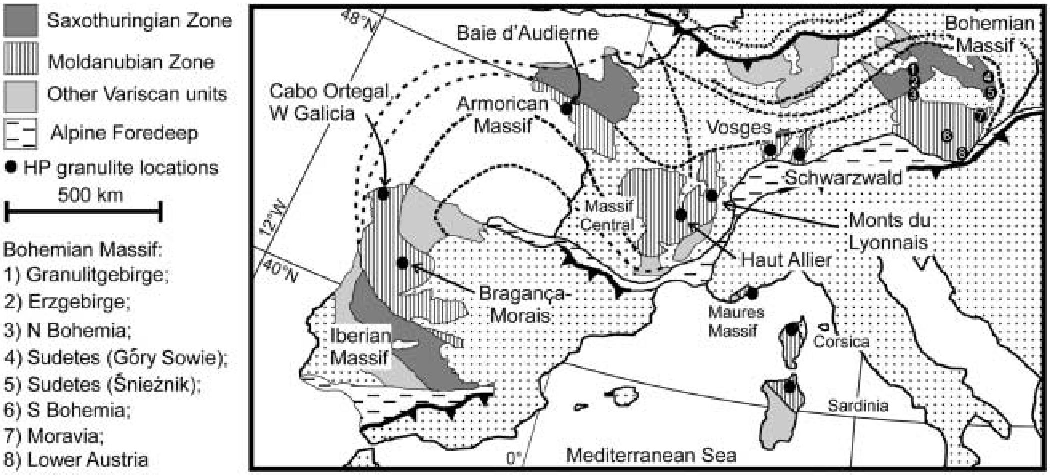

Fig. 2. Map of the Variscan basement units of Europe with important granulite bodies marked.

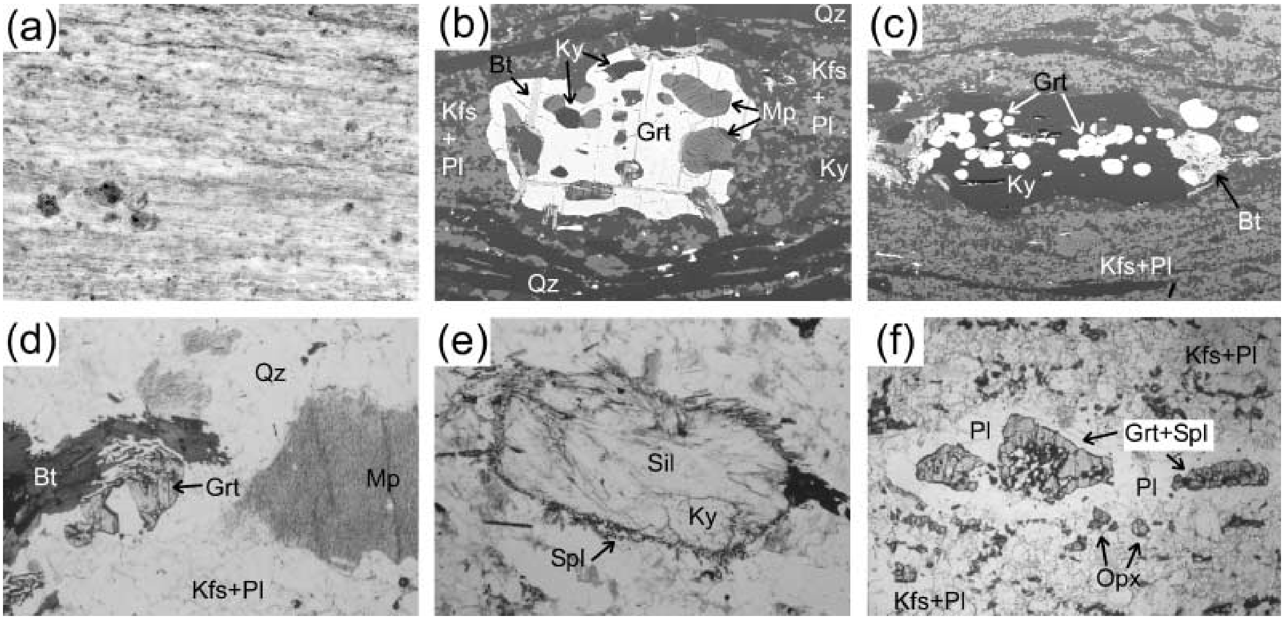

Fig. 3. Textural features of the felsic granulites. (a) Hand specimen (4 cm width) exhibiting the mylonitic fabric and secondary biotite. (Granulitgebirge) (b) Back-scattered electron (BSE) image showing poikilitic garnet (Grt) with inclusions of mesoperthite (Mp) and kyanite (Ky) and secondary biotite (Bt) along cracks, set in a matrix of K-feldspar and plagioclase (Kfs + Pl) between quartz ribbons (Qz). (Granulitgebirge, width 4 mm) (c) Kyanite, aligned in a two-feldspar matrix, enclosing garnet. BSE image. (Granulitgebirge, width 2 mm) (d) Photomicrograph of a weakly deformed sample showing garnet partially replaced by biotite and large mesoperthite grains in a quartz-rich matrix. (South Bohemia, width 2 mm) (e) Kyanite partially pseudomorphed by sillimanite (Sil) with minor spinel (Spl) at margins. Photomicrograph. (South Bohemia, width 2 mm) (f) Secondary garnet with spinel inclusions (Grt + Spl) enclosed by a plagioclase collar (Pl) in an orthopyroxene (Opx)-bearing granulite. Photomicrograph. (South Bohemia, width 4 mm).

strongly resembles features known from incongruent garnet-producing melt reactions (e.g. Waters & Whales, 1984). An origin of the granulites by melting processes has long been promoted by Czech petrologists (e.g. Vrána & Jakeš, 1982; Vrána, 1989) and is substantiated by more recent experimental data from Kotková & Harley (1999) which show HP leucogranitic melts with peritectic Grt + Kfs + Ky as likely protoliths for the granulites.

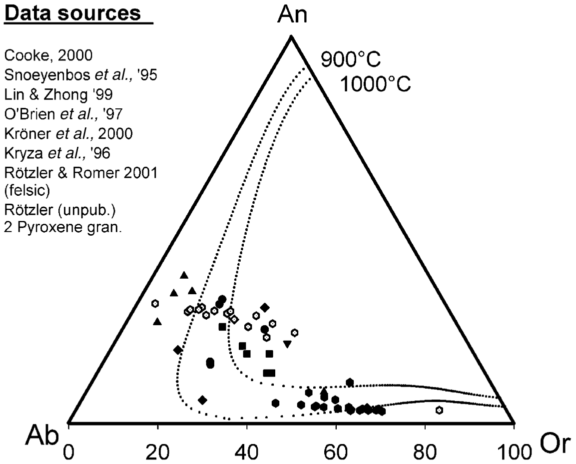

Fig. 4. Selected analyses from the literature of reconstituted ternary feldspars in granulites along with the 1.5 GPa, 900 and 1000 °C solvus curves deduced from the feldspar activity model of Fuhrman & Lindsley (1988).

Interest in the Variscan granulites has increased enormously in the last few years since the finding of diamond and coesite in Erzgebirge samples (Nasdala & Massonne, 2000; Massonne, 2001). Indications for possible former coesite or supersilicic pyroxene are also known from Polish (Bakun-Czubarow, 1992; Bröcker & Klemd, 1996; Klemd & Bröcker, 1999) and German (Gayk *et al.*, 1995) granulites. These indicate pressures deep in the eclogite rather than granulite stability field with conditions as found for the associated garnet peridotites (e.g. Brueckner & Medaris, 1998). Many mafic granulites appear to have been plagioclase-bearing at peak conditions (e.g. Scharbert & Carswell, 1983; Carswell *et al.*, 1989) so the question as to whether only parts of the complexes experienced UHP–UHT conditions or whether the whole crustal slice was subducted to mantle depths and plagioclase survived metastably remains to be answered. Certainly, the *P–T* conditions determined for the rest of the assemblage in diamond-bearing samples does not indicate pressures in the diamond field and so compositional information for the peak conditions is incomplete.

Considering the wide distribution of the HP granulites in the Bohemian Massif it is remarkable how many locations have yielded zircon ages within a very

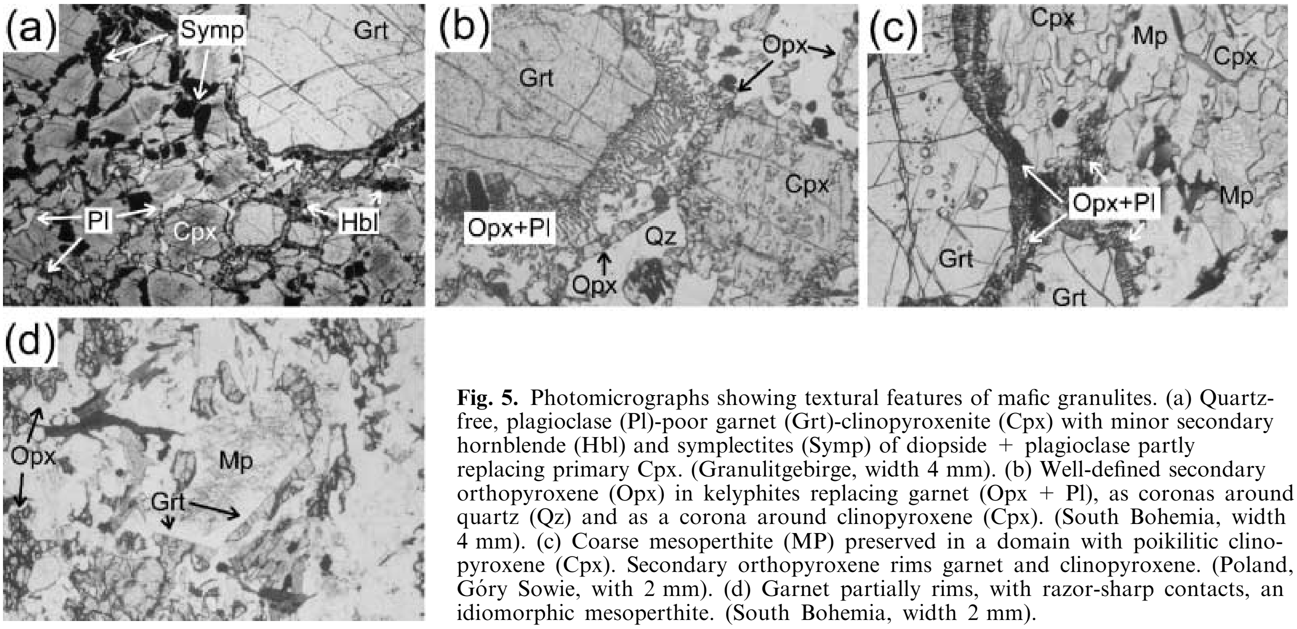

Fig. 5. Photomicrographs showing textural features of mafic granulites. (a) Quartz-free, plagioclase (Pl)-poor garnet (Grt)-clinopyroxenite (Cpx) with minor secondary hornblende (Hbl) and symplectites (Symp) of diopside + plagioclase partly replacing primary Cpx. (Granulitgebirge, width 4 mm). (b) Well-defined secondary orthopyroxene (Opx) in kelyphites replacing garnet (Opx + Pl), as coronas around quartz (Qz) and as a corona around clinopyroxene (Cpx). (South Bohemia, width 4 mm). (c) Coarse mesoperthite (MP) preserved in a domain with poikilitic clinopyroxene (Cpx). Secondary orthopyroxene rims garnet and clinopyroxene. (Poland, Góry Sowie, with 2 mm). (d) Garnet partially rims, with razor-sharp contacts, an idiomorphic mesoperthite. (South Bohemia, width 2 mm).

narrow age range of around 340 Ma (van Breemen *et al.*, 1982; von Quadt, 1993; Kröner & Willner, 1998; Kotková *et al.*, 1996; Becker, 1997; Kröner *et al.*, 1998; Kröner *et al.*, 2000; Romer & Rötzler, 2001). This age is even deduced from samples where orthopyroxene and cordierite indicate medium and lower pressure overprints still at high temperature (Kröner *et al.*, 2000) and the lack of a correlation between age and grain size of zircon rules out a resetting by diffusive lead loss. The granulite-bearing nappe units were cut by shallow-level granite intrusions by 330 Ma and in places appeared at the surface extremely rapidly after their formation as indicated by the presence of zircon-dated clasts in Lower Carboniferous sedimentary basins (Kotková *et al.*, 2001). All factors point to a rapid exhumation of granulites from mantle depths at cm a^{-1} rather than mm a^{-1} rates (e.g. Romer & Rötzler, 2001): a history confirmed by diffusion modelling of mineral zoning patterns in the peridotites enclosed within the granulites (Medaris *et al.*, 1990).

The HP–HT granulites of the Variscan belt, although the most intensely investigated, are not the only examples of this rock type. Snoeyenbos *et al.* (1995) described felsic granulites with a metamorphic age of at least 2.6 Ga from the Snowbird Tectonic Zone in northern Saskatchewan, western Canadian shield. This complex, covering an area of 400 km^2, contains mafic, felsic and even quartzitic and calc-silicate gneisses. The light colour, mylonitic microstructure, presence of kyanite and mesoperthite, exsolution of rutile needles in garnet, and deduced high *P–T* equilibration conditions (minimum of 1000 °C, 1.5 GPa) are identical to the features of the Variscan felsic granulites. Clinopyroxene in mafic granulites has a high Ca-Tschermaks content and in some variants kyanite breakdown has produced abundant sapphirine. A much younger example of felsic, kyanite-bearing granulite has been reported from the eastern syntaxis of the Himalaya, near the mountain Namche Barwa, by Liu & Zhong (1997). In these rocks, conditions of around 1.7–1.8 GPa, *c.* 890 °C were followed by decompression leading to sillimanite, spinel and cordierite growth. Ding & Zhong (1999) and Ding *et al.* (2001) reported zircon ages of *c.* 40 Ma for the HP stage in pristine samples and 23–23 Ma (U–Pb, zircon; Ar–Ar, amphibole) for the overprint. Also in China, but of undetermined age, are the felsic granulites from East Qinling (Liu *et al.*, 1996).

A variety of rock types preserve sporadic relics of presumed pre-Caledonian HP granulite facies metamorphism (850–900 °C, *c.* 1.4 GPa) in the NE Ox inlier, north-west Ireland (Sanders *et al.*, 1987). Mesoperthite, ribbon quartz and large kyanite inclusions in garnet, in the felsic and pelitic rocks, resemble features of Saxony-type granulites whereas in metabasites Ca-Tschermaks-rich clinopyroxene occurs in corona and poikilitic (with plagioclase) textures together with Ca-rich garnet and quartz.

In the Lewisian Complex in NW Scotland, HP–HT conditions have been deduced for granulites of both Badcallian (at least 2.49 Ga but possibly over 2.7 Ga) age in the Scourian Complex on the mainland and of Laxfordian (> 1.87 Ga) age in the Outer Hebrides (South Harris) (Wood, 1977; Cliff *et al.*, 1983; Cartwright & Barnicoat, 1989; Corfu *et al.*, 1994; Friend & Kinny, 1995; Baba, 1998). In South Harris, pelitic (Ky + Kfs-bearing), mafic (Grt + Cpx-bearing), quartzo-feldspathic and ultramafic rocks all show HP assemblages representing the peak of metamorphism at 800 ± 30 °C, 1.3–1.4 GPa (Wood, 1977; Baba, 1998). In contrast, the mesoperthite-bearing Scourian granulites reached temperatures of 1000 ± 50 °C at pressures above 1.2 GPa and basic orthogneisses with clinopyroxene containing a significant Ca-Tschermaks content yielded 990 °C at pressures of at least 1.1 GPa (Cartwright & Barnicoat, 1989).

MODERATE TEMPERATURE AND OVERPRINTED ECLOGITE TYPES

A common textural feature in eclogites of gneiss terranes, resulting from reaction (such as R5) at pressures below those of the eclogite facies, is the replacement of eclogite facies omphacite by symplectitic intergrowths of sodic plagioclase and clinopyroxene (Fig. 6a: O'Brien *et al.*, 1992) with lower Na and Al content than the initial clinopyroxene. In some cases, in more aluminous bulk compositions, the symplectitic pyroxene is still omphacite but in most cases it is diopside with jadeite content below 20%. The resulting mineral assemblage of Grt + Cpx + Pl + Qtz is the same as that found in high-pressure mafic granulites without evidence of an eclogite facies evolution but, importantly, it can also occur over a wide temperature range (above about 650 °C) in the amphibolite facies (see, e.g. Bucher & Frey, 1994). As an example of this problem, Ghent *et al.* (1983) showed how Grt-Cpx-Pl-Qtz-bearing mafic rocks from Mica Creek, British Colombia, were cofacial with amphibolite facies metapelites. Also, in the Dalradian of Scotland, the Grampian metamorphism produced the same assemblage in metabasites, associated with migmatitic garnet-sillimanite gneisses, at *c.* 820–850 °C, 0.7–0.9 GPa (Baker & Droop, 1983). The problem of the determination of this boundary is covered in detail by Pattison (2003) and so will not be further discussed.

A large number of rocks that were once at eclogite facies conditions did not get catapulted back to cold, shallow conditions. These rocks show *P–T* paths that heat up at high pressure (1.0–1.4 GPa) and that clearly enter the granulite field, at least at lower pressures (0.6–1.0 GPa), as orthopyroxene is commonly documented in reaction textures around garnet or within the symplectite domains together with diopside (O'Brien, 1997a,b). For rocks of basaltic composition, the transition from eclogite to granulite facies conditions results in the production of plagioclase by reactions R3, R4, R5 and R6, i.e. by decomposition of both garnet and clinopyroxene. The fact that coronitic, symplectitic and kelyphitic reaction textures are common in such rocks (Fig. 6) clearly indicates a lack of textural equilibrium. It is also not unusual to find that plagioclase compositions are distinctly different in each of the reaction domains such that compositional equilibrium is at best only domainal. An additional problem when trying to reconstruct the *P–T* conditions for the orthopyroxene-free garnet + clinopyroxene stage is the interpretation of the extent to which the garnet, pyroxene and plagioclase compositions have been modified by subsequent medium- and low-pressure reactions. Despite the high temperature overprint many of these rocks still preserve compositional zoning in garnet pertaining to the prograde or eclogite facies stages, albeit modified to some extent, and so the different compositions must be correctly correlated with

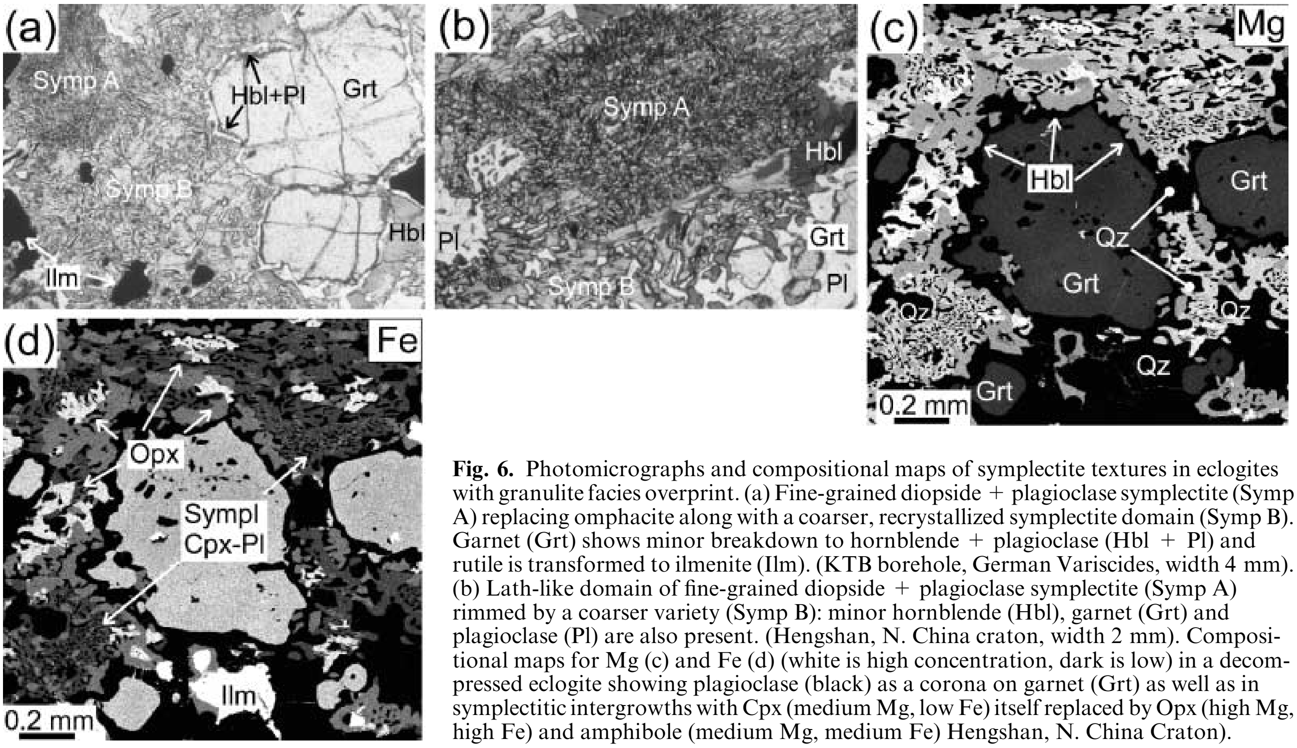

Fig. 6. Photomicrographs and compositional maps of symplectite textures in eclogites with granulite facies overprint. (a) Fine-grained diopside + plagioclase symplectite (Symp A) replacing omphacite along with a coarser, recrystallized symplectite domain (Symp B). Garnet (Grt) shows minor breakdown to hornblende + plagioclase (Hbl + Pl) and rutile is transformed to ilmenite (Ilm). (KTB borehole, German Variscides, width 4 mm). (b) Lath-like domain of fine-grained diopside + plagioclase symplectite (Symp A) rimmed by a coarser variety (Symp B): minor hornblende (Hbl), garnet (Grt) and plagioclase (Pl) are also present. (Hengshan, N. China craton, width 2 mm). Compositional maps for Mg (c) and Fe (d) (white is high concentration, dark is low) in a decompressed eclogite showing plagioclase (black) as a corona on garnet (Grt) as well as in symplectitic intergrowths with Cpx (medium Mg, low Fe) itself replaced by Opx (high Mg, high Fe) and amphibole (medium Mg, medium Fe) Hengshan, N. China Craton).

the different stages in the metamorphic evolution before reliable *P–T* conditions may be determined.

Several HP granulites of this type have been identified around the world (see Table 1). Excellent examples of this variety of HP granulite of Precambrian age are known from the North China craton and have been the subject of numerous publications in recent years (e.g. Guo *et al.*, 1996, 2002; Dirks *et al.*, 1997; Zhao *et al.*, 1999, 2001; Wei *et al.*, 2001). Zhao *et al.* (1999) subdivided the North China craton into regions with granulites showing either (1) anticlockwise *P–T*–t paths with MP granulite facies peak conditions or (2) isothermal decompression from HP granulite conditions followed by isobaric cooling. Most HP granulites studied contained the assemblage Opx + Cpx + Pl + Qz + Grt but in some locations such as Hengshan, Sanggan area, or Jianping complex (Zhao *et al.*, 2001; Wei *et al.*, 2001; Guo *et al.*, 2002), Cpx-Pl symplectites (Fig. 6b,c,d) point strongly to a former eclogite facies stage before formation of a texturally well-equilibrated Grt-Cpx-Pl-Qtz-Rt assemblage at *c.* 800 °C and 1.4 GPa. Later reaction in these rocks was at lower pressures and led to growth of orthopyroxene at the expense of both garnet and clinopyroxene. In these samples, the scarcity of well-developed vermicular symplectites and the abundance of coarser poikilitic clinopyroxene-plagioclase intergrowths is probably a reflection of the longer times spent at high grade conditions.

The Archean cratons of Africa are surrounded by collision belts that were active in Palaeoproterozoic and Neoproterozoic times and which produced high-pressure rocks (granulites and/or eclogites). Surrounding the Tanzanian Shield are some of the oldest eclogites of the world, transformed to granulites, in the Ubendian (Sklyarov *et al.*, 1998; Boven *et al.*, 1999) and Usagaran (Möller *et al.*, 1995) belts. The breakdown of clinopyroxene produced rod- and bleb-like plagioclase grains rather than fingerprint-like symplectites more typical for lower temperature omphacite breakdown. In addition, in the Pan-African Mozambique belt to the east of the craton, kyanite-bearing metapelites and Grt + Cpx + Qtz-bearing mafic granulites of the Furua, Uluguru, Pare, Usambara and Ukaguru mountains yield *P–T* conditions of 810 ± 40 °C, 0.95–1.1 GPa (Appel *et al.*, 1998; Coolen, 1980). Moving further south, eclogitised gabbros and granulites after eclogite are reported from the Zambezi belt, at the margin of the Zimbabwe craton, in both NW and NE Zimbabwe (Treloar *et al.*, 1990; Dirks & Sithole, 1999). In both cases, deduced temperatures (*c.* 750 °C) are close to the boundary between HP amphibolite and HP granulite.

At the margin of the West African craton, Pan-African (*c.* 600 Ma) eclogites and granulites are known from the Dahomeyides in Ghana and Togo (Attoh, 1998a,b) and coesite-bearing eclogites showing an overall colder subduction and exhumation path exist in Mali (Caby, 1994). Metamorphic conditions of 800–900 °C, 1.2–1.4 GPa were deduced for mafic HP granulites in gneisses whereas coronas in metagabbro formed at temperatures more typical for the amphibolite or eclogite facies (Attoh, 1998a,b). The pre-Atlantic extension of this zone in South America has revealed both eclogites and HP granulites in Proterozoic collision zones at the edge of the Sao Francisco craton in Brazil. Choudhuri *et al.* (1978) reported eclogites with a HP granulite overprint (Grt + Qz + Rt with symplectitic Cpx + Pl) and Campos Neto & Caby (1999, 2000) deduced formation conditions of *c.* 900 °C, 1.2 GPa and 750 °C, 1.5 GPa for Grt + Ky + Kfs-bearing granulites in two different nappe units.

Another Precambrian area with Grt-Cpx-Pl-Qtz-bearing mafic rocks covering a considerable areal extent (50 by 500 km!) is the Kapuskasing Structural Zone within the Superior Province of the Canadian Shield (Percival, 1983). In this case the low Ca-Tschermaks contents of clinopyroxene, the sporadic presence of orthopyroxene in the metabasites, occurrence of orthopyroxene in pelitic and dioritic and anorthositic rocks, and deduced metamorphic pressures of around 0.6 GPa point to a medium rather than high pressure evolution for this series.

Several locations of HP granulites generally representing overprinted eclogites have been identified within the (now) dispersed terranes once forming part of the Grenvillian (*c.* 1000 Ma) orogenic belt. In the Canadian Grenville Province, HP relics are documented from the Gagnon and Molsen Lake terranes as well as from the Manicouagan Imbricate Zone (Indares, 1993, 1995, 1997). Non-mafic Grt + Ky + Kfs-bearing metapelites, indicating formation conditions in the range 700–800 °C, 1.3–1.6 GPa, accompany the meta-eclogites in the Gagnon terrane of the eastern Grenville Province (Indares, 1995). Interesting in these rocks is the preservation of strong prograde compositional zoning (Fe/(Fe + Mg) = 0.83–0.63 from core to rim) in garnet despite the high peak temperature. In the Manicouagan Imbricate Zone HP conditions of 720–900 °C, 1.3–2.0 GPa are reflected by the occurrence of kyanite-bearing garnet-clinopyroxenites, Grt + Ky + Kfs as restite in leucogranites formed by mica dehydration melting reactions, and metamorphic Grt + Cpx replacing magmatic phases in corona gabbros (Indares, 1997; Cox & Indares, 1999; Indares & Dunning, 2001). Further west, in the Rosseau subdomain of the Central Gneiss Belt, Davidson (1990) noted peraluminous sapphirine in kyanite-breakdown domains in eclogites.

Metamorphic basement complexes of Grenvillian age in SW Sweden are dominantly amphibolite facies but relict HP Grt + Cpx ± Ky ± Qz assemblages (700–800 °C, 0.95–1.2 GPa) are sporadically preserved which indicate an early eclogite facies assemblage overprinted at HP granulite facies conditions but with prograde zoning preserved in garnet (Möller, 1998). Both symplectitic and coronitic textures of clinopyroxene are found as well as peraluminous sapphirine (with corundum, spinel and Ca-plagioclase) after kyanite (Möller, 1998, 1999).

The Precambrian high-grade terranes of southern India are well known for their medium-pressure granulite facies assemblages in dominant TTG gneisses of Archean and Proterozoic age. However, minor mafic bodies enclosed in banded iron formation sequences near Kanjamalai, Tamil Nadu state, contain partially preserved HP-granulite assemblages yielding peak conditions of 900 ± 50 °C, 1.4 ± 0.2 GPa (Mukhopadhyay & Bose, 1994). The Al^{iv}-Al^{vi}-values for clinopyroxene from these rocks plot close to the eclogite trend of Lovering & White (1969) although there is nothing resembling a symplectite-like texture, indicating decompression from the eclogite field, in the presented petrographic sketches.

The Caledonian eclogites and ultra-high-pressure rocks of the Norwegian Western Gneiss Region are well known but less attention has been paid to parts of the Region (Roan) where HP granulites (870 ± 50 °C, 1.45 ± 0.2 GPa) exist (Johansson & Möller, 1986; Möller, 1988). Apart from Grt + Cpx + Pl-bearing mafic rocks there are also Ky-Kfs-bearing paragneisses but most spectacular are reaction textures producing peraluminous sapphirine (± Spl ± Crn ± Opx + Pl) after kyanite and orthopyroxene-bearing coronas after both garnet and clinopyroxene. This same sapphirine-bearing texture is recorded from Palaeozoic eclogites overprinted at granulite facies conditions from numerous locations (e.g. NE Greenland, Elvevold & Gilotti 2000; N Greece, Liati & Seidel, 1994; W France, Godard & Mabit 1998, Czech Republic, O'Brien, 1994; O'Brien & Vrána, 1995; S Switzerland, Brouwer 2000) where it is generally attributed to a HP granulite stage.

Two well-characterised examples of moderate-temperature, high-pressure granulites that were formed by subduction, but without reaching eclogite facies conditions, are Fiordland, New Zealand, and the Jijal Complex, Pakistan. In many ways these locations are similar in that high-grade assemblages in magmatic rocks are overprinted by a distinct vein-related garnet growth at HP granulite facies conditions due to thickening related to magmatic arc accretion. In Fiordland, gabbros and diorites of Palaeozoic to Early Cretaceous age metamorphosed to two-pyroxene MP-granulite assemblages are cut by distinct veins within which Grt + Cpx-bearing corona reaction textures are documented (Bradshaw, 1989; Ireland & Gibson, 1998; Clarke *et al.*, 2000). These Grt + Cpx + Pl + Qz ± Hbl ± Ky vein-related assemblages formed at *c.* 1.4 GPa and > 750 °C and indicate a significant thickening interpreted as a short-lived subduction event (Clarke *et al.*, 2000) although alternative models based on magma loading are also published (e.g. Brown, 1996). In northern Pakistan, metagabbros from deep crustal levels of the Kohistan oceanic island arc of Cretaceous age have been exposed as a result of Tertiary India-Asia collision (Bard *et al.*, 1980). In the Jijal complex, Grt + Qz coronas are developed around pyroxene of older two-pyroxene MP granulite facies assemblages along obvious fracture zones (Jan & Karim, 1995 Yamamoto & Yoshino, 1998; Yoshino *et al.*, 1998). Formation conditions of 0.8–1.1 GPa, *c.* 800 °C for the garnet-bearing overprint requires a crustal thickening either by magma loading (Yoshino *et al.*, 1998) or collision.

Elsewhere in the Himalaya, Grt + Cpx + Pl-bearing metabasic rocks resembling overprinted eclogites are known from the contact between the Nanga Parbat–Haramosh syntaxis and the Kohistan arc at Stak (Pognante *et al.*, 1993) and, rather anomalously, within the Lesser Himalayan sequences in the Kharta region, east of Everest (Lombardo & Rolfo, 2000). In both cases, deduced temperatures at HP conditions below 750 °C and high Jd:CaTs in clinopyroxene point to HP amphibolite rather than HP granulite facies conditions.

This is far from being a complete list of the overprinted eclogites showing the assemblage Grt + Cpx + Pl + Qz ± Hbl but should serve to show that there are locations where deduced temperatures are below *c.* 750 °C and are more akin to conditions of the high-pressure amphibolite facies and other locations where calculated temperatures lie above 750 °C thus indicating HP granulite facies conditions. A difficulty is of course the problem of possible resetting of garnet Fe-Mg at lower pressure, especially in rocks with later orthopyroxene-bearing assemblages, such that *P–T* estimates for the earlier clinopyroxene-bearing stage are shifted to higher temperatures.

XENOLITH TYPES

Granulites in xenoliths suites within mantle-derived magmas have long been recognised as samples of the lower crust and upper mantle (e.g. Rudnick, 1992). It is expected, from normal continental heat flow values of 40 mWm^{-2}, that eclogite or high-pressure granulite assemblages should be stable in the lowermost crust and upper mantle of stable cratonic areas. The scarcity of high-pressure granulites in regionally exposed granulite terranes, however, has led to the conclusion that these terranes represent middle rather than lower crust (e.g. Rudnick, 1992). The majority of lower crustal xenoliths sampled are from areas of Phanerozoic crust (e.g. Downes, 1993) but HP granulite xenoliths are recorded from regions of Archean or Proterozoic crust for example in the Baltic Shield (Kempton *et al.*, 1995), Canada/USA (Montana/Alberta: Collerson *et al.*, 1988; Davis *et al.*, 1995), West African craton (Toft *et al.*, 1989), within and at the margin of the Kaapvaal craton in South Africa and Lesotho (Rogers, 1977; Griffin *et al.*, 1979; Pearson *et al.*, 1995), Mongolia (Stosch *et al.*, 1995) and eastern margin of Australia (Griffin *et al.*, 1990).

The important feature of some of these rocks is a clear transition from granulite to eclogite facies (e.g.

Griffin *et al.*, 1990) resulting from a decrease in heat flow in old, thickened continental root-zones over time. The path documented in such rocks is thus an isobaric cooling from granulite into eclogite facies and a crossing of the plagioclase stability curve for a given bulk composition. Apart from these xenolith examples, where relationships between neighbouring rocks are lost and it is not clear whether samples are from the crust or the mantle, there are also exposed occurrences of deep crustal sections where the same features are documented. The eclogite- to HP-granulite facies (700–750 °C, 1.2–1.3 GPa) -shear zones reported by Ellis & Maboko (1992) from the Musgrave Range, Australia, overprint granulites formed at 850–900 °C, 1.2 GPa, and represent an example of an evolution from high to low temperature. However, it now appears that the HP event was due to the much younger (560–520 Ma) Petermann Orogeny (e.g. Scrimgeour & Close, 1999) rather than a simple cooling from peak temperatures.

PROBLEMS OF *P-T* DETERMINATION

A selection of peak formation *P–T* conditions for the granulites listed in Table 1 is plotted in Fig. 7 along with the field for HP granulites as defined in Fig. 1 and also the range of plotted granulite *P–T* values from Harley (1989). One of the major problems with determining the peak-metamorphic *P–T* conditions in granulites is the fact that, during cooling, components important for exchange geothermometers are often reset by diffusion whereas net-transfer reactions recording geobarometric information are less severely reset. This problem, the 'granulite uncertainty principle' (Frost & Chacko, 1989; Harley, 1989), generally results in calculated *P–T* points offset from the actual *P–T* paths experienced by the samples.

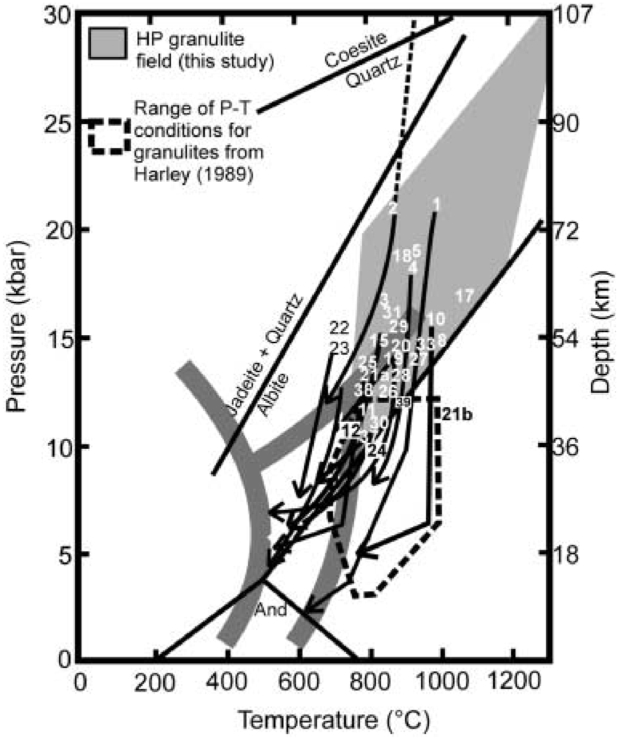

Fig. 7. Peak formation conditions for selected HP granulites from the list in Table 1.

A major controlling factor is of course the duration at high-temperature conditions as this is the main control on the degree of diffusive resetting. The theory was founded on the basis of *P–T* results from the large number of Precambrian granulite terranes which represent former mid- to lower-crustal levels exposed by tectonic events significantly younger than the granulite-forming event. However, most of the granulites discussed here do not represent such slowly cooled crustal segments but rather show many features indicating a rapid exhumation following subduction of upper crustal rocks to mantle depths. Rapid exhumation, combined with fast cooling, as is the case for the Variscan granulites, has allowed preservation of mineral compositions related to peak *P–T* conditions. In some of the Austrian mafic HP granulites for example, prepeak-*P–T* garnet compositions are preserved in garnet cores and have not been homogenised as is normally presumed for granulite facies garnet (Cooke *et al.*, 2000). Indares (1995) noticed similar features in Grenville samples. In these cases not only can the peak *P–T* conditions be determined but also part of the prograde path as well as the maximum duration of the HP-HT event (with constraints from diffusion modelling). In contrast, one of the difficulties in the granulites derived from former eclogites is that the *P–T* path may have moved towards higher temperatures during decompression such that the lower temperature of the eclogite facies stage may no longer be recoverable. In such cases, deduced *P–T* paths tend to give the impression of an isothermal decompression rather than heating during decompression. This is certainly a feature common in most papers on Variscan eclogites (see, e.g. O'Brien *et al.*, 1990).

More problematic for *P–T* determination is the strong mylonitisation of all UHT felsic granulites. Cooling from peak conditions has resulted in mesoperthite formation from former hypersolvus feldspars which, during mylonitisation, are strung-out to produce the characteristic two-feldspar + quartz strips between ribbon-quartz (Fig. 3a). Rare augen of mesoperthite are all that remain in the matrix and so it is often necessary to seek out armoured relics of mesoperthite included in garnet or clinopyroxene. Granulites of intermediate composition generally offer a greater chance of preservation of undeformed mesoperthite between the more resistant garnet and clinopyroxene clusters (Fig. 5c). The whole procedure of reintegration of feldspars is fraught with uncertainty but, in such coarse mesoperthites, especially in the antiperthites of the rocks of intermediate composition, the sought primary feldspar—constrained to fall between the measured plagioclase and K-feldspar compositions—clearly lies in the realm of a very high-temperature solvus even for relative errors of 10% or more in modal proportions (Fig. 4).

In addition to the problems with feldspar composition, peak *P–T* garnet composition in UHT granulites has generally been modified, at least at rims, by lower pressure decomposition to produce biotite and more calcic plagioclase: a serious problem in samples with garnet grain sizes around 0.2–0.3 mm as is typical for many Variscan felsic granulites. There are examples, however, where garnet breakdown reactions are distinctly restricted in extent and where one-sided Fe-Mg zoning in garnet facing biotite-bearing zones indicates the absence of a fluid phase such that volume diffusion operated more effectively than grain boundary diffusion (O'Brien, 1999). In this particular example, garnet-biotite thermometry using rim compositions yields 800 °C thus confirming the lack of significant resetting. Pairing garnet interior compositions with biotite in these samples yields temperatures above 1000 °C but these do not represent equilibrium compositions as is demonstrated by comparing garnet compositions from biotite-free parts of the same sample. More of a problem is the common presence of a second generation of garnet, with a composition close to that of rims of primary grains, overgrowing Spl ± Spr ± Crn + Pl (Ca-rich) aggregates (Fig. 3f) in domains of kyanite decomposition (Owen & Dostal, 1996; O'Brien, 1999). Utilising such garnet assuming it represents a relict prograde growth stage results in a serious underestimation of both temperature and pressure as Mg/(Fe + Mg) in such secondary grains is significantly lower than in the cores of the primary garnet in the same rocks.

Because pressure determination relies on reaction R2 (not forgetting that the anorthite activity required is that of the An-component in the original ternary feldspar) cutting the equilibrium curve from two-feldspar (solvus) geothermometry, the resetting of Ca-content in garnet is critical. In some cases (e.g. O'Brien, 1999) the extent of resetting of garnet Ca around inclusions of feldspar as well as at grain margins, generally accessible using compositional mapping techniques, allows an estimation of the degree of resetting relative to grain size and thus aids selection of suitable grain compositions. The most reliable samples for geothermometry are those with garnet of mm-size or greater – in many cases restricting study to rocks of intermediate or basic compositions. The kyanite-bearing nonfelsic granulites allow a crosscheck of the pressure determination via reaction R5 although it is clear that Al-Na zoning in clinopyroxene needs to be evaluated in order to choose suitable mineral compositions for geobarometry.

Regardless of the difficulties with *P–T* determination of peak conditions in the UHT granulites due to postpeak-*P–T* recrystallization and diffusive modification, values estimated are easily distinguishable from those calculated for a subsequent generally, medium-pressure granulite facies overprint. As in all such nonequilibrated rocks with a multistage metamorphic history, the key to solving the *P–T* evolution is to identify the different reactions and their products and then finding domains in the samples where a particular stage clearly dominates. Just because the overprint is also at granulite facies does not mean that phases have been homogenised and only show results of resetting during cooling. This has to be proven by targeted analysis and compositional mapping of grains and domains. The days where simple 'core and rim' analysis for garnet, pyroxene and feldspar was sufficient for geothermobarometry are long gone.

TECTONIC SCENARIOS FOR HP GRANULITE FORMATION

Granulites should not be viewed statically simply as rocks whose formation conditions plot in the granulite facies *P–T* field. Important for understanding their evolution are the factors leading to the relevant *P–T* conditions, the duration of these conditions and the events leading to subsequent exposure at the surface. The *P–T* field for HP granulites (Fig. 1) shows that, apart from a very small segment, the expected pressures lie outside those expected in normal, stable continental crust of 35 km thickness. Medium- and low-pressure granulite form at depths attainable in normal crust and so the main problem in the case of these granulite types is to explain the heat source for the high temperatures. In contrast, HP granulites, although also rocks of the continental crust, reach pressures corresponding to mantle depths. Some HP granulites, as mentioned earlier, form in the lower part of the thickened crustal segment of old lithosphere where internal radiogenic heat production has decreased over time and thermal gradients have evolved to lower values. The majority of the rocks described here, however, formed as a result of subduction of crust into the mantle.

The main features of the Variscan granulites were discussed in detail by Pin & Vielzeuf (1983). Advances in analytical and thermobarometric techniques have, however, led to the establishment of extremely high temperatures (over 1000 °C) for the metamorphic peak in these rocks. In addition, the discovery of diamond and coesite, and the common (although not universal) finding of single-grain zircon ages clustered around 340 Ma: an age only shortly predating (by < 10 Myr) the time of exhumation of granulite-bearing units in thrust-bounded units and subsequent cross-cutting of tectonic boundaries by voluminous granites allow better constraints on peak pressures and the timing of metamorphism.

The establishment of this young, Carboniferous age for the HP granulite facies stage is important as there was an earlier, 420–380 Ma eclogite facies event in the Variscides. The earlier event is recorded in widespread eclogite-bearing gneiss-metabasite units associated with garnet-free ophiolitic peridotites (e.g. O'Brien *et al*., 1990) whereas the younger HP granulites are dominated by quartzo-feldspathic rocks with minor layers of mafic rocks and tectonic lenses of garnet-bearing peridotites (O'Brien, 2000). It can certainly be no coincidence that large bodies of garnet peridotite are a common constituent of the Variscan UHT granulite complexes, a situation requiring interdigitation of crust and mantle. All the evidence taken together, upper crustal, granitic bulk composition, extremely high temperatures, high pressures corresponding to mantle depths, presence of peridotites, and extremely rapid exhumation, supports a model of deep subduction of crust to mantle depths followed by fast buoyancy-driven exhumation at least to normal crustal depths. This scenario is most probably valid for all of the UHT-HP granulites described here.

The HP granulites that formed from eclogites show a different path. These are rocks that were subducted into the eclogite field but were not exhumed fast enough to overcome the effects of thermal relaxation and thus experienced heating during decompression. The P–T paths of such overprinted eclogites are often difficult to determine because the high temperatures have commonly erased, or at least significantly modified the record of the prograde path up to the eclogite facies pressure peak. It is quite probable that all terranes, where well preserved eclogites can be examined, also have deeper levels where eclogites, formed at the same time but that did not reach shallow, cooler levels quickly enough, have undergone a higher temperature overprint. In collisional belts such as the Variscan, where two subduction events follow close on each other, eclogites with a high-pressure granulite/high-pressure amphibolite facies overprint formed at the end of the first stage may well be exhumed as a result of the second collisional phase. This has limited the extent of the high-temperature overprint and has allowed partial preservation of the eclogite stage in the form of mineral zoning and inclusion suites. In other areas without this second collisional stage only less deformed crustal segments would allow preservation of textural features, such as symplectites after omphacite, pointing to former plagioclase-free conditions. In the north China craton, the cores of massive mafic bodies often provide the necessary rigidity, as well as an effective buffer-zone for fluid infiltration, to allow preservation of high-pressure relics despite a very strong regional granulite facies overprint.

A possible third grouping is that of crustal xenoliths representing rocks of the crust–mantle boundary (e.g. Griffin *et al*., 1990). Exposed equivalents of the rocks sampled by the mafic and ultramafic diatremes may be areas such as the Musgrave Block, Australia or Grenville Belt, Canada. Both of these areas contain plagioclase-free mafic rocks that are eclogites or 'eclogite-like' (garnet pyroxenites) but the absence of voluminous ultramafic rocks points to a crustal rather than mantle environment (i.e. shallower than the petrological Moho). The textural information points to transformation of magmatic precursor assemblages from mafic intrusions into the lower crust (or upper mantle in the case of some xenoliths) due to post-magmatic cooling. However, it is by no means clear that cooling and recrystallization directly follow the magmatic event: in the case of the Musgrave example (Scrimgeour & Close, 1999) there is a long period before the rocks were reactivated.

CONCLUSIONS

The P–T conditions for granulites from a variety of locations around the world are notable in that virtually all plot outside the field of data compiled by Harley (1989). These HP granulites require, in most cases, tectonic burial to mantle depth along relatively high dP/dT gradients, i.e. gradients typical for subduction processes. In other words, the UHT-HP granulite is taken to the heat source rather than having heat applied to it as is the case with the Sil + Opx-bearing crustal UHT granulites (Harley, 1998). The exception is deep levels of old, thickened crust where cooling over time takes a stable geotherm into the HP granulite or even eclogite field. Mafic HP granulites are characteristically Opx-free and exhibit Grt + Cpx + Pl + Qz- (mafic rocks) or Grt + Ky + K-feldspar-bearing (meta-pelites and felsic rocks) assemblages.

Taking the experimentally determined mineral stability curves for tholeiitic basalt and adamellite for Opx-free assemblages leads to the surprising find that the Saxonian granulites plot in the eclogite field. If kyanite stability is taken to limit HP granulites from sillimanite-bearing rocks then only a narrow stability corridor exists for plagioclase-bearing HP granulites of tholeiitic composition. A broader definition restricting the eclogite facies boundary to plagioclase-free rocks of high-Al basaltic composition extends the granulite field to higher pressures and thus allows clinopyroxene with a significant jadeite component (even omphacite) to coexist with plagioclase in HP granulites.

The HT-HP formation conditions (of the UHT group), rapid exhumation, and presence of garnet peridotite, points to a subduction followed by buoyancy-driven exhumation origin. The fact that a significant age range is represented (*c*. 45? Ma, Namche Barwa; 340 Ma, European Variscides; 1.8 Ga, Hengshan, China; 1.9 Ga, Snowbird, Canada; 2.5 Jianping, China) suggests that similar tectonic processes have operated since the Archean.

The overprinted eclogite group shows a higher $\mathrm{d}P/\mathrm{d}T$ trend followed by relaxation to higher temperatures during exhumation because the rocks were not rapidly exhumed. This is just a subtle reminder that the remnants of a subduction orogen can be found at many structural levels, not just in the rocks that race back to the surface. Just consider the Alps and Himalaya in 50 Ma when the coesite-relic-bearing eclogites are eroded and deeper crustal levels are exposed.

ACKNOWLEDGEMENTS

Thanks to G. Droop and S. Harley for their careful reviews, and to A. Indares and J. Martignole for their hard work in organising and managing the meeting and the special issue. Remaining errors and deficiencies are down to us. Part of the research presented here has been generously supported by the DFG.

REFERENCES

Appel, P., Möller, A. & Schenk, V., 1998. High-pressure granulite facies metamorphism in the Pan-African belt of eastern Tanzania: *P-T-t* evidence against granulite formation by continent collision. *Journal of Metamorphic Geology*, **16,** 491–509.

Attoh, K., 1998a. High-pressure granulite facies metamorphism in the Pan-African Dahomeyide orogen, West Africa. *Journal of Geology*, **106,** 236–246.

Attoh, K., 1998b. Models for orthopyroxene-plagioclase and other corona reactions in metanorites, Dahomeyide orogen, West Africa. *Journal of Metamorphic Geology*, **16,** 345–362.

Baba, S., 1998. Proterozoic anticlockwise P-T path of the Lewisian Complex of South Harris, Outer Hebrides, NW Scotland. *Journal of Metamorphic Geology*, **16,** 819–841.

Baker, A. J. & Droop, G. T. R., 1983. Grampian metamorphic conditions deduced from mafic granulites and sillimanite-K-feldspar gneisses in the Dalradian of Glen Muick, Scotland. *Journal of the Geological Society of London*, **140,** 489–497.

Bakun-Czubarow, N., 1992. Quartz pseudomorphs after coesite and quartz exsolutions in eclogitic omphacites of the Zote Mountains in the Sudetes (SW Poland). *Archiwum Mineralogiczne*, **48,** 3–25.

Baldwin, J. A., Bowring, S. A. & and Williams, M. L., 2003. Petrologic and geochronologic constraints on high-pressure, high-temperature metamorphism in the Snowbird tectonic zone, Canada. *Journal of Metamorphic Geology*, **21,** 81–98.

Ballèvre, M., Marchand, J., Godard, G., Goujou, J. C. & Jean-Christian & Wyns, R., 1994. Eo-Hercynian events in the Armorican Massif. In: *Pre-Mesozoic Geology in France and Related Areas* (ed. J. D. Keppie). pp. 183–194. Springer, Berlin.

Bard, J. P., Maluski, H., Matte, Ph & Proust, F., 1980. The Kohistan sequence: crust and mantle of an obducted island arc. *Geological Bulletin, University of Peshawar, Special Issue*, **13,** 87–93.

Becker, H., 1997. Sm-Nd garnet ages and cooling history of high-temperature garnet peridotite massifs and high-pressure granulites from lower Austria. *Contributions to Mineralogy and Petrology*, **127,** 224–236.

Behr, H. J., Den Tex, E., De Waard, D. *et al*., 1971. Granulites – results of a discussion I. *Neues Jahrbuch für Mineralogie, Monatsheft*, **1971,** 97–123.

Bohlen, S. R., 1987. Pressure-temperature-time paths and a tectonic model for the evolution of granulites. *Journal of Geology*, **95,** 617–632.

Boven, A., Theunissen, K., Sklyarov, E. *et al*., 1999. Timing of exhumation of a high-pressure mafic granulite terrane of the Paleoproterozoic Ubende belt (West Tanzania). *Precambrian Research*, **93,** 119–137.

Bradshaw, J. Y., 1989. Early Cretaceous vein-related garnet granulite in Fiordland, southwest New Zealand: a case for infiltration of mantle-derived CO_2-rich fluids. *Journal of Geology*, **97,** 697–717.

van Breemen, O., Aftalion, M., Bowes, D. R., Dudek, A., Mísař, Z., Povondra, P. & Vrána, S., 1982. Geochronological studies of the Bohemian Massif, Czechoslovakia, and their significance in the evolution of Central Europe. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **73,** 89–108.

Bröcker, M. & Klemd, R., 1996. Ultrahigh-pressure metamorphism in the Śnieżnik Mountains, (Sudetes, Poland): P-T constraints and geological implications. *Journal of Geology*, **104,** 417–433.

Brouwer, F. M., 2000. Thermal evolution of high-pressure metamorphic rocks in the Alps. *Geologica Ultraiectina*, **199,** 1–121.

Brown, E. H., 1996. High-pressure metamorphism caused by magma loading in Fiordland, New Zealand. *Journal of Metamorphic Geology*, **14,** 441–452.

Brueckner, H. K. & Medaris, L. G., 1998. A tale of two orogens: the contrasting P-T-t history and geochemical evolution of mantle in high- and ultrahigh-pressure metamorphic terranes of the Norwegian Caledonides and the Czech Variscides. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **78,** 293–307.

Bucher, K. & Frey, M., 1994. *Petrogenesis of Metamorphic Rocks*. Springer-Verlag, Heidelberg.

Caby, R., 1994. First record of Precambrian coesite from Northern Mali: implications for Late Proterozoic plate tectonics in the trans-Saharan segment of the Pan-African belt. *European Journal of Mineralogy*, **6,** 235–244.

Campos Neto, M. D. & Caby, R., 1999. Neoproterozoic high-pressure metamorphism and tectonic constraint from the nappe system south of the Sao Francisco Craton, southeast Brazil. *Precambrian Research*, **97,** 3–26.

Campos Neto, M. D. & Caby, R., 2000. Terrane accretion and upward extrusion of high-pressure granulites in the Neoproterozoic nappes of southeast Brazil: Petrologic and structural constraints. *Tectonics*, **19,** 669–687.

Carrington, D. P. & Harley, S. L., 1995. Partial melting and phase relations in high grade metapelites: an experimental petrogenetic grid in the KFMASH system. *Contributions to Mineralogy and Petrology*, **120,** 270–291.

Carswell, D. A. & Möller, C. & O'Brien, P. J., 1989. Origin of sapphirine symplectites in metabasites from Mitterbachgraben, Dunkelsteinerwald granulite complex, Lower Austria. *European Journal of Mineralogy*, **1,** 455–466.

Carswell, D. A. & O'Brien, P. J., 1993. Thermobarometry and geotectonic significances of high-pressure granulites: examples from the Moldanubian Zone of the Bohemian Massif in Lower Austria. *Journal of Petrology*, **34,** 427–459.

Cartwright, I. & Barnicoat, A. C., 1989. Evolution of the Scourian Complex. In: *Evolution of Metamorphic Belts, Special Publication, 43*. (eds Daly, J. S., Cliff, R. A. & Yardley, B. W. D.), pp. 297–301. Geological Society, London.

Choudhuri, A., Fiori, A. P., Winters, A. A. M., Bettencourt, J. S. & Rodrigues, J. E., 1978. A note on small bodies of eclogite as inclusions in high grade gneisses north of Pousa Alegre, Minas Gerais. *Revista Brasileira de Geociencias*, **8,** 63–68.

Clarke, G. L., Klepeis, K. A. & Daczko, N. R., 2000. Cretaceous high-P granulites at Milford Sound, New Zealand: metamorphic history and emplacement in a convergent margin setting. *Journal of Metamorphic Geology*, **18,** 359–374.

Cliff, R. A., Gray, C. M. & Huhma, H., 1983. A Sm-Nd isotope study of the South Harris Igneous Complex, the Outer Hebrides. *Contributions to Mineralogy and Petrology*, **82,** 91–98.

Collerson, K. D., Hearn, B. C., MacDonald, R. A., Upton, B. F. & Park, J. G., 1988. Granulite xenoliths from the Bearpaw Mountains, Montana: constraints on the character and evoluion of lower continental crust. *Terra Cognita*, **8,** 270.

Cooke, R. A., O'Brien, P. J. & Carswell, D. A., 2000. Garnet zoning and the identification of equilibrium mineral compositions in high-pressure–temperature granulites from the Moldanubian Zone, Austria. *Journal of Metamorphic Geology*, **18,** 551–569.

Coolen, J. J. M. M. M., 1980. *Chemical Petrology of the Furua Complex, Southern Tanzania*. GUA Papers of Geology, **13,** Amsterdam.

Corfu, F., Heaman, L. M. & Rogers, G., 1994. Polymetamorphic evolution of the Lewisian Complex, NW Scotland, as recorded by U-Pb isotopic compositions of zircon, titanite and rutile. *Contributions to Mineralogy and Petrology*, **117,** 215–228.

Costa, S., Maluski, H. & Lardeaux, J.-M., 1993. ^{40}Ar-^{39}Ar chronology of Variscan tectono-metamorphic events in an exhumed crustal nappe: the Monts du Lyonnais complex (Massif Central, France). *Chemical Geology*, **105,** 339–359.

Cox, R. & Indares, A., 1999. Transformation of Fe-Ti gabbro to coronite, eclogite and amphibolite in the Baie du Nord segment, Manicouagan Imbricate Zone, eastern Grenville Province. *Journal of Metamorphic Geology*, **17,** 537–555.

Davidson, A., 1990. Evidence for eclogite metamorphism in the southwestern Grenville Province. *Geological Survey of Canada, Paper*, **90–1C,** 113–118.

Davis, W. J., Berman, R. & Kjarsgaard, B., 1995. U-Pb geochronology and isotopic studies of crustal xenoliths from the Archean Medicine Hat Block, northern Montana and southern Alberta: Paleoproterozoic reworking of Archean crust. *1995 Alberta Basement Transacts Workshop* (Ross, G.M., compiler). *Lithoprobe Report*, **47,** 330–335.

De Waard, D., 1965. A proposed subdivision of the granulite facies. *American Journal of Science*, **263,** 455–461.

Del Lama, E. A., Zanardo, A., Oliviera, M. A. F. & Morales, N., 2000. Exhumation of high-pressure granulites of the Guaxupé Complex, southeastern Brazil. *Geological Journal*, **35,** 231–249.

Ding, L. & Zhong, D., 1999. Metamorphic characteristics and geotectonic implications of the high-pressure granulites from Namjagbarwa, eastern Tibet. *Science in China (D)*, **42,** 491–505.

Ding, L., Zhong, D. L., Yin, A., Kapp, P. & Harrison, T. M., 2001. Cenozoic structural and metamorphic evolution of the eastern Himalayan syntaxis (Namche Barwa). *Earth and Planetary Science Letters*, **192,** 423–438.

Dirks, P. H. G. M. & Sithole, T. A., 1999. Eclogites in the Makuti gneisses of Zimbabwe: implications for the tectonic evolution of the Zambezi Belt in southern Africa. *Journal of Metamorphic Geology*, **17,** 593–612.

Dirks, P. H. G. M., Zhang, J. S. & Passchier, C. W., 1997. Exhumation of high-pressure granulites and the role of lower crustal advection in the North China craton near Datong. *Journal of Structural Geology*, **19,** 1343–1358.

Downes, H., 1993. The nature of the lower continental crust of Europe: petrological and geochemical evidence from xenoliths. *Physics of the Earth and Planetary Interiors*, **79,** 195–218.

Dufour, E., Lardeaux, J. M. & Coffrant, D., 1985. Eclogites and granulites in the Monts du Lyonnais area: an eo-Hercynian plurifacial metamorphic evolution. *Comptes Rendus de L'academie des Sciences, Paris*, **300,** 141–144.

Eigenfeld, R., 1963. Über die mineralfazielle Stellung der Pyroxen-granulite (auf Grund von Untersuchungen des Prototyps von Hartmannsdorf/Sa. Als polymetamorphemeklogitogenen Metabasit in Hornfels-fazies). *Geologische Rundschau*, **52,** 65–94.

Ellis, D. J. & Maboko, M. A. H., 1992. Precambrian tectonics and the physicochemical evolution of the continental crust. I. The gabbro-eclogite transition revisited. *Precambrian Research*, **55,** 491–506.

Elvevold, S. & Gilotti, J. A., 2000. Pressure-temperature evolution of retrogressed kyanite eclogites, Weinschenk Island, North-East Greenland Caledonides. *Lithos*, **53,** 127–147.

Eskola, P., 1952. On the granulites of Lappland. *American Journal of Science*, **250,** Bowen volume, 133–171.

Faryad, S. W., 1999. Metamorphic evolution of the Precambrian South Badakhshan block, based on mineral reactions in metapelites and metabasites associated with whiteschists from Sare Sang (Western Hindu Kush, Afghanistan). *Precambrian Research*, **98,** 223–241.

Fiala, J., Matejovská, O. & Vaňková, V. B., 1987. Moldanubian granulites: source material and petrogenetic considerations. *Neues Jahrbuch für Mineralogie, Abhandlungen*, **157,** 133–165.

Friend, C. R. L. & Kinny, P. D., 1995. New evidence for protoliths ages of Lewisian granulites, northwest Scotland. *Geology*, **23,** 1027–1030.

Frost, B. R. & Chacko, T., 1989. The granulite uncertainty principle: limitations on thermobarometry in granulites. *Journal of Geology*, **97,** 435–450.

Fuhrman, M. L. & Lindsley, D. H., 1988. Ternary-feldspar modelling and thermometry. *American Mineralogist*, **73,** 201–215.

Gálan, G. & Marcos, A., 2000. The metamorphic evolution of the high pressure mafic granulites of the Bacariza Formation (Cabo Ortegal Complex, Hercynian belt, NW Spain). *Lithos*, **54,** 139–171.

Gardien, V., Tegyey, M., Lardeaux, J. M., Misseri, M. & Dufour, E., 1990. Crust-mantle relationships in the French Variscan chain: the example of the Southern Monts du Lyonnais unit (eastern French Massif Central). *Journal of Metamorphic Geology*, **8,** 477–492.

Gayk, T. & Kleinschrodt, R., 2000. Hot emplacement of garnet-peridotites followed by fast uplift of the lower crust. Hints from the central Vosges Mountains (E-France). *Journal of Metamorphic Geology*, **18,** 293–306.

Gayk, T., Kleinschrodt, R., Langosch, A. & Seidel, E., 1995. Quartz exsolution in clinopyroxenes of high-pressure granulites from the Münchberg massif. *European Journal of Mineralogy*, **7,** 1217–1220.

Ghent, E. D., Stout, M. Z. & Raeside, R. P., 1983. Plagioclase-clinopyroxene-garnet-quartz equilibria and the geobarometry and geothermometry of garnet amphibolites from Mica Creek, British Colombia. *Canadian Journal of Earth Science*, **20,** 699–706.

Godard, G. & Mabit, J.-L., 1998. Peraluminous sapphirine formed during retrogression of a kyanite-bearing eclogite from Pays de Lyon, Armorican Massif, France. *Lithos*, **43,** 15–29.

Godard, G., Martin, S., Prosser, G., Kienast, J. R. & Morten, L., 1996. Variscan migmatites, eclogites and garnet-peridotites of the Ulten zone, Eastern Austroalpine system. *Tectonophysics*, **259,** 313–341.

Green, D. H. & Lambert, I. B., 1965. Experimental crystallisation of anhydrous granite at high pressures and temperatures. *Journal of Geophysical Research*, **70,** 5259–5268.

Green, D. H. & Ringwood, A. E., 1967. An experimental investigation of the gabbro to eclogite transformation and its petrological applications. *Geochimica et Cosmochimica Acta*, **31,** 767–833.

Griffin, W. L., Carswell, D. A. & Nixon, P. H., 1979. Lower crustal granulites and eclogites from Lesotho, Southern Africa. In: *The Mantle Sample* (eds Boyd, F. R. & Meyer, H. O. A.), pp. 59–86. American Geophysical Union, Washington.

Griffin, W. L., O'Reilly, S. Y. & Pearson, N. J., 1990. Eclogite stability near the crust–mantle boundary. In: *Eclogites and Related Rocks* (ed. Carswell, D. A.), pp. 291–314. Blackie, Glasgow.

Guo, J. H., Bian, A. G. & Shi, X., 1996. High-pressure granulite, retrograde eclogite and granite: early Precambrian Sangan Structure Zone. In: *Granulites and Lower Continental Crust in North China Archaean Craton* (ed. Zhai, M. G.), pp. 21–48. Seismological Press, Beijing, China.

Guo, J. H., O'Brien, P. J. & Zhai, M. G., 2002. High pressure granulites in the Sanggan area, North China craton: metamorphic evolution, P-T paths and geotectonic significance. *Journal of Metamorphic Geology*, **20,** 741–757.

Hansen, B., 1981. The transition from pyroxene granulite facies to garnet clinopyroxene granulite facies: Experiments in the system CaO-MgO-Al_2O_3-SiO_2. *Contributions to Mineralogy and Petrology*, **76,** 234–242.

Harley, S. L., 1989. The origins of granulites: a metamorphic prospective. *Geological Magazine*, **126,** 215–247.

Harley, S. L., 1998. On the occurrence and characterization of ultrahigh-temperature crustal metamorphism. In: *What Drives Metamorphism and Metamorphic Reactions? Special Publication 138*. (eds Treloar, P. J. & O'Brien, P. J.), pp. 81–107. Geological Society, London.

Harley, S. L. & Carswell, D. A., 1990. Experimental studies on the stability of eclogite facies mineral assemblages. In: *Eclogite Facies Rocks* (ed. Carswell, D. A.), 53–82, Blackie, Glasgow.

Hölttä, P., Huhma, H., Mänttäri, I., Peltonen, P. & Juhanoja, J., 2000. Petrology and geochemistry of mafic granulite xenoliths from the Lahtojoki kimberlite pipe, eastern Finland. *Lithos*, **51,** 109–133.

Indares, A., 1993. Eclogitized gabbros from the eastern Grenville Province: texture, metamorphic context, and implication. *Canadian Journal of Earth Sciences*, **30,** 159–173.

Indares, A., 1995. Metamorphic interpretation of High-Pressure-Temperature metapelites with preserved growth zoning in garnet, Eastern Grenville Province, Canadian Shield. *Journal of Metamorphic Geology*, **13,** 475–486.

Indares, A., 1997. Garnet-kyanite clinopyroxenites and garnet-kyanite restites from the Manicouagan Imbricate Zone: a case of high-P-high-T metamorphism in the Grenville Province. *Canadian Mineralogist*, **35,** 1161–1171.

Indares, A. & Dunning, G., 2001. Partial melting of high-P-T metapelites from the Tshenukutish terrane (Grenville Province): Petrography and U-Pb geochronology. *Journal of Petrology*, **42,** 1547–1565.

Ireland, T. R. & Gibson, G. M., 1998. SHRIMP monazite and zircon geochronology of high grade metamorphism in New Zealand. *Journal of Metamorphic Geology*, **16,** 149–167.

Ito, K. & Kennedy, G. C., 1971. An experimental study of the basalt-garnet granulite-eclogite transition. In: *The Structure and Physical Properties of the Earth's Crust, Monograph no. 14* (ed. Heacock, J. G.), pp. 303–314. American Geophysical Union, Washington DC.

Jan, M. Q. & Karim, A., 1995. Coronas and high-P veins in metagabbros of the Kohistan island arc, northern Pakistan: evidence for crustal thickening during cooling. *Journal of Metamorphic Geology*, **13,** 357–366.

Johannes, W. & Holtz, F., 1996. *Petrogenesis and Experimental Petrology of Granitic Rocks*. Springer-Verlag, Heidelberg.

Johansson, L. & Möller, C., 1986. Formation of sapphirine during retrogression of a basic high-pressure granulite, Roan, Western Gneiss Region, Norway. *Contributions to Mineralogy and Petrology*, **94,** 29–41.

Kalt, A., Altherr, R. & Hanel, M., 2000. The Variscan basement of the Schwarzwald. *European Journal of Mineralogy*, **12,** 1–43.

Kempton, P. D., Downes, H., Sharkov, E. V. *et al*., 1995. Petrology and geochemistry of xenoliths from the Northern Baltic shield: evidence for partial melting and metasomatism in the lower crust beneath an Archaean terrane. *Lithos*, **36,** 157–184.

Kleemann, U., 1991. Die P-T.t-d-Entwicklung im Grenzbereich zwischen der Zone von Erbendorf-Vohenstrauß (ZEV) und dem Moldanubikum in der Oberpfalz/NE Bayern. *Doctoral Thesis, University of Bochum, Germany*.

Klemd, R. & Bröcker, M., 1999. Fluid influence on mineral reactions in ultrahigh-pressure granulites: a case study in the Snieznik Mts. (West Sudetes, Poland). *Contributions to Mineralogy and Petrology*, **136,** 358–373.

Kotková, J., Gerdes, A., Parrish, R. R. & Novak, M., 2001. Pressure-temperature-time evolution of granulite clasts from Lower Carboniferous conglomerates – evidence for rapid exhumation at the eastern margin of the Variscan Bohemian Massif. *Journal of Conference Abstracts*, **6,** 434.

Kotková, J. & Harley, S. L., 1999. Formation and evolution of high-pressure leucogranulites: experimental constraints and unresolved issues. *Physics and Chemistry of the Earth (a)*, **24,** 299–304.

Kotková, J., Kröner, A., Todt, W. & Fiala, J., 1996. Zircon dating of North Bohemian granulites, Czech Republic: further evidence for the Lower Carboniferous high-pressure event in the Bohemian Massif. *Geologische Rundschau*, **85,** 154–161.

Kretz, R., 1983. Symbols for rock forming minerals. *American Mineralogist*, **68,** 277–279.

Kroner, U., 1995. Post-collisional extension at the northern margin of the Bohemian Massif: the exhumation of the Saxonian Granulite Massif (in German). *Freiberger Forschungshefte*, **C457,** 1–114.

Kröner, A., Jaeckel, P., Reischmann, T. & Kroner, U., 1998. Further evidence for an early Carboniferous (similar to 340 Ma) age of high-grade metamorphism in the Saxonian granulite complex. *Geologische Rundschau*, **86,** 751–766.

Kröner, A., O'Brien, P. J., Nemchin, A. A. & Pidgeon, R. T., 2000. Zircon ages for high pressure granulites from South Bohemia, Czech Republic, and their connection to Carboniferous high temperature processes. *Contributions to Mineralogy and Petrology*, **138,** 127–142.

Kröner, A. & Willner, A. P., 1998. Time of formation and peak of Variscan HP-HT metamorphism of quartz-feldspar rocks in the central Erzgebirge, Saxony, Germany. *Contributions to Mineralogy and Petrology*, **132,** 1–20.

Kryza, R., Pin, C. & Vielzeuf, D., 1996. High-pressure granulites from the Sudetes (south-west Poland): evidence of crustal subduction and collisional thickening in the Variscan Belt. *Journal of Metamorphic Geology*, **14,** 531–546.

Latouche, L., Fabries, J. & Guiraud, M., 1992. Retrograde evolution of granulite facies gneisses from the Vosges Mountains (NE France): tectonic implications. *Tectonophysics*, **205,** 387–407.

Le Breton, N. & Thompson, A. B., 1988. Fluid-absent (dehydration) melting of biotite in metapelites in the early stages of crustal anatexis. *Contributions to Mineralogy and Petrology*, **99,** 226–237.

Liati, A. & Seidel, E., 1994. Sapphirine and högbohmitein overprinted kyanite-eclogites of central Rhodop, N. Greece: first evidence of granulite-facies metamorphism. *European Journal of Mineralogy*, **6,** 733–738.

Libourel, G., 1988. Le Complexe de Santa-Lucia di Mercurio (Corse): un nouveau jalon de la base de la croûte varisque en Méditerranée occidentale. *Comptes Rendus de L'academie des Sciences, Paris*, **307,** 1067–1073.

Liu, Y. & Zhong, D., 1997. Petrology of high-pressure granulites from the eastern Himalayan syntaxis. *Journal of Metamorphic Geology*, **15,** 451–466.

Liu, L., Zhou, D. W., Wang, Y., Chen, D. L. & Liu, Y., 1996. Study and implication of the high pressure felsic granulite in the Qinling complex of East Qinling. *Science in China*, **39,** 60–68.

Lombardo, B. & Rolfo, F., 2000. Two contrasting eclogite types in the Himalayas: implications for the Himalayan orogeny. *Journal of Geodynamics*, **30,** 37–60.

Lovering, J. P. & White, A. J. R., 1969. Granulitic and eclogitic inclusions from basic pipes of Delegate, Australia. *Contributions to Mineralogy and Petrology*, **21,** 9–52.

Marques, F. O., Ribeiro, A. & Munhá, J. M., 1996. Geodynamic evolution of the Continental Allochthonous Terrane (CAT) of the Bragança Nappe Complex, NE Portugal. *Tectonics*, **15,** 747–762.

Massonne, H.-J., 2001. First find of coesite in the ultrahigh-pressure metamorphic area of the central Erzgebirge, Germany. *European Journal of Mineralogy*, **13,** 565–570.

Medaris, L. G., Beard, B. L., Johnson, C. M. *et al*., 1995b. Garnet pyroxenite and eclogite in the Bohemian Massif: geochemical evidence for Variscan recycling of subducted lithosphere. *Geologische Rundschau*, **84,** 489–505.

Medaris, L. G., Jelínek, E. & Mísař, Z., 1995a. Czech eclogites: Terrane settings and implications for Variscan tectonic evolution of the Bohemian Massif. *European Journal of Mineralogy*, **7,** 7–28.

Medaris, L. G., Wang, H. F., Mísař, Z. & Jelínek, E., 1990. Thermobarometry, diffusion modelling and cooling rates of crustal garnet peridotites: two examples from the Moldanubian Zone of the Bohemian Massif. *Lithos*, **25,** 189–202.

Mehnert, K. R., 1972. Granulites – results of a discussion II. *Neues Jahrbuch für Mineralogie, Monatshefte*, **1972,** 139–150.

Möller, C., 1988. Geology and metamorphic evolution of the Roan area, Vestranden, Western Gneiss Region, Central Norwegian Caledonides. *Norges Geologiske Undersøkelse*, **413,** 1–31.

Möller, C., 1998. Decompressed eclogites in the Sveconorwegian (-Grenvillian) orogen of SW Sweden: petrology and tectonic implications. *Journal of Metamorphic Geology*, **16,** 641–656.

Möller, C., 1999. Sapphirine in SW Sweden: a record of Sveconorwegian (-Grenvillian) late-orogenic tectonic exhumation. *Journal of Metamorphic Geology*, **17,** 127–141.

Möller, A., Appel, P., Mezger, K. & Schenk, V., 1995. Evidence for a 2 Ga subduction zone: eclogites in the Usagaran belt of Tanzania. *Geology*, **23,** 1067–1070.

Mukhopadhyay, B. & Bose, M. K., 1994. Transitional granulite eclogite facies metamorphism of basic supracrustals in a shear zone complex in the Precambrian shield of South India. *Mineralogical Magazine*, **58,** 97–118.

Nasdala, L. & Massonne, H.-J., 2000. Microdiamonds from the Saxonian Erzgebirge, Germany: in situ micro-Raman characterisation. *European Journal of Mineralogy*, **12,** 495–498.

O'Brien, P. J., 1994. The formation of sapphirine and orthopyroxene during overprinting of Mariánské Lázne Complex eclogites. *Zentralblatt für Geologie und Paläontologie, Teil*, **I** (1992)**,** 827–836.

O'Brien, P. J., 1997a. Garnet zoning and reaction textures in overprinted eclogites, Bohemian Massif, European Variscides: a record of their thermal history during exhumation. *Lithos*, **41,** 119–133.

O'Brien, P. J., 1997b. Granulite facies overprints of eclogites: short-lived events deduced from diffusion modelling. In: *Precambrian Geology and Metamorphic Petrology, Proceedings 30th Internationl Geological Congress, 17, part II*, (eds Qian, X., You, Z., Jahn, B.-M. & Halls, H. C.), pp. 157–171. Dordrecht.

O'Brien, P. J., 1999. Asymmetric zoning profiles in garnet from HP-HT granulite and implications for Volume and grain boundary diffusion. *Mineralogical Magazine*, **63,** 227–238.

O'Brien, P. J., 2000. The fundamental Variscan problem: high-temperature metamorphism at different depths and high-pressure metamorphism at different temperatures. In: *Orogenic Processes: Quantification and Modelling in the Variscan Belt, Special Publication, 179* (eds Franke, W., Haak, V., Onken, O. & Tanner, D.), pp. 369–386. Geological Society. London.

O'Brien, P. J., Carswell, D. A. & Gebauer, D., 1990. Eclogite Formation and Distribution in the European Variscides. In: *Eclogite Facies Rocks* (ed. Carswell, D. A.), pp. 204–224. Blackie & Son Ltd., Glasgow.

O'Brien, P. J., Kröner, A., Jaeckel, P., Hegner, E., Żelaźniewicz, A. & Kryza, R., 1997. Petrological and isotopic studies on Palaeozoic high-pressure granulites, Góry Sowie Mts, Polish Sudetes. *Journal of Petrology*, **38,** 433–456.

O'Brien, P. J., Röhr, C., Okrusch, M. & Patzak, M., 1992. Eclogite facies relics and a multistage breakdown in metabasites of the KTB pilot hole, NE Bavaria: implications for the the Variscan tectonometamorphic evolution of the NW Bohemian Massif. *Contributions to Mineralogy and Petrology*, **112,** 261–278.

O'Brien, P. J. & Vrána, S., 1995. Eclogites with a short-lived granulite facies overprint in the Moldanubian Zone, Czech Republic: petrology, geochemistry and diffusion modelling of garnet zoning. *Geologische Rundschau*, **84,** 473–488.

Owen, J. V. & Dostal, J., 1996. Contrasting corona structures in mafic granulite from the Blansky les complex, Bohemian Massif, Czech Republic. *Canadian Mineralogist*, **34,** 959–966.

Patiño Douce, A. E. & Beard, J. S., 1995. Dehydration-melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar. *Journal of Petrology*, **36,** 707–738.

Pattison, D. R. M., 2003. Petrogenetic significance of orthopyroxene-free garnet + clinopyroxene + plagioclase-bearing metabasites with respect to the amphibolite and granulite facies. *Journal of Metamorphic Geology*, **21,** 21–31.

Pearson, N. J., O'Reilly, S. Y. & Griffin, W. L., 1995. The crust–mantle boundary beneath cratons and craton margins: a transect across the south-west margin of the Kaapvaal craton. *Lithos*, **36,** 257–287.

Percival, J. A., 1983. High-grade metamorphism in the Chapleau-Foleyet Area, Ontario. *American Mineralogist*, **68,** 667–686.

Pin, C. & Vielzeuf, D., 1983. Granulites and related rocks in Variscan median Europe: a dualistic interpretation. *Tectonophysics*, **93,** 47–74.

Pin, C. & Vielzeuf, D., 1988. Les granulites de haute-pression d'Europe moyenne témoins d'une subduction éo-hercynienne. Implications sur l'origine des groupes leptyno-amphiboliques. *Bulletin de la Société Géologique de France*, **8** (4)**,** 13–20.

Pognante, U., Benna, P. & Le Fort, P., 1993. High-pressure metamorphism in the High Himalayan Crystallines of the Stak valley, northeastern Nanga Parbat – Haramosh syntaxis, Pakistan Himalaya. In: *Himalayan Tectonics, Special Publication, 74*, (eds Treloar, P. J. & Searle, M. P.), pp. 161–172. Geological Society London.

Pouba, Z., Padera, K. & Fiala, J., 1985. Omphacite granulite from the NE marginal area of the Bohemian Massif, (Rychleby Mts). *Neues Jahrbuch für Mineralogie, Abhandlungen*, **151,** 29–52.

von Quadt, A., 1993. The Saxonian Granulite Massif: new aspects from geochronological studies. *Geologische Rundschau*, **82,** 516–530.

Reinhardt, J. & Kleemann, U., 1994. Extensional unroofing of granulitic lower crust and related low-pressure, high-temperature metamorphism in the Saxonian Granulite Massif, Germany. *Tectonophysics*, **238,** 71–94.

Rogers, N. W., 1977. Granulite xenoliths from Lesotho kimberlites and the lower continental crust. *Nature*, **270,** 681–684.

Romer, R. & Rötzler, J., 2001. P-T-t evolution of ultrahigh-temperature granulites from the Saxon Granulite Massif, Germany. Part II: U-Pb dating of trace and major phases. *Journal of Petrology*, **42,** 2015–2032.

Rötzler, J., 1992. Zur Petrogenese im Sächsischen Granulitgebirge: die pyroxenfreien Granulite und die Metapelite. *Geotektonische Forschungen*, **77,** 1–100.

Rötzler, J. & Romer, R. L., 2001. P-T-t evolution of ultrahigh-temperature granulites from the Saxon Granulite Massif, Germany. Part I: Petrology. *Journal of Petrology*, **42,** 1995–2013.

Rudnick, R., 1992. Xenoliths – samples of the lower continental crust. In: *The Continental Crust* (eds Fountain, D. M., Arculus, R. J. & Kay, R. W.), pp. 269–316. Elsevier, New York.

Rushmer, T., 1993. Experimental high-pressure granulites: some applications to natural mafic xenolith suites and Archean granulite terranes. *Geology*, **21,** 411–414.

Sanders, I. S., Daly, J. S. & Davies, G. R., 1987. Late Proterozoic high-pressure granulite facies metamorphism in the north-east Ox inlier, north-west Ireland. *Journal of Metamorphic Geology*, **5,** 69–85.

Santos Zalduegui, J. F., Schärer, U., Gil Ibarguchi, J. I. & Girardeau, J., 1996. Origin and evolution of the Paleozoic Cabo Ortegal ultramafic-mafic complex (NW Spain): U-Pb, RbSr and Pb-Pb isotope data. *Chemical Geology*, **129,** 281–304.

Schaltegger, U., Fanning, C. M., Günther, D., Maurin, J. C., Schulmann, K. & Gebauer, D., 1999. Growth, annealing and recrystallisation of zircon and preservation of monazite in high-grade metamorphism: conventional and in-situ U-Pb isotope, cathodoluminescence and microchemical evidence. *Contributions to Mineralogy and Petrology*, **134,** 186–201.

Scharbert, H. G. & Carswell, D. A., 1983. Petrology of garnet-clinopyroxene rocks in a granulite facies environment, Bohemian Massif of Lower Austria. *Bulletin Mineralogique*, **106,** 761–774.

Scheumann, K. H., 1961. 'Granulit', eine petrographische definition. *Neues Jahrbuch für Mineralogie, Monatshefte*, **1961,** 75–80.

Scrimgeour, I. & Close, D., 1999. Regional high-pressure metamorphism during intracratonic deformation: the Petermann Orogeny, central Australia. *Journal of Metamorphic Geology*, **17,** 557–572.

Sklyarov, E. V., Theunissen, K., Melnikov, A. I., Klerkx, J., Gladkochub, D. P. & Mruma, A., 1998. Paleoproterozoic eclogites and garnet pyroxenites of the Ubende belt (Tanzania). *Schweizerische Mineralogische und Petrographische Mitteilungen*, **78,** 257–271.

Snoeyenbos, D. R., Williams, M. L. & Hanmer, S., 1995. Archean high-pressure metamorphism in the western Canadian Shield. *European Journal of Mineralogy*, **7,** 1251–1272.

Spear, F. S., 1993. *Metamorphic phase equilibria and pressure-temperature-time paths*. Mineralogical Society of America, Washington, DC.

Spear, F. S., Kohn, M. J. & Cheney, J. T., 1999. *PT* paths from anatectic pelites. *Contributions to Mineralogy and Petrology*, **134,** 17–32.

Stosch, H.-G., Ionov, D. A., Puchtel, I. S., Galer, S. J. G. & Sharpouri, A., 1995. Lower crustal xenoliths from Mongolia and their bearing on the nature of the deep crust beneath central Asia. *Lithos*, **36,** 227–242.

Toft, P. B., Hills, D. V. & Haggerty, S. E., 1989. Crustal evolution and the granulite to eclogite transition in xenoliths from kimberlites in the West African Craton. *Tectonophysics*, **161,** 213–231.

Treloar, P. J., Carney, J. N., Crow, M. J., Evans, J. A. & Barton, C. N., 1990. Pressure-temperature-time paths of granulite metamorphism and uplift, Zambesi Belt, N.E. Zimbabwe. In: *Granulites and Crustal Evolution* (eds Vielzeuf, D. & Vidal, Ph), pp. 223–241. Kluwer, Dordrecht.

Vielzeuf, D. & Holloway, J. R., 1988. Experimental determination of the fluid absent melting relations in the pelitic system. *Contributions to Mineralogy and Petrology*, **98,** 257–276.

Vrána, S., 1989. Perpotassic granulites from southern Bohemia. A new rock-type derived from partial melting of crustal rocks under upper mantle conditions. *Contributions to Mineralogy and Petrology*, **103,** 510–522.

Vrána, S. & Jakeš, P., 1982. Orthopyroxene and two-pyroxene granulites from a segment of charnockitic crust in southern Bohemia. *Bulletin of the Geological Survey, Prague*, **57,** 129–143.

Waters, D. J. & Whales, C. J., 1984. Dehydration melting and the granulite transition in metapelites from southern Namaqualand, S. Africa. *Contributions to Mineralogy and Petrology*, **88,** 269–275.

Weber, M. B. I., Tarney, J., Kempton, P. D. & Kent, R. W., 2002. Crustal make-up of the northern Andes: evidence based on deep crustal xenolith suites, Mercaderes, SW Colombia. *Tectonophysics*, **345,** 49–82.

Wei, C. J., Zhang, C. G., Zhang, A. L., Wu, T. H. & Li, J. H., 2001. Metamorphic P-T conditions and geological significance of high-pressure granulite from the Jianping complex, western Liaoning province. *Acta Petrologica Sinica*, **17,** 269–282.

Weiss, C. S., 1803. Über die Gebirgsart des sächsichen Erzgebirges, welche unter dem Namen Weiss-Stein neuerlich bekannt gemacht worden ist. *Neue Schriften Gesellschaft Naturforschender Freunde*, **4,** 342–366.

Willner, A. P., Rotzler, K. & Maresch, W. V., 1997. Pressure-temperature and fluid evolution of quartzo-feldspathic metamorphic rocks with a relic high-pressure, granulite-facies history from the Central Erzgebirge (Saxony, Germany). *Journal of Petrology*, **38,** 307–336.

Winkler, H. G. F., 1979, *Petrogenesis of Metamorphic Rocks*, 5th edn. Springer-Verlag, New York Inc. 348pp.

Wood, B. J., 1977. The activities of components in clinopyroxene and garnet solid solutions and their application to rocks. *Philosophical Transactions of the Royal Society of London*, **286,** 331–342.

Wood, B. J., 1987. Thermodynamics of multicomponent systems containing several solid solutions. In: *Thermodynamic Modeling of Geological Materials: Minerals, Fluids and Melts, Reviews in Mineralogy, 17,* (eds Carmichael, I. S. E. & Eugster, H. P.), pp. 71–95. Mineralogical Society of America, Washington, DC.

Yamamoto, H. & Yoshino, T., 1998. Superposition of replacements in the mafic granulites of the Jijal complex of the Kohistan arc, northern Pakistan: dehydration and rehydration within deep arc crust. *Lithos*, **43,** 219–234.

Yoshino, T., Yamamoto, H., Okudaira, T. & Toriumi, M., 1998. Crustal thickening of the lower crust in the Kohistan arc (N Pakistan) deduced from Al zoning in clinopyroxene and plagioclase. *Journal of Metamorphic Geology*, **16,** 729–748.

Zhao, G. C., Cawood, P. A., Wilde, S. A. & Lu, L. Z., 2001. High-pressure granulites (retrograded eclogites) from the Hengshan Complex, North China Craton: Petrology and tectonic implications. *Journal of Petrology*, **42,** 1141–1170.

Zhao, G. C., Wilde, S. A., Cawood, P. A. & Lu, L. Z., 1999. Thermal evolution of two textural types of mafic granulites in the North China craton: evidence for both mantle plume and collisional tectonics. *Geological Magazine*, **136,** 223–240.

Received 21 December 2001; revision accepted 6 June 2002.