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Metamorphic evolution of garnet-spinel peridotites from the Variscan Schwarzwald (Germany)

Abstract Garnet-spinel peridotites form small, isolated, variably retrogressed bodies within the low-pressure high-temperature gneisses and migmatites of the Variscan basement of the Schwarzwald, southwest Germany. Detailed mineralogical and textural studies as well as geothermobarometric calculations on samples from three occurrences are presented. Two of the garnet-spinel peridotites have equilibrated at 680–770 °C, 1.4–1.8 GPa within the garnet-spinel peridotite stability field, one of the samples having experienced an earlier stage within the spinel peridotite stability field (790 °C, <1.8 GPa). The third sample, with only garnet and spinel preserved, probably equilibrated within the garnet peridotite stability field at higher pressures. These findings are in line with the distinction of two groups of ultramafic garnet-bearing high-pressure rocks with different equilibration conditions within the Schwarzwald (670–740 °C, 1.4–1.8 GPa and 740–850 °C, 3.2–4.3 GPa) which has previously been established (Kalt et al. 1995). The equilibration conditions of 670–770 °C and 1.4–1.8 GPa for garnet-spinel peridotites from the Central Schwarzwald Gneiss Complex (CSGC) are similar to those for eclogites of the Schwarzwald and also correspond quite well to those for garnet-spinel peridotites from the Moldanubian zone of the Vosges mountains and of eclogites from the Moldanubian s.str. of the Bohemian Massif.

Key words Garnet-spinel peridotite · Geothermobarometry · Schwarzwald · Variscan orogen · Moldanubian

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Introduction

Low-pressure high-temperature gneiss terranes of collisional belts often bear small isolated bodies of high-pressure metamorphic rocks that are commonly either eclogites, peridotites or pyroxenites. If these high-pressure metamorphic rocks have survived retrogression during their exhumation, the P-T-(t) paths recorded by their mineral assemblages can give valuable information on orogenic processes. Most eclogites form by mineral reactions from basalts that are part of the subducted plate. Their mineral compositions usually record peak metamorphic conditions characterised by a high P/T gradient and, depending on their retrograde evolution, several stages of low-pressure high-temperature overprint (O'Brien et al. 1992; O'Brien 1993; O'Brien and Vrána 1995). On the contrary, peridotites and pyroxenites may evolve in various tectonic settings and under different P-T conditions as parts of either the subducted oceanic plate (Ernst 1978; Evans and Trommsdorff 1978; Obata 1980) or the overriding continental lithosphere (Medaris et al. 1990; Jamtveit 1987a, b).

The various P-T histories recorded by eclogites, peridotites and pyroxenites can also serve to characterise petrologically their low-pressure high-temperature metamorphic host units. This is extremely important for the Variscan orogenic belt in Central Europe where petrological correlations between isolated basement areas have to be made (Franke 1989) in order to understand the nappe character of the orogen and to place constraints on palaeogeography. Within the Variscan belt, eclogites and peridotites occur in the Moldanubian zone (Fig. 1) and in several allochthonous nappes within the Saxothuringian zone. Within the Bohemian Massif, three major Moldanubian nappes or terranes have been recognised on the basis of structures, lithology and metamorphic grade: (a) the Teplá-Barrandian block, (b) the Gföhl unit and (c) the Moldanubian s. str. consisting of a Monotonous and a Varied series.

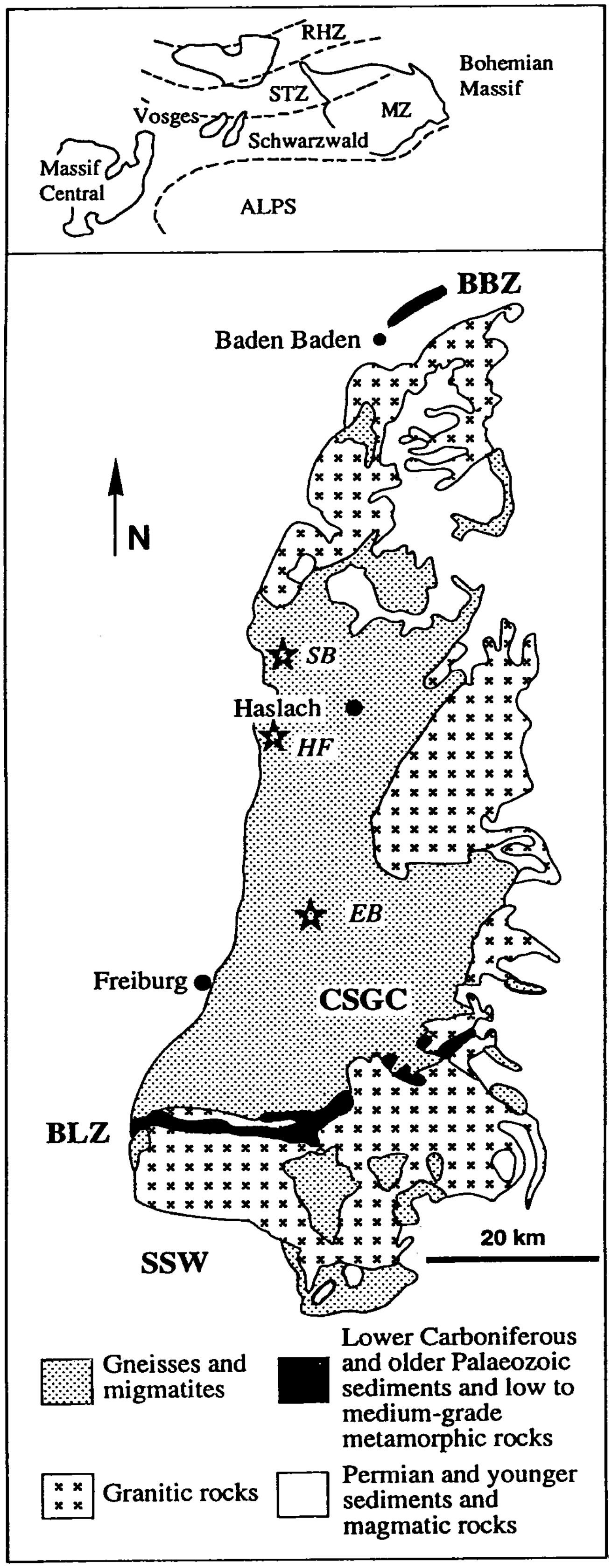


Fig. 1 Simplified geological sketch map of the Schwarzwald showing the main geological units and the sample sites (*SB*, *HF* and *EB*). *BBZ* Baden-Baden-Zone; *BLZ* Badenweiler-Lenzkirch-Zone; *CSGC* Central Schwarzwald Gneiss Complex; *SSW* Südschwarzwald. *Inset:* The Schwarzwald within the Variscan setting. *RHZ* Rhenohercynian zone; *MZ* Moldanubian zone; *STZ* Saxothuringian zone

The high-pressure metamorphic basement inliers of these nappes also record contrasting P-T histories and different peak metamorphic P-T conditions (O'Brien 1989; Medaris et al. 1990; Carswell and O'Brien 1993; Medaris et al. 1995a, b; O'Brien and Vrâna 1995).

The metamorphic basement of the Schwarzwald is generally assigned to the Monotonous series of the Moldanubian zone (Franke 1989). Apart from the distinction of some more varied lithologies (Wimmenauer 1980) that are devoid of high-pressure relicts, the monotonous low-pressure high-temperature gneisses and migmatites proper could not be subdivided into different units in terms of lithology, structures and metamorphic grade. Nevertheless, the high-pressure metamorphic rocks within this monotonous low-pressure high-temperature metamorphic basement record different P-T histories (Kalt et al. 1995). Previous geothermobarometric estimates on eclogites and garnet-bearing ultramafic high-pressure rocks point to the existence of two groups of high-pressure rocks that are defined by contrasting P-T evolutions and different peak pressures (Kalt et al. 1994b; Kalt et al. 1995).

The purpose of the current investigation of further garnet-spinel peridotites from the Schwarzwald, which have not yet been described, is thus twofold. The first objective is to set out the P-T history of their high-pressure metamorphic basement inliers and thus contribute to the correlation of Moldanubian basement units. The second aim was to test whether all garnet-bearing peridotites in the Schwarzwald can be assigned to the two groups previously established for the Schwarzwald.

Geological setting

From north to south, the Schwarzwald can be divided into four major tectonic units (Fig. 1), the northernmost belonging to the Saxothuringian zone of the Variscan orogen and the three others being part of the Moldanubian zone. The northernmost part, the Baden-Baden-zone (BBZ) consists mainly of low- to medium-grade metamorphic schists. To the south, it dips under a high-grade basement unit, the Central Schwarzwald Gneiss Complex (CSGC). The latter is in turn bordered to the south by a series of north-dipping low- to medium-grade metamorphic Palaeozoic sediments and volcanics, the Badenweiler-Lenzkirch-zone (BLZ), so that the CSGC is generally regarded as an allochthonous unit that has been tectonically emplaced onto the two lower-grade units during Variscan convergence (Eisbacher et al. 1989). The southernmost unit, the Südschwarzwald (SSW) is a further high-grade metamorphic block.

Apart from amphibolites and several zones of mylonitic granulites, the CSGC and the SSW consist mainly of low-pressure high-temperature metamorphic gneisses and migmatites intruded by numerous granites. The peak of low-pressure high-temperature metamorphism in both units has been dated at 330–335 Ma (Kalt et al. 1994a), and the intrusion of granites can be bracketed between 335 and 310 Ma (Wendt et al. 1974; Todt 1976; compilation in Echtler and Chauvet 1991/92). Both the CSGC and the SSW bear small lenses of mafic to ultramafic rocks. In the SSW these are spinel peridotites and fragments of a former large gabbroic intrusion. In the CSGC spinel peridotites also occur, but additionally, garnet-bearing peridotites and websterites, as well as eclogites, are found.

Geothermobarometric estimates on these eclogites indicate minimum values of 670–750 °C at 1.6 GPa for pressures and temperatures at the peak of high-pressure metamorphism (337–332 Ma; Kalt et al. 1994b). Peak equilibration conditions of 670–740 °C and 1.4–1.8 GPa are also recorded by the mineral compositions of two garnet-spinel peridotites (Kalt et al. 1995). On the other hand, two garnet websterites have obviously experienced a high-temperature stage within the spinel peridotite stability field before equilibrating at 740–850 °C and 3.2–4.3 GPa (Kalt et al. 1995).

Figure 1 shows the sample sites of the current investigation. Their precise locations are listed in the appendix. Samples from Strohbach (SB) and Eichbühl (EB) have been found as loose blocks. At Höfen (HF) samples were taken from a small abandoned quarry. No contacts to the country rocks are exposed.

Textures and mineral compositions

Mineral compositions for sample HF are listed in Table 1; those for samples SB and EB in Table 2. Analytical techniques are described in the appendix.

Table 1 Representative mineral compositions for garnet-spinel peridotite HF

	cpx I porph core	opx I porph core	spl I porph core	am I porph	ol I matrix	cpx II matrix	opx II matrix	spl II matrix	am II matrix	opx III kel	spl III kel	am III kel	grt KA-1
SiO_2	54.27	56.14	0.00	45.15	40.82	54.70	57.32	0.03	47.00	57.63	0.06	47.20	42.02
TiO_2	0.09	0.02	0.03	0.24	0.02	0.04	0.03	0.02	0.23	0.00	0.01	0.15	0.05
Al_2O_3	1.38	3.07	47.07	12.88	0.00	0.75	0.91	27.57	12.46	1.07	63.37	12.88	22.44
Cr_2O_3	0.19	0.20	19.67	1.13	0.00	0.29	0.09	39.59	0.75	0.12	4.51	0.42	1.64
Fe_2O_3	n.c.	n.c.	2.40	1.50	n.c.	n.c.	n.c.	2.09	1.82	n.c.	0.35	1.63	n.c.
FeO	1.86	6.23	14.21	2.75	9.70	1.81	6.59	18.72	1.75	6.57	9.26	1.71	8.93
MnO	0.03	0.06	0.00	0.05	0.14	0.07	0.13	0.18	0.04	0.21	0.06	0.06	0.41
NiO	n.d.	n.d.	n.d.	n.d.	0.34	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MgO	17.44	34.73	16.46	18.15	49.62	17.53	34.74	11.25	18.75	35.05	21.10	19.12	18.87
CaO	24.54	0.20	0.00	12.77	0.02	24.41	0.12	0.03	13.13	0.18	0.09	12.76	6.25
Na_2O	0.26	0.00	0.00	2.08	0.02	0.36	0.00	0.03	1.65	0.01	0.01	1.81	0.00
K_2O	0.00	0.00	0.01	0.58	0.00	0.01	0.00	0.01	0.22	0.02	0.00	0.01	0.00
H_2O				2.11					2.14			2.15	
Total	100.06	100.65	99.85	99.40	100.68	99.95	99.94	99.51	99.90	100.84	98.81	99.91	100.61
Si	1.968	1.922	0.000	6.413	0.994	1.985	1.977	0.001	6.570	1.971	0.002	6.573	2.995
Ti	0.002	0.001	0.001	0.026	0.000	0.001	0.001	0.001	0.024	0.000	0.000	0.016	0.003
Al	0.059	0.124	1.523	2.156	0.000	0.032	0.037	0.994	2.053	0.043	1.900	2.114	1.885
Cr	0.005	0.005	0.427	0.127	0.000	0.008	0.002	0.957	0.082	0.003	0.091	0.046	0.092
Fe^{3+}	n.c.	n.c.	0.049	0.160	n.c.	n.c.	n.c.	0.048	0.191	n.c.	0.007	0.171	n.c.
Fe^{2+}	0.056	0.178	0.326	0.326	0.198	0.055	0.190	0.479	0.205	0.188	0.197	0.199	0.532
Mn	0.001	0.002	0.000	0.006	0.003	0.002	0.004	0.005	0.004	0.006	0.001	0.007	0.025
Ni	n.d.	n.d.	n.d.	n.d.	0.007	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Mg	0.943	1.773	0.674	3.843	1.802	0.948	1.786	0.513	3.908	1.787	0.800	3.970	2.005
Ca	0.953	0.007	0.000	1.943	0.001	0.949	0.004	0.001	1.962	0.006	0.002	1.904	0.477
Na	0.018	0.000	0.000	0.574	0.001	0.026	0.000	0.002	0.446	0.000	0.000	0.490	0.000
K	0.000	0.000	0.000	0.106	0.000	0.000	0.000	0.000	0.039	0.001	0.000	0.002	0.000
Total	4.007	4.012	3.000	15.679	3.006	4.007	4.002	3.000	15.485	4.006	3.000	15.492	8.014
X_{Mg}	0.944	0.896	0.674	0.922	0.901	0.945	0.904	0.517	0.950	0.905	0.802	0.952	0.790
X_{Cr}			0.219					0.491			0.046		

Formula calculations on the basis of 6 oxygens for cpx and opx, 4 oxygens for ol, 12 oxygens for grt, 4 oxygens and 3 cations for spl, and 15 cations without Na + K, 2 OH for amphiboles; X_{Mg} for grt, ol, opx, cpx calculated on the assumption that all Fe is divalent; X_{Mg} for spl and am calculated using $Fe^{2+}/(Fe^{2+}+Fe^{3+})$ ratios as given in formula calculations. For mineral abbreviations see section on textures and mineral compositions. kel kelyphite; n.c. not calculated; n.d. not determined; porph porphyroclast; KA-1 garnet model composition (see section on choice of geothermobarometers)

Table 2 Representative mineral compositions for garnet-spinel peridotites SB and EB

	SB								EB				
	opxI matrix core	cpxI matrix core	spl I matrix core	am I matrix	ol I	opx II kel	am II kel	sol II kel	grt I porph core	grt I porph core	spl I matrix core	spl I matrix rim	am I matrix
SiO_2	56.64	53.90	0.01	44.65	40.75	55.99	45.02	0.04	41.93	41.87	0.01	0.01	45.25
TiO_2	0.00	0.16	0.05	0.48	0.00	0.01	0.31	0.00	0.05	0.07	0.16	0.06	0.52
Al_2O_3	2.07	1.63	37.50	13.47	0.01	2.82	14.48	64.70	23.21	23.01	28.26	32.73	13.03
Cr_2O_3	0.21	0.27	30.62	1.11	0.00	0.19	0.68	2.97	0.49	0.24	37.97	35.54	1.40
Fe_2O_3	n.c.	n.c.	1.34	1.14	n.c.	n.c.	0.45	0.56	n.c.	n.c.	2.41	0.34	1.78
FeO	6.57	2.06	15.65	2.91	9.22	6.85	3.06	9.20	10.38	10.22	18.42	17.55	1.76
MnO	0.21	0.07	0.15	0.02	0.15	0.12	0.02	0.04	0.35	0.56	0.13	0.15	0.07
NiO	n.d.	n.d.	n.d.	n.d.	0.39	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MgO	34.76	17.49	14.47	18.16	50.14	34.00	18.12	21.31	18.28	18.46	11.61	12.59	18.42
CaO	0.26	24.72	0.00	12.60	0.00	0.30	12.66	0.00	5.37	6.00	0.00	0.00	12.73
Na_2O	0.01	0.17	0.00	1.98	0.00	0.01	2.17	0.02	0.00	0.00	0.00	0.00	1.93
K_2O	0.00	0.01	0.00	0.95	0.01	0.00	0.62	0.00	0.00	0.00	0.00	0.00	0.26
H_2O				2.11			2.13						2.12
Total	100.71	100.48	99.79	99.58	100.67	100.28	99.72	98.84	100.06	100.33	98.96	98.97	99.27
Si	1.941	1.951	0.000	6.340	0.991	1.930	6.349	0.001	3.003	2.992	0.000	0.000	6.398
Ti	0.000	0.004	0.001	0.051	0.000	0.000	0.033	0.000	0.003	0.004	0.004	0.001	0.055
Al	0.084	0.069	1.272	2.254	0.000	0.115	2.408	1.929	1.960	1.942	1.018	1.151	2.171
Cr	0.006	0.008	0.697	0.125	0.000	0.005	0.076	0.059	0.028	0.013	0.918	0.838	0.156
Fe^{3+}	n.c.	n.c.	0.029	0.122	n.c.	n.c.	0.047	0.011	n.c.	n.c.	0.056	0.008	0.190
Fe^{2+}	0.188	0.062	0.377	0.346	0.187	0.197	0.361	0.195	0.622	0.612	0.471	0.438	0.209
Mn	0.006	0.002	0.004	0.002	0.003	0.003	0.002	0.001	0.021	0.034	0.003	0.004	0.009
Ni	n.d.	n.d.	n.d.	n.d.	0.008	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Mg	1.775	0.944	0.621	3.844	1.818	1.747	3.810	0.804	1.952	1.971	0.529	0.560	3.884
Ca	0.009	0.959	0.000	1.917	0.000	0.011	1.913	0.000	0.412	0.460	0.000	0.000	1.928
Na	0.001	0.012	0.000	0.546	0.000	0.001	0.593	0.001	0.000	0.000	0.000	0.000	0.529
K	0.000	0.000	0.000	0.172	0.000	0.000	0.111	0.000	0.000	0.000	0.000	0.000	0.047
Total	4.009	4.012	0.300	15.718	3.009	4.010	15.704	0.300	8.001	8.027	3.000	3.000	15.576
X_{Mg}	0.904	0.938	0.622	0.917	0.907	0.899	0.913	0.805	0.758	0.763	0.529	0.561	0.949
X_{Cr}			0.354					0.030			0.474	0.421	

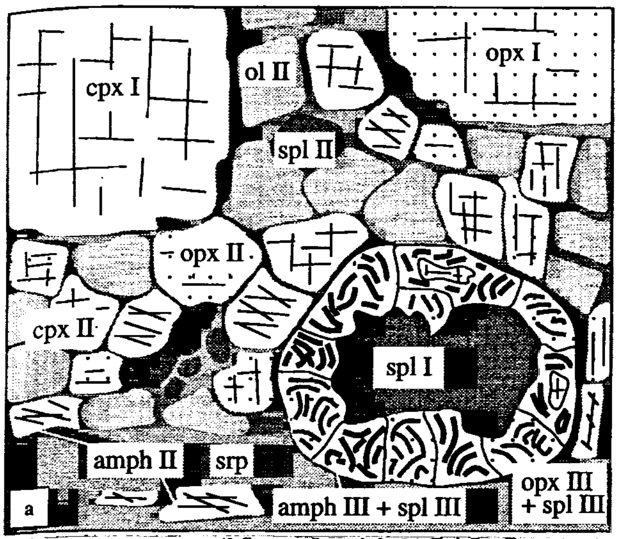
NOTE: Same parameters as Table 1

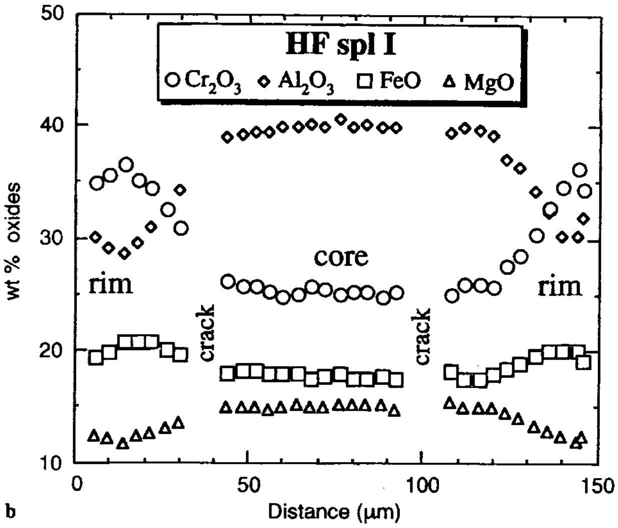
Garnet-spinel peridotite HF

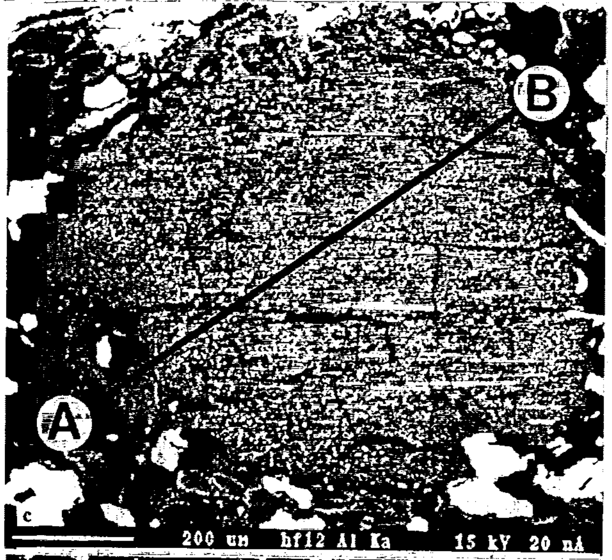
The rock is very fine grained and shows two successive textures: an older porphyroclastic texture with porphyroclasts up to 3 mm in diameter that is overgrown by smaller matrix crystals and dominant serpentine (Fig. 2a). The rock displays a pronounced foliation defined by oriented porphyroclasts and serpentine fibres. Additionally, there is a layering parallel to foliation, consisting of porphyroclast-rich, only partly serpentinised layers and alternating heavily serpentinised layers that are virtually devoid of porphyroclasts. The porphyroclasts are orthopyroxene (opx I), clinopyroxene (cpx I) and amphibole (am I), as well as round clusters of fine-grained kelyphitic spinel (spl III), orthopyroxene (opx III) and amphibole (am III; Fig 2a), which may include large spinel grains (spl I) and which are interpreted as pseudomorphs after garnet (see below). Matrix phases are olivine (ol II), orthopyroxene (opx II), clinopyroxene (cpx II), amphibole (am II), spinel (spl II), and magnetite in order of decreasing abundance.

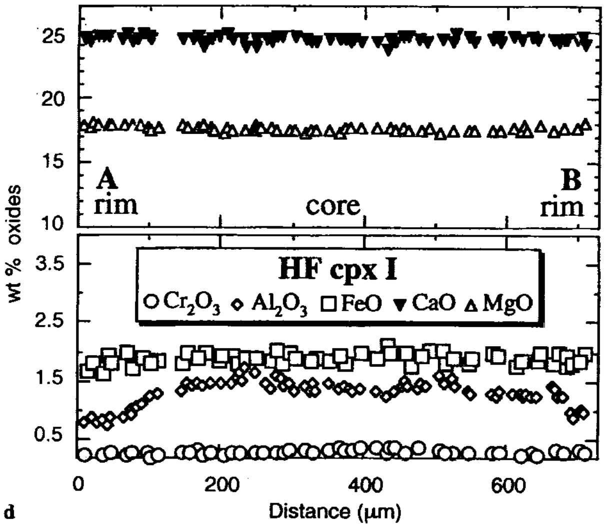
Cpx I grains are uniform in their CaO (24.0–24.8 wt%), Na_2O (0.25–0.32 wt%), Cr_2O_3 contents (0.19–0.25 wt%) and $Mg/(Mg+Fe)=X_{Mg}$ (0.939–0.948), but show zoning in Al with higher values forming broad plateaus of 1.3–1.7 wt% Al_2O_3 in cores and decreasing to 0.8–1.0 wt% at the rims (Fig. 2d), the rim zones being of variable width (Fig. 2c). Opx I grains show more complex zoning patterns (Fig. 2e and f). They display constant X_{Mg} of 0.898–0.906 and low CaO contents between 0.16 and 0.30 wt% (Fig. 2f). Al_2O_3 contents show broad plateaus of 2.9–3.3 wt% within cores, followed by steep rimward decreases to below 2.0 wt%. Al_2O_3 contents then increase up to 1.8–3.0 wt% towards the rims and finally drop to 1.0 wt% at

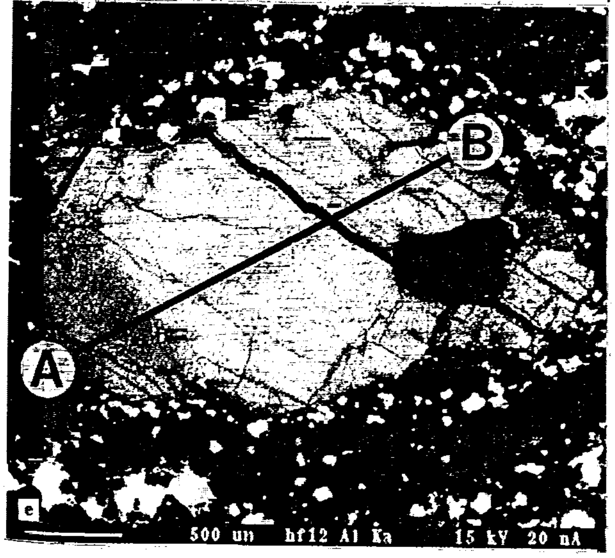
Fig. 2 a–f Textures and mineral compositions of garnet-spinel ▶ peridotite HF. **a** The main textural features (omitting the foliation), with special regard to the clusters of orthopyroxene, spinel and amphibole, interpreted as kelyphite pseudomorphing former garnet. In this case the cluster contains a large spl I inclusion. For mineral abbreviations and detailed descriptions see section on textures and mineral compositions. **b** Microprobe traverse through a typical spl I grain. **c** Chemical mapping for Al in a large cpx I porphyroclast. *Darker areas* (pressure shadows) correspond to lower contents; *lighter areas* to higher contents. Note the lamellae of amph I. **d** Microprobe traverse through the cpx I grain as shown in Fig. 2c. **e** Chemical mapping for Al in a large opx I porphyroclast. *Darker areas* correspond to lower contents; *lighter areas* to higher contents. **f** Microprobe traverse through the opx I grain as shown in Fig. 2e

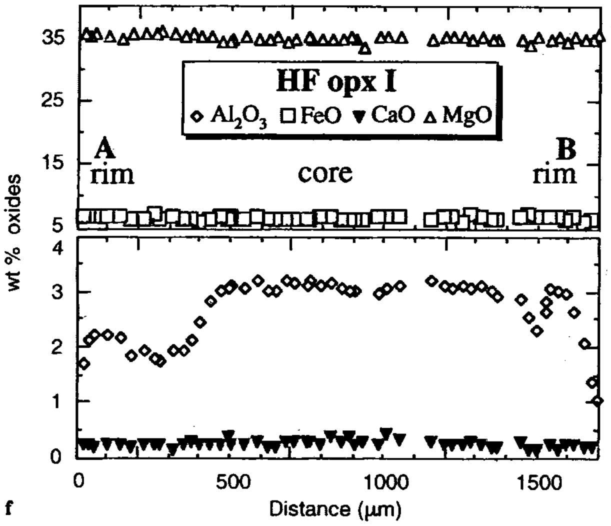

cpx I
ol II
opx I
spl II
opx II
cpx II
spl I
amph II
srp
amph III + spl III
opx III
+ spl III
a


HF spl I
○ Cr2O3 ◇ Al2O3 □ FeO △ MgO
rim
core
rim
crack
crack
wt % oxides
50
40
30
20
10
0
50
100
150
Distance (µm)
b


B
A
c
200 un hf12 Al Ka 15 kV 20 nA


HF cpx I
○ Cr2O3 ◇ Al2O3 □ FeO ▼ CaO △ MgO
A
rim
core
B
rim
wt % oxides
25
20
15
10
3.5
2.5
1.5
0.5
0
200
400
600
Distance (µm)
d


B
A
e
500 un hf12 Al Ka 15 kV 20 nA


HF opx I
◇ Al2O3 □ FeO ▼ CaO △ MgO
A
rim
core
B
rim
wt % oxides
35
25
15
5
4
3
2
1
0
0
500
1000
1500
Distance (µm)
f

the outermost margins (Fig. 2e and f). Cr mimics the Al profile at very low concentration levels (0.15–0.34 wt% Cr_2O_3). As in cpx I, the rim zones have variable widths or may not be developed at all (Fig. 2e), suggesting that the low-Al rims of the pyroxene porphyroclasts represent an overgrowth feature, rather than growth zoning or diffusion-controlled post-growth zoning. The concentration of overgrown material within the pressure shadows of the porphyroclasts with respect to the foliation (Fig. 2e) further suggests that overgrowth took place during deformation and recrystallisation of the peridotite.

The large am I grains are homogeneous pargasitic hornblendes (Leake 1978) with 1.0–1.3 wt% Cr_2O_3 and up to 0.6 wt% K_2O . They seem to be in the same textural position as the pyroxene porphyroclasts, but because cpx I porphyroclasts often display secondary amphibole lamellae with the same compositions along their cleavage traces (Fig. 2c), it is likely that also the large am I grains formed at the expense of cpx I during a later stage.

The large and abundant clusters of opx III, am III, and spl III, and very rare clinopyroxene, are also in textural equilibrium with the pyroxene porphyroclasts and display a patchwork-like structure (Fig. 2a). Some patches consist of very fine-grained symplectitic intergrowths of spl III and opx III. Spl III is a picotite with X_{Mg} of 0.772–0.810 and $X_{Cr} = Cr/(Cr + Al)$ of 0.020–0.046. Opx III is indistinguishable from opx I and opx II (see below) in terms of X_{Mg} and CaO contents. Opx III shows variable Al_2O_3 contents up to very high values (5.6 wt%), but these are probably due to the very intimate intergrowth with spinel ($< 1 \mu m$) and resulting analyses of opx–spl mixtures. The other kelyphite patches consist of a less fine-grained intergrowth of spinel (spl III), amphibole (am III) and rare relict clinopyroxene (cpx II, see below). Am III is an edenitic hornblende (Leake 1978) with Cr_2O_3 contents of 0.5–0.7 wt% that seems to grow at the expense of cpx II. The clusters may include large Cr–Al spinel grains (spl I) which are strongly zoned (Fig. 2b) with increasing X_{Cr} (0.219–0.513) and decreasing X_{Mg} (0.670–0.484) from core to rim. The clusters have structures and compositions typical of kelyphites and are thus interpreted as having grown at the expense of garnet during pressure release. The large spinel grains most likely represent former inclusions in garnet, implying that garnet grew at the expense of spinel during an earlier pressure increase and/or temperature decrease. This interpretation is in line with the rimward increase of X_{Cr} in spl I (O'Neill 1981; Nickel 1986) and with the description of such garnet-forming reactions in peridotites from the Massif Central (Lasnier 1971) and the Austridic Crystalline Complex in northern Italy (Obata and Morten 1987).

Porphyroclasts and kelyphite clusters are surrounded by a matrix of smaller ol II, opx II, cpx II, spl II and am II grains. Ol II is unzoned with X_{Mg} ranging from 0.899 to 0.906, whereas NiO contents are in the range of 0.34–0.46 wt%. Opx II and cpx II differ from the respective porphyroclast compositions only in their lower Al_2O_3 contents (and lower Cr_2O_3 contents for opx), which correspond to those of the inner- and outermost porphyroclast rims (Fig. 2d and f). Large spl II grains show essentially the same compositional zoning as spl I, although most of the spl II grains are small and only display the rim compositions of the larger spl I and spl II grains. Am II grains have the same compositions as am III.

Garnet-spinel peridotite SB

The rock is medium- to fine-grained and heavily serpentinised. There is no relict porphyroclastic texture visible as in sample HF. Grains of olivine (ol I), orthopyroxene (opx I), clinopyroxene (cpx I), spinel (spl I), am (am I) and clusters of fine-grained kelyphitic orthopyroxene (opx II), spinel (spl II) and amphibole (am II), and rare clinopyroxene (cpx II), interpreted as pseudomorphs after garnet (see below), are embedded in a matrix of serpentine. Parts of the rock display a weak foliation defined mainly by oriented am I flakes.

Ol I is unzoned with X_{Mg} ranging from 0.896 to 0.907 and has NiO contents of 0.31–0.42 wt%. Opx I grains have X_{Mg} of 0.897–0.906, CaO contents between 0.20 and 0.32 wt%, and show no zoning in these elements. The largest grains (200–400 μm) display a very weak zoning in Al_2O_3 contents (Fig. 3a) with lower values of 1.9–2.1 wt% in cores and 2.1–2.4 wt% at rims. Cpx I grains are homogeneous with respect to their CaO contents (24.3–24.7) and X_{Mg} (0.938–0.945). The largest grains (up to 800 μm) show a very weak zoning in Al (Fig. 3b) with core plateaus of 1.3–1.6 wt% Al_2O_3, rim contents of 1.0–1.1 wt% and a further minimum and maximum within this range in between. Spl I grains are also zoned (Fig. 3c) with decreasing X_{Cr} (0.350–0.285) and increasing X_{Mg} (0.594–0.652) from core to rim. Am I blasts are unzoned pargasitic hornblende with X_{Mg} from 0.985–0.910 and Cr_2O_3 contents of 1.0–1.2 wt%.

The clusters of fine-grained kelyphitic opx II, cpx II, spl II and am II have the shape and structure of those described for sample HF and are therefore also interpreted as retrograde phases after garnet. The former existence of garnet is further indicated by relics of the reaction grt + ol = opx + cpx + spl within the kelyphites, indicating that the reaction took place between garnet and olivine inclusions. The relics are elongate olivine grains rimmed by comparatively coarse-grained orthopyroxene, clinopyroxene and scarce spinel from the surrounding fine-grained kelyphite. Pyroxene and spinel rims around olivine are compositionally indistinguishable from the respective cluster phases (opx II, cpx II, spl II). Opx II compositions differ from those of opx I only in their higher Al_2O_3 contents (2.8–3.3 wt%) and a larger scatter in X_{Mg} towards lower values. Cpx II grains display the same compositional variety as cpx I,

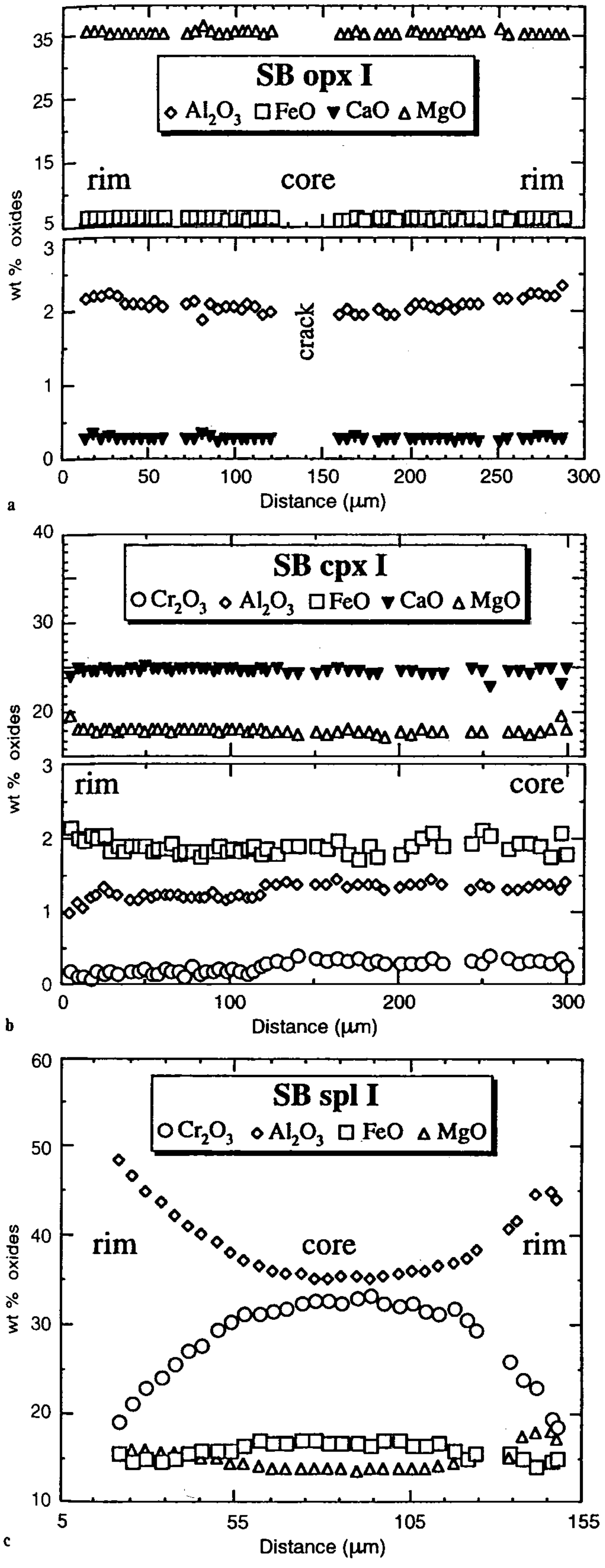


Fig. 3 a–c Microprobe traverses through stage I mineral phases of garnet-spinel peridotite SB. **a** opx I; **b** cpx I; **c** spl I

but trend towards slightly lower X_{Mg}. Spl II is an aluminous spinel very low in X_{Cr} (0.030–0.038). Am II has a composition similar to am I, except for lower Cr_2O_3 contents of 0.4–0.7 wt%.

Garnet-spinel peridotite EB

The rock is comparatively coarse grained and almost entirely hydrated and serpentinised. Only garnet (grt I), spinel (spl I), and amphibole (am I) are preserved in terms of measurable mineral compositions. Former blasts of olivine (ol I), clinopyroxene (cpx I) and orthopyroxene (opx I) are still recognisable from their microscopically visible outlines, but have been completely hydrated and serpentinised. Olivine and the pyroxenes obviously coexisted with spinel (spl I), but all of these phases may have grown later than garnet because garnet grain size is much larger and grt I is devoid of spinel inclusions.

Grt I grains reach diameters of 2000 μm and are always rimmed by kelyphite. They are unzoned with X_{Mg} between 0.758 and 0.769, CaO contents between 5.36 and 6.27 wt% and remarkably low Cr_2O_3 contents of 0.24–0.51 wt%. Kelyphites consist of a Cr-poor spinel (spl II) with X_{Cr} of 0.032–0.042 and X_{Mg} between 0.70 and 0.795, of completely hydrated orthopyroxene (opx II), and of rare amphibole (am II). Spinel grains (spl I) are zoned with decreasing X_{Cr} (0.477–0.372) and increasing X_{Mg} (0.497–0.574) from cores to rims. Am I blasts are pargasitic hornblendes with X_{Mg} of 0.867–0.901 and 0.8–1.4 wt% Cr_2O_3.

Metamorphic stages and thermobarometry

Choice of thermometers and barometers

A variety of geothermometers and geobarometers may be used to calculate P-T conditions for peridotites. Most of these formulations have been checked experimentally (Brey et al. 1990; Brey and Köhler 1990), and those found to reproduce experimental results especially well have been chosen for this study.

The calculation of pressures using the Al contents of coexisting orthopyroxene and garnet is hampered by the complete transformation of garnet to kelyphite in samples HF and SB. Thus, pressures have been estimated with three different garnet-model compositions: the garnet composition of garnet-spinel peridotites KA-1 and HH-10 from the Schwarzwald (Kalt et al. 1995) and a composition derived from kelyphites. Because variations in garnet compositions within the peridotite system are limited, and because the Al-in-opx barometer (Brey and Köhler 1990) is not very sensitive to garnet composition (1.15, 1.19 and 1.21 GPa for the three model compositions using the same orthopyroxene analysis), this procedure seems justified and the KA-1 composition (Table 3) has been used later for calcula-

Table 3 Results of geothermobarometric calculations

	HF stage I	HF stage 2	SB stage 1
	opx Ic, cpx Ic, spl Ic, ol I	opx II, cpx II spl II, grt II	opx I, cpx I, ol I, grt I, spl I
T in °C at 2.0 GPa			
Sachtleben and Seck (1981) Cr/Al in opx	824±28		
Brey and Köhler (1990) Ca in opx	754±26	694±18	799±18
Bertrand and Mercier (1985)[a] opx-cpx	667±32	661±27	693±31
Brey and Köhler (1990) opx-cpx	636±51	619±42	680±41
P in GPa at 800 °C			
Brey and Köhler (1990) Al in opx		2.8±0.1	1.5±0.1
Webb and Wood (1986) $P_{max\ spl}$	1.8±0.1		
P in GPa at 700 °C			
Brey and Köhler (1990) Al in opx		2.1±0.1	1.0±0.1
Webb and Wood (1986) $P_{max\ spl}$	1.8±0.1		

[a] A modified version according to Brey and Köhler (1990)

tion. Additionally, maximum pressures for the early spinel peridotite stage of sample HF have been estimated from spinel compositions (Webb and Wood 1986).

Fe–Mg exchange thermometers involving garnet were not used for samples HF and SB because they are very sensitive to Fe/Mg ratios in garnet and because the exact compositions of the respective garnets are not known. Temperatures were calculated using the enstatite-diopside solvus (Brey and Köhler 1990; Bertrand and Mercier 1985, in a modified version as suggested by Brey and Köhler 1990), the amount of Ca in orthopyroxene (Brey and Köhler 1990) and the Cr/Al ratios of orthopyroxene coexisting with spinel (Sachtleben and Seck 1981). From P-T calculations on other garnet spinel peridotites (Kalt et al. 1995) it is known that the Fe–Mg exchange thermometers generally yield lower temperatures than other thermometers within the low-temperature range. Several reasons may account for this observation:

1. None of the thermometers are calibrated at such low temperatures.
2. The higher diffusion coefficients for Fe and Mg in garnets, pyroxenes and olivines when compared with Ca and Al (Chakraborty and Ganguly 1991; Morioka and Nagasawa 1991; Ganguly and Zazzoli 1994), imply Fe–Mg exchange down to lower temperatures.
3. The presence of ferric iron in garnets and pyroxenes may have influence on the temperature calculations.

For these reasons, Fe–Mg temperatures in low-temperature peridotites must be treated with caution. For sample EB none of the mentioned geothermobarometers are applicable because pyroxenes are not preserved. Pressures and temperatures have been roughly estimated using the Ca vs Cr contents of garnet in peridotitic systems (Nickel 1983; Brey 1989).

Because the outermost rim compositions of the mineral phases in all samples have been modified by the formation of late-stage phases, such as serpentine and kelyphite, only core and inner-rim compositions were used for P-T calculations. The results are listed in Table 3 and presented graphically in Figs. 4 and 5.

Garnet-spinel peridotite HF

Opx I and cpx I porphyroclasts seem to have been in textural equilibrium with former garnet (now kelyphite; Fig. 2a). On the other hand, pyroxenes show zoning in Al and the kelyphites often contain large, strongly zoned spl I grains (former inclusions in garnet), so that opx I and cpx I cores may have coexisted only with spl I cores prior to garnet formation. These two possibilities must be discussed separately because they imply different P-T evolutions and the application of different geothermobarometers.

If the large spl I inclusions in kelyphite represent an older stage and opx I and cpx I cores already coexisted with garnet (stage I: garnet-spinel peridotite stability field), Al contents of orthopyroxenes are a function of pressure and temperature and can be used to constrain pressures. The Cr/Al ratios of opx I grains cannot be used to calculate temperatures because they are not merely dependent on the spinel composition, but also on garnet. Ca-in-opx temperatures (Brey and Köhler 1990) are 754±26 °C at 2.0 GPa. 2-px temperatures are

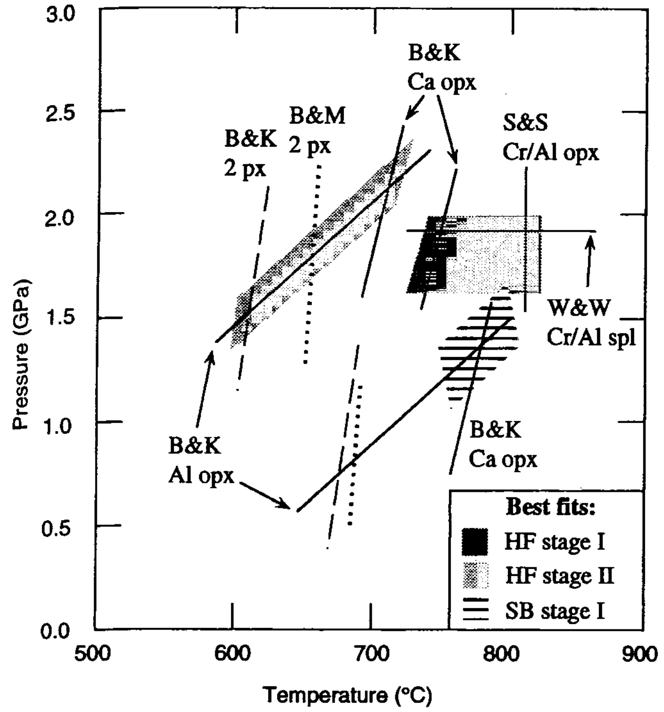


Fig. 4 Pressure-temperature diagram showing the results of thermobarometric calculations on samples HF and SB. Stage I for sample HF is based on temperatures calculated with the Al/Cr-in-opx thermometer (Sachtleben and Seck 1981), the Ca-in-opx thermometer (Brey and Köhler 1990) and on maximum pressures calculated with Cr/Al ratios of spinel (Webb and Wood 1986) for opx I, cpx I and spl I core compositions. Stage II for sample HF is derived from Ca-in-opx temperatures (Brey and Köhler 1990), 2-px-temperatures (Bertrand and Mercier 1985; Brey and Köhler 1990) and from Al-in-opx pressures (Brey and Köhler 1990) calculated with opx II, cpx II, grt KA-1 and spl II compositions. Stage I for sample SB is based on temperatures calculated with the Ca-in-opx thermometer (Brey and Köhler 1990) and on pressures calculated with the Al-in-opx barometer (Brey and Köhler 1990). Note that for reasons of clarity the size of the best-fit areas is not to scale with respect to errors (see Table 3)

significantly lower at 667±32 (Bertrand and Mercier 1985) and 636±51 °C (Brey and Köhler 1990), but should be treated with caution as set out above. Additionally, the lack of zoning in X_{Mg} in opx I and cpx I, along with the preserved zoning in Al, clearly implies that X_{Mg} in pyroxene cores has been adjusted during stage II. Pressures calculated with the Al-in-opx barometer (Brey and Köhler 1990) are 1.0±0.4 GPa. The garnet-spinel peridotite stability field can only extend to such low pressures in Cr-free systems with X_{Mg} lower than 0.80 (Gasparik 1987). Because this is not the case for sample HF, the hypothesis is abandoned and it is further assumed that opx I and cpx I cores coexisted with spl I cores.

If the high-Al opx I and cpx I cores coexisted only with spl I cores (stage I: spinel-peridotite stability field), the Cr/Al ratios of opx I grains depend exclusively on the spinel composition and give pressure-independent equilibration temperatures of 824±28 °C (Sachtleben and Seck 1981). Ca-in-opx temperatures

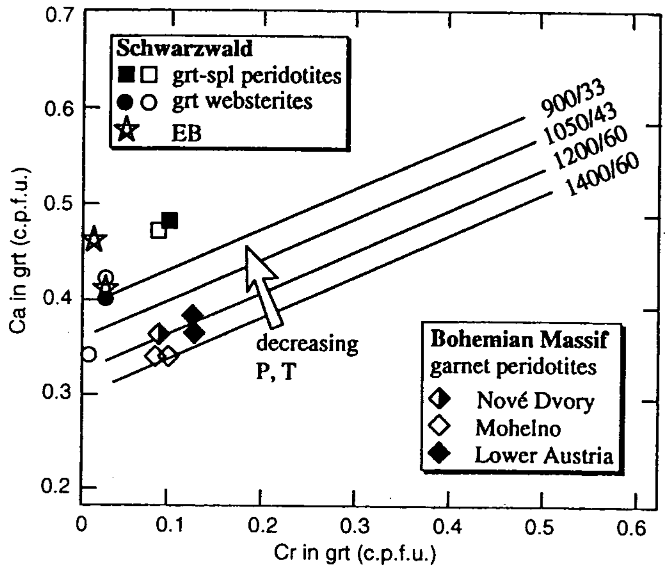


Fig. 5 Ca vs Cr contents in garnets of Moldanubian garnet peridotites. The isotherms–isobars were calculated from experimental results (Brey 1989; Nickel 1983). Numbers on isotherms–isobars are temperatures in °C and pressures in kbar. Shown are the Ca vs Cr contents of garnet-spinel peridotite EB as well as data from other garnet-spinel peridotites and garnet websterites from the Schwarzwald (Kalt et al. 1995). Also shown are Ca vs Cr contents of garnet peridotites from Nové Dvory and Mohelno in the Czech Republic (Medaris et al. 1990) and from the Dunkelsteiner Wald in Lower Austria (Carswell 1991)

are slightly lower as mentioned above (754±26 °C; Brey and Köhler 1990). 2-px temperatures are significantly lower at 667±32 (Bertrand and Mercier 1985) and 636±51 °C (Brey and Köhler 1990), but do not correspond to stage 1 (see above). The maximum pressure calculated with spinel core compositions (Webb and Wood 1986) is 1.8±0.1 GPa. The graphically derived best fit for temperatures and pressures at stage I is thus ~800 °C/<1.8 GPa (Fig. 4).

During a subsequent pressure increase, the rock passed into the garnet-spinel peridotite stability field (stage II) and garnet formed around the spinel wherever pyroxenes were present. This is consistent with the kelyphite structures which confirm the former presence of garnet, with increasing X_{Cr} in spl I from core to rim (Nickel 1986), with decreasing Al in pyroxenes from core to inner rim (Brey and Köhler 1990) at constant Fe/Mg ratios and with the crystallisation of low-Al matrix pyroxenes (opx II, cpx II) and high-Cr matrix spinels (spl II). Temperatures calculated for stage II show a large spread. Ca-in-opx temperatures (Brey and Köhler 1990) are 694±18 °C at 2.0 GPa for opx II (matrix) and 2-px temperatures calculated with matrix opx II and cpx II are 661±27 °C (Bertrand and Mercier 1985), and 680±41 °C (Brey and Köhler 1990) at 2.0 GPa. Pressures calculated with the Al-in-opx barometer (Brey and Köhler 1990) using the KA-1 garnet composition (see above and Table 1) are 2.1±0.1 GPa at 700 °C. Thus, the graphically derived best fit for stage II is 680 °C/1.8 GPa (Fig. 4).

During a later stage (stage III), the rock must have entered the spinel-peridotite stability again during uplift and cooling. Kelyphites of spl III, opx III and am III formed during this stage. The Al increase at the outer rims of opx I (Fig. 2f) might also be explained in this context. The timing of amphibole growth (am I–III) is difficult to constrain. Because amphiboles from all textural positions have broadly the same compositions and because they seem to form mainly at the expense of cpx I and cpx II, they should have grown no earlier than stage II.

Garnet-spinel peridotite SB

The metamorphic evolution of sample SB is not as complex as that of sample HF. There is no porphyroclastic texture, and no metamorphic stage within the spinel-peridotite stability field is preserved. Matrix pyroxenes (opx I, cpx I) obviously coexisted with matrix spinel (spl I) and with former garnet (now kelyphite). The kelyphites only very rarely have spinel inclusions.

Ca-in-opx temperatures (Brey and Köhler 1990) for opx I cores are 799±18 °C at 2.0 GPa. 2-px temperatures are lower at 693±31 (Bertrand and Mercier 1985) and 680±41 °C (Brey and Köhler 1990). Al-in-opx pressures (Brey and Köhler 1990) calculated with the KA-1 garnet composition (see above) are 1.5±0.1 GPa at 800 °C and 1.0±0.1 GPa at 700 °C. The best fit for temperatures and pressures is approximately 770 °C at 1.4 GPa. 2-px temperatures have not been considered because they yield P-T values outside the garnet-spinel peridotite stability field at these pressures.

Decompression during a later stage is indicated by increasing Al contents in opx I and cpx I from core to rim at constant Fe/Mg ratios, by decreasing X_{Cr} in spl I grains from cores to rims, and by the formation of kelyphites (spl II, opx II) and amphibole.

Garnet-spinel peridotite EB

Due to the lack of preserved olivine and pyroxenes, information on the metamorphic evolution of sample EB is scarce. According to the textures, garnet may have grown earlier than olivine, pyroxenes and spinel. Nevertheless, garnets show no zoning, meaning that they should have equilibrated at some time with pyroxenes and olivine, either within the garnet-peridotite stability field or within the garnet-spinel peridotite stability field.

The Ca vs Cr contents of garnets may be used to estimate temperatures and pressures for garnet-bearing peridotites (Brey 1989; Fig. 5). This observation and the calculated isotherms–isobars shown in Fig. 5 are based on experimental results (Nickel 1983; Brey 1989). The very low Ca and Cr contents of the EB garnets do not allow for a precise P-T estimate. Nevertheless, three conclusions may be drawn from Fig. 5:

1. Sample EB shows no evidence of a metamorphic stage at very high temperatures and pressures as the Cr vs Ca contents of the garnets plot within the low-temperature part of the diagram.
2. The Ca vs Cr contents of sample EB garnets are similar to those of garnet websterites from the Schwarzwald, which have equilibrated at higher pressures than the garnet-spinel peridotites (Kalt et al. 1995).
3. The very low Ca and Cr contents of the garnets may be due to mixing with pyroxenites. In the latter case no conclusions from Cr vs Ca contents are possible, because garnets did not then equilibrate with a peridotite system.

Discussion

Comparison with other peridotites from the Schwarzwald

Although samples HF and SB differ in what is preserved of their metamorphic evolution, their mineral assemblages record equilibration conditions within the garnet-spinel peridotite stability field. These are 680 °C/1.8 GPa for garnet-spinel peridotite HF and 770 °C/1.4 GPa for garnet-spinel peridotite SB. Similar equilibration conditions at comparatively low temperatures and pressures (670–740 °C, 1.4–1.8 GPa) have already been constrained for other garnet-spinel peridotite occurrences from the Schwarzwald (Fig. 6; Kalt et al. 1995), whereby the lower temperatures have also been obtained with Mg–Fe exchange thermometers. Similar to the samples of this study, the previously studied garnet-spinel peridotites also show no evidence of a metamorphic stage at (very) high temperatures prior to their equilibration within the garnet-spinel peridotite stability field. The P-T conditions recorded by the garnet-spinel peridotites are virtually the same as those indicated by the mineral assemblages of eclogites from the Schwarzwald (670–750 °C at 1.6 GPa; Fig. 6; Kalt et al. 1994b; and unpublished data). The decompression paths followed by the garnet-spinel peridotites were probably diverse in terms of temperature, time and fluid activity as indicated by varying pyroxene zoning patterns, different retrograde breakdown products of garnet and the degree of retrogression and hydration.

Apart from these garnet-spinel peridotites, another group of ultramafic high-pressure rocks has been described for the Schwarzwald (Kalt et al. 1995). These are garnet websterites with comparatively low-bulk X_{Mg}, Cr and Ni contents. These rocks are interpreted as former cumulates. They experienced a high-temperature stage within the spinel-peridotite stability field before equilibrating in the garnet-peridotite stability field at 740–850 °C and 3.2–4.3 GPa (Fig. 6).

Although the P-T conditions for sample EB cannot be quantified, there are a few arguments for relating this sample to the second group of ultramafic high-pressure rocks:

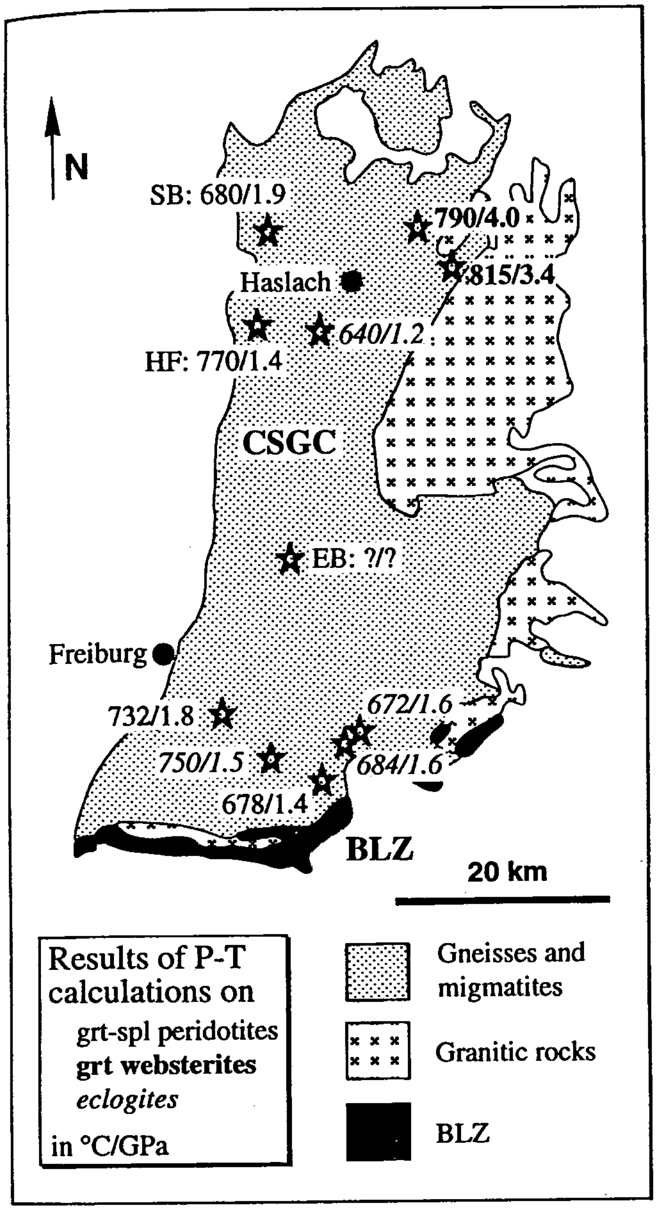


Fig. 6 Geological sketch map of the Schwarzwald showing pressures and temperatures calculated for eclogites (numbers in italics; Kalt et al. 1994b; unpublished data), garnet websterites (numbers in boldface; Kalt et al. 1995) and garnet-spinel peridotites (Kalt et al. 1995; this study)

1. The absence of spinel inclusions in garnet may point to equilibration conditions within the garnet-peridotite stability field.
2. The very low Cr contents suggest the involvement of pyroxenitic material.
3. The Ca vs Cr contents of EB garnets are virtually identical to those of the two garnet websterites (HO-2 and OW-41; Fig. 5) and differ significantly from those of the garnet-spinel peridotites in which garnet is preserved (HH-10 and KA-1; Fig. 5; Kalt et al. 1995).

The Ca vs Cr contents of garnets from the websterites and from garnet-spinel peridotite EB point to higher equilibration conditions as compared with the other garnet-spinel peridotites (which is in accordance with P-T calculations), although it must be stressed that the Ca–Cr relationship in garnets is only valid for more Mg- and Cr-rich systems. Thus, despite the fact that P-T conditions for sample EB-1 cannot be clearly constrained, it seems that the distinction of two groups of ultramafic high-pressure rocks previously made (Kalt et al. 1995) is confirmed by the results of this study.

Geological implications

Although a distinction between two groups of ultramafic high-pressure rocks with different equilibration conditions has been made for the CSGC (Fig. 1), no lithological, structural or petrological differences between the respective host rocks have been constrained up to now, a fact that is due mainly to the lack of outcrops and detailed structural data. The few visible contact relations between high-pressure rocks and country rocks indicate uniform metapsammitic and minor metapelitic gneisses and migmatites as host rocks (Stenger et al. 1989). These rocks have experienced high-temperature metamorphic conditions between 335 and 330 Ma (Kalt et al. 1994a) and lack clear evidence of a former high-pressure stage, except for some scarce occurrences in the immediate vicinity of eclogite lenses (Wimmenauer and Stenger 1989). Eclogites and ultramafic high-pressure rocks could thus be confined to very thin layers or nappes of lithospheric mantle material that were either intensively folded into or tectonically stacked between a comparatively uniform high-temperature basement.

The Variscan context

Within the Variscan belt eclogites and peridotites occur in the Moldanubian zone (Fig. 1) and in several allochthonous nappes within the Saxothuringian zone. To the east of the Schwarzwald, within the Bohemian Massif, three major Moldanubian nappes or terranes have been recognised on the basis of structures, lithology, metamorphic grade and high-pressure metamorphic basement inliers:

1. The Gföhl unit in the Czech Republic and in Lower Austria is characterised by abundant granulites, garnet peridotites, garnet pyroxenites and eclogites that have experienced temperatures above 1000 °C at various high pressures (Dudek and Fediuková 1974; Medaris et al. 1990; Carswell 1991; Beard et al. 1992; Becker and Altherr 1992; Carswell and O'Brien 1993; Medaris et al. 1995a).
2. The Teplá-Barrandian terrane is a low-grade metamorphic unit containing eclogites and spinel peridotites as parts of a meta-ophiolite sequence with min-

imum P-T conditions of 625–730 °C and 1.4–1.6 GPa (O'Brien 1991; Medaris et al. 1995a).

3. The Moldanubian zone s.str. consists of a Monotonous and a Varied series metamorphosed at low pressures and high temperatures with the Monotonous series containing isolated small lenses of eclogites which record minimum P-T conditions of 615–770 °C and 1.3–1.6 GPa (Dudek and Fediuková 1974; O'Brien 1989; Medaris et al. 1995b, O'Brien and Vrána 1995).

To the west of the Schwarzwald, in the Vosges mountains, a nappe character of the Moldanubian crystalline basement has also been recognised (Rey et al. 1989; Latouche et al. 1992). One unit, called "granulitic leptynites" (Latouche et al. 1992), contains lenses of garnet peridotites and garnet-spinel peridotites. The garnet peridotites within this unit record equilibration conditions of >1050 °C and >4.0 GPa, whereas the garnet-spinel peridotites equilibrated at pressures lower than 2.0 GPa and temperatures below 800 °C (Altherr and Kalt, in preparation). This unit with "granulitic leptynites" and garnet-bearing peridotites may be similar to the Gföhl unit in Lower Austria and the Czech Republic, although neither petrography nor P-T conditions of the "granulitic leptynites" are well constrained. A second composite unit consists of a Varied group and a Monotonous group (Latouche et al. 1992), the Monotonous group containing spinel peridotites which equilibrated at low P-T conditions (Altherr and Kalt, in preparation). This latter composite unit seems to be similar to the Monotonous and Varied series of the Moldanubian zone in the Bohemian Massif, although the correlation is again not perfect: Whereas in the Vosges mountains, garnet-cordierite gneisses (kinzigitic gneisses) are assigned to the Varied group (Latouche et al. 1992), they form part of the Monotonous series of the Bohemian Massif (Blümel 1983), which otherwise consists of metapsammitic gneisses and migmatites.

The CSGC in the Schwarzwald seems to be devoid of a granulite-peridotite unit comparable to the Gföhl unit of the Bohemian Massif or the granulitic leptynites of the Vosges in terms of lithology and P-T conditions. In these respects, the CSGC is more similar to the Monotonous series of the Vosges and to the metapsammitic rocks of the Monotonous series in the Bohemian Massif. The P-T conditions recorded by eclogites and garnet-spinel peridotites from the CSGC (670–770 °C, 1.4–1.8 GPa) are similar to those for eclogites in the Monotonous and Varied series of the Bohemian Massif (see above) and resemble those indicated by garnet-spinel peridotites in the Vosges mountains.

For the second group of ultramafic high-pressure rocks from the CSGC, characterised by a high-temperature stage prior to equilibration at 740–850 °C and 3.2–4.3 GPa, there seems to be hardly any equivalent in the Moldanubian s.str. Garnet websterites similar to those of the CSGC have been described from the Massif Central (Lasnier 1971; Bonnot and Piboule 1980), but no P-T estimates are available and their tectonic position within the Moldanubian zone is unclear. Comparable rocks may also be those of the Mohelno peridotite body, which experienced a high-temperature stage within the spinel-peridotite stability field and subsequently passed into the garnet-peridotite stability field on cooling (Medaris et al. 1990), but the Mohelno rocks equilibrated at higher temperatures and lower pressures and belong to the Gföhl unit.

Not only the lack of comparable rocks within the Monotonous series, but also the field relations in the Schwarzwald may give rise to speculations on the tectonic significance of the two groups of ultramafic HP rocks recognised in the Schwarzwald. As has been set out above, no lithological, structural or petrological differences between the respective host rocks have been constrained thus far. Nevertheless, three major SW- to NE-trending shear zones have been mapped in the Schwarzwald, one of them cutting very close to the websterite occurrences. The rocks found within these zones have been described as strongly mylonitic granulites, but petrological evidence for the granulite stage is still lacking. Thus, it may be possible that a strongly retrograded allochthonous unit similar to the Gföhl unit in the Bohemian Massif is present in the Schwarzwald, but further field and petrological studies are necessary before further speculations are made.

Conclusions

A detailed investigation of textures and mineral compositions of three garnet-spinel peridotite occurrences from the Moldanubian CSGC of the Schwarzwald and thermobarometric calculations on these rocks have been presented. In the context of previously published petrological results on metamorphic rocks from the Schwarzwald, the following conclusions emerge:

1. Two of the examined samples have equilibrated within the garnet-spinel peridotite stability field at 680–770 °C, 1.4–1.8 GPa. One of these samples experienced an earlier porphyroclastic stage at slightly higher temperatures (790 ± 48 °C) within the spinel peridotite stability field ($P < 1.8$ GPa). The equilibration conditions of 670–770 °C, 1.4–1.8GPa correspond to those found previously in other garnet-spinel peridotites from the CSGC (670–740 °C, 1.4–1.8 GPa; Kalt et al. 1995).
2. In the third sample pyroxenes and olivine have been completely hydrated. The rock most likely equilibrated within the garnet peridotite stability field, but the P-T conditions can only be estimated on the basis of Ca vs Cr contents of garnets. For similar garnet websterites of the CSGC, equilibration conditions of 740–850 °C, 3.2–4.3 GPa have been constrained (Kalt et al. 1995).
3. The results of this investigation thus confirm the distinction of two groups of ultramafic garnet-bearing high-pressure metamorphic rocks with different equilibration conditions within the CSGC as estab-

lished previously (Kalt et al. 1995). All data now available reveal that garnet-spinel peridotites and eclogites of the CSGC experienced similar P-T conditions within the garnet-spinel peridotite stability field, whereas garnet websterites and probably also one garnet peridotite (EB) equilibrated at higher pressures.

4. Further field and petrological work must reveal whether or not the high-temperature low-pressure metamorphic rocks hosting these two different high-pressure groups belong to the same tectonic and lithological unit as has been assumed thus far.
5. The equilibration conditions of garnet-spinel peridotites and eclogites of the CSGC correspond quite well to those for garnet-spinel peridotites from the Moldanubian zone of the Vosges mountains and for eclogites from the Moldanubian s. str. of the Bohemian Massif. The equilibration pressures of the second group of high-pressure ultramafic rocks in the CSGC (3.2–4.3 GPa) are similar to those of peridotites and pyroxenites from the Gföhl unit in Lower Austria, but the equilibration temperatures (740–850 °C) are much lower.

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Appendix

Sample locations

The investigated samples have the following locations on the "Topographische Karte der Bundesrepublik Deutschland", 1:25000:HF, sheet 7713 Schuttertal r 34 22 67 h 53 47 09; SB, sheet 7614 Zell a. H. r 34 27 00 h 53 61 67; EB, sheet 7914 St. Peter r 34 34 47 h 53 27 80.

Analytical techniques

Mineral analyses were performed using a Camebax SX 50 microprobe equipped with five wavelength-dispersive spectrometers. Operating parameters were 20 nA beam current, 15 kV accelerating voltage, 10 s counting time for all elements except Ni, Ca, Al in olivine (30 s), Mg, Ti, Cr, Si in olivine (20 s), Ti in spinels (30 s), and Mg, Ca, Al in spinels (20 s). PAP correction was applied to the data. Natural and synthetic silicate and oxide standards were used for calibration.

References

Beard BL, Medaris LG, Johnson GM, Brueckner HK, M'sar Z (1992) Petrogenesis of Variscan high-temperature Group A eclogites from the Moldanubian zone of the Bohemian Massif, Czechoslovakia. Contrib Mineral Petrol 111:468–483

Becker H, Altherr R (1992) Evidence from ultra-high-pressure marbles for recycling of sediments into the mantle. Nature 358:745–748

Bertrand P, Mercier JMM (1985) The mutual solubility of coexisting ortho- and clinopyroxene: towards an absolute geothermometer for the natural system? Earth Planet Sci Lett 76:109–122

Blümel P (1983) The western margin of the Bohemian Massifin Bavaria. Fortschr Min 61:171–195

Bonnot H, Piboule M (1980) Mise en évidence d'une dualité d'origine des ultrabasites a grenat du Limousin et recherche de la signification des péridotites d'origine mantellique dans le Massif Central français. Comptes Rend Acad Sci Paris 291 Ser D: 129–132

Brey GP (1989) Geothermobarometry for lherzolites: Experiments from 10–60 kb, new thermometers and application to natural rocks. Unpubl Dr. habil. Thesis, University of Darmstadt

Brey GP, Köhler T (1990) Geothermobarometry in four-phase lherzolites II. New thermobarometers, and practical assessment of existing thermobarometers. J Petrol 31:1353–1378

Brey GP, Köhler T, Nickel G (1990) Geothermobarometry in four-phase lherzolites I. Experimental results from 10 to 60 kb. J Petrol 31:1313–1352

Carswell DA (1991) Variscan high P-T metamorphism and uplift history in the Moldanubian zone of the Bohemian Massifin Lower Austria. Eur J Mineral 3:323–342

Carswell DA, O'Brien PJ (1993) Thermobarometry and geotectonic significance of high-pressure granulites: examples from the Moldanubian zone of the Bohemian Massifin Lower Austria. J Petrol 34:427–249

Chakraborty S, Ganguly J (1991) Compositional zoning and cation diffusion in garnet. In: Ganguly J (ed) Diffusion, atomic ordering and mass transport. Springer, Berlin Heidelberg New York, pp 120–175

Dudek A, Fediuková E (1974) Eclogites of the Bohemian Moldanubicum N Jahrb Min Abh 121:127–159

Echtler HP, Chauvet A (1991/92) Carboniferous convergence and subsequent crustal extension in the southern Schwarzwald (SW Germany). Geodynam Acta 5:37–49

Eisbacher GH, Lüschen E, Wickert F (1989) Thrusting and extension in the Hercynian Schwarzwald and Vosges, Central Europe. Tectonics 8:2–21

Ernst WG (1978) Petrochemical study of lherzolitic rocks from the western Alps. J Petrol 19:341–392

Evans BW, Trommsdorff V (1978) Petrogenesis of garnet lherzolite, Cima di Gagnone, Lepontine Alps. Earth Planet Sci Lett 40:333–348

Franke W (1989) Tectonostratigraphic units in the Variscan belt of central Europe. Geol Soc Am Spec Pap 230:67–90

Ganguly J, Zazzoli V (1994) Fe^{2+}-Mg interdiffusion in orthopyroxene:retrieval from the data on intercrystalline exchange reaction. Am Mineral 79:930–937

Gasparik T (1987) Orthopyroxene thermometry in simple and complex systems. Contrib Mineral Petrol 96:357–370

Jamtveit B (1987a) Metamorphic evolution of the Eiksunddal eclogite complex, western Norway, and some tectonic implications. Contrib Mineral Petrol 95:82–99

Jamtveit B (1987b) Magmatic and metamorphic controls on chemical variations within the Eiksunddal eclogite complex, Sunnmøre, western Norway. Lithos 20:369–389

Kalt A, Grauert B, Baumann A (1994a) Rb-Sr and U-Pb studies on migmatites from the Schwarzwald (F.R.G.): constraints on isotopic resetting during high-temperature metamorphism. J Metam Geol 12:667–680

Kalt A, Hanel M, Schleicher H, Kramm U (1994b) Petrology and geochronology of eclogites from the Variscan Schwarzwald (F.R.G.). Contrib Mineral Petrol 115:287–302

Kalt A, Altherr R, Hanel M (1995) Contrasting P-T conditions recorded in ultramafic high-pressure rocks from the Variscan Schwarzwald. Contrib Mineral Petrol 121:45–60

Lasnier B (1971) Les péridotites et pyroxénolites à grenat du Bois des Feuilles (Monts du Lyonnais) (France). Contrib Mineral Petrol 34:29–41

Latouche L, Fabriès J, Guiraud M (1992) Retrograde evolution in the Central Vosges mountains (northeastern France):implications for the metamorphic history of high-grade rocks during the Variscan orogeny. Tectonophysics 205:387–407

Leake BA (1978) Nomenclature of amphiboles. Can Mineral 16:501–520

Medaris LG, Carswell DA (1990) Petrogenesis of Mg-Cr garnet peridotites in European metamorphic belts. In: Carswell DA (ed) Eclogite facies rocks. Blackie, Glasgow London, pp 260–290

Medaris LG, Wang HF, M'sar Z, Jel'nek 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

Medaris LG, Beard BL, Johnson CM, Valley JW, Spicuzza MJ, Jel'nek E, Misar Z (1995a) Garnet pyroxenite and eclogite in the Bohemian Massif: geochemical evidence for Variscan recycling of subducted lithosphere. Geol Rundsch 84:489–505

Medaris LG, Jel'nek E, Misar Z (1995b) Czech eclogites: terrane settings and implications for Variscan tectonic evolution of the Bohemian Massif. Eur J Mineral 7:7–28

Morioka M, Nagasawa H (1991) Ionic diffusion in olivine. In: Ganguly J (ed) Diffusion, atomic ordering and mass transport. Springer, Berlin Heidelberg New York, pp 176–197

Nickel KG (1983) Petrogenesis of garnet and spinel peridotites. A study with particular reference to the role of chromium in geothermometry and geobarometry. PhD thesis, University of Tasmania

Nickel KG (1986) Phase equilibria in the system SiO_2-MgO-Al_2O_3-CaO-Cr_2O_3(SMACCR) and their bearing on spinel/garnet lherzolite relationships. N Jahrb Min Abh 155:259–287

O'Brien PJ (1989) The petrology of retrograded eclogites of the Oberpfalz Forest, NE Bavaria, West Germany. Tectonophysics 157:195–212

O'Brien PJ (1991) A multistage metamorphic evolution in eclogites from the Mariánské Lázne complex, NW Bohemia, Czechoslovakia: the implications for uplift mechanisms. Terra Abstr 3:93

O'Brien PJ (1993) Partially retrograded eclogites of the Münchberg Massif, Germany: records of a multistage Variscan uplift history in the Bohemian Massif. J Metam Geol 11:241–260

O'Brien PJ, Carswell DA (1993) Tectonometamorphic evolution of the Bohemian Massif:evidence from high-pressure metamorphic rocks. Geol Rundsch 82:531–555

O'Brien PJ,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. Geol Rundsch 84:473–488

O'Brien PJ, 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 Variscan tectonometamorphic evolution in the NW Bohemian Massif. Contrib Mineral Petrol 112:261–278

O'Neill HStC (1981) The transition between spinel lherzolite and garnet lherzolite, and its use as a geobarometer. Contrib Mineral Petrol 77:185–194

Obata M (1980) The Ronda peridotite: garnet-, spinel-, and plagioclase-lherzolite facies and the P-T trajectories of a high-temperature mantle intrusion. J Petrol 21:533–572

Obata M, Morten L (1987) Transformation of spinel lherzolite to garnet lherzolite in ultramafic lenses of the Austridic Crystalline Complex, northern Italy. J Petrol 28:599–623

Rey P, Burg JP, Lardeaux JM, Fluck P (1989) Evolutions métamorphiques contrastées dans les Vosges orientales: témoins d'un charriage dans la chaine varisque. Comptes Rend Acad Sci Paris 309 (2): 825–821

Sachtleben T, Seck HA (1981) Chemical control of Al-solubility in orthopyroxene and its implication on pyroxene geothermometry. Contrib Mineral Petrol 78:157–165

Stenger R, Baatz K, Klein H, Wimmenauer W (1989) Metamorphic evolution of the pre-Hercynian basement of the Schwarzwald (Federal Republic of Germany). Tectonophysics 157:117–121

Todt W (1976) Zirkon U/Pb-Alter des Malsburg-Granits vom Südschwarzwald. N Jahrb Min Mh 12:929–955

Webb SAC, Wood BJ (1986) Spinel-pyroxene-garnet relationships and their dependence on Cr/Al ratio. Contrib Mineral Petrol 92:471–480

Wendt I, Lenz H, Höhndorf A (1974) Das Alter des Bärhalde-Granites (Schwarzwald) und der Uran-Lagerstätte Menzenschwand. Geol Jahrb E2:131–143

Wimmenauer W (1980) Lithology of the Precambrian in the Schwarzwald. An interim report. N Jahrb Min Mh: 364–372

Wimmenauer W, Stenger R (1989) Acid and intermediate HP metamorphic rocks in the Schwarzwald (Federal Republic of Germany). Tectonophysics 157:109–116