

Exhumation History of the UHPM Brossasco-Isasca Unit, Dora-Maira Massif, as Inferred from a Phengite-Amphibole Eclogite

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Abstract

A well-preserved phengite-amphibole eclogite (Br2F) from the UHP Brossasco-Isasca Unit (BIU) of the Dora-Maira Massif was studied in detail. The eclogite consists of the peak assemblage omphacite, garnet, phengite, rutile, and quartz. A porphyroblastic blue-green amphibole statically overgrows the eclogitic foliation defined by the preferred orientation of phengite flakes, and by the alignments of abundant accessory rutile grains. Both omphacite and phengite are partially replaced by fine-grained symplectites, consisting of clinopyroxene + albite and biotite + oligoclase, respectively. The metamorphic evolution of eclogite Br2F was reconstructed combining microstructural observations, conventional thermobarometry, and pseudosection analysis. A first pseudosection was calculated in the NCKFMASH system in the pressure range 5–45 kbar to model the peak and early retrogressive conditions, whereas a second pseudosection, calculated in the NCFMASH system, was used to model the albite + clinopyroxene symplectite after omphacite. Peak metamorphic conditions of $P = 37.7$ kbar and $T = 732^{\circ}\text{C}$ were estimated. The decompressional P-T path is associated with significant cooling from about 730°C at 38 kbar to 630°C at 14 kbar. These data, obtained combining pseudosection analysis with conventional thermobarometric methods, are in agreement with the P-T paths estimated from other lithologies by Hermann (2003), Castelli et al. (2004), and Groppo et al. (2006), and confirm that the BIU equilibrated within the diamond stability field.

Introduction

ECLOGITES CHARACTERISTICALLY represent the key to reconstruct the metamorphic P-T path of tectono-metamorphic units because, in contrast to their host rocks, they generally preserve peak (and in some cases also prograde) paragenesis. Thermobarometric methods, such as the garnet-clinopyroxene Fe-Mg exchange thermometer (Ellis and Green, 1979; Powell, 1985; Krogh, 1988; Pattison and Newton, 1989; Perkins and Vielzeuf, 1992; Ravna, 2000), the garnet-phengite thermometer (Krogh and Råheim, 1978; Green and Hellman, 1982), the phengite barometer (Powell and Evans, 1983; Massonne and Schreyer, 1987, 1989), and the

garnet-omphacite-phengite thermometer (Waters and Martin, 1993; Krogh Ravna and Terry, 2004) have been used to obtain information about the metamorphic peak for HP and UHP units. Although these methods provide satisfactory results, they also have disadvantages in that: (1) it is difficult to choose the proper compositions of mineral pairs used as thermometer or barometer for the peak assemblage (rutile, omphacite, garnet $\pm$ phengite) because the silicate minerals are typically zoned; (2) thermobarometric methods generally are affected by great uncertainties, because at high P and T, minerals change in composition only slowly with changing P-T conditions; (3) possibly large uncertainties derive from the estimation of $\text{Fe}^{+2}/\text{Fe}^{+3}$ ratios in omphacite and, to a lesser extent, in garnet.

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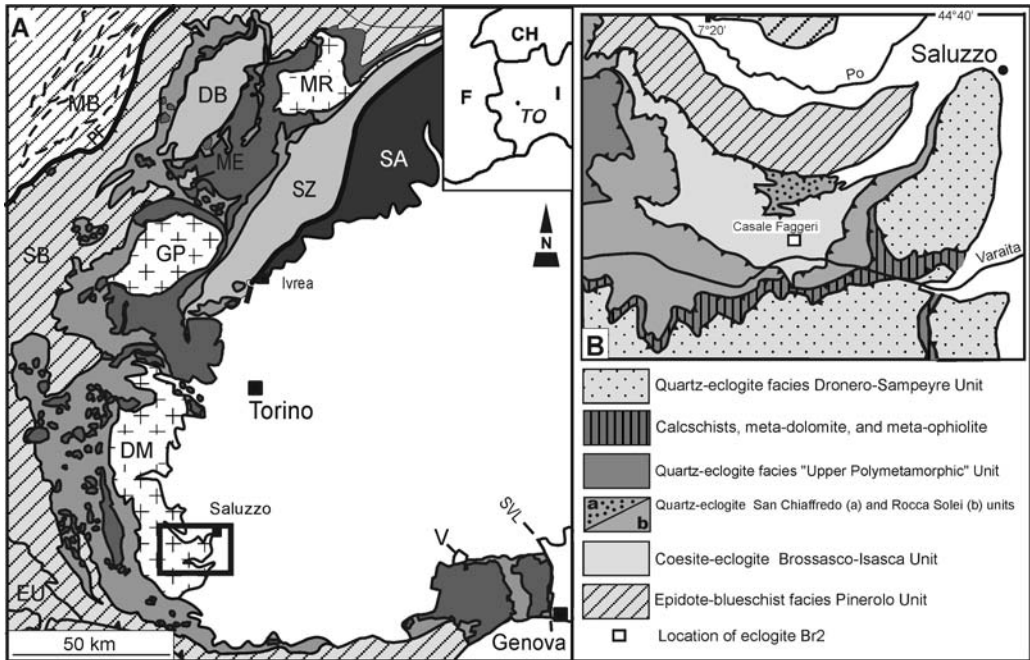


FIG. 1. A. Simplified tectonic sketch map of the Italian Western Alps. Helvetic-Dauphinois domain: MB = Mont Blanc-Aiguilles-Rouges. Penninic domain: SB = Grand St. Bernard Zone; MR = Monte Rosa; GP = Gran Paradiso; DM = Dora-Maira; V = Valosio internal crystalline massifs. Piemonte zone of calcschists (light grey) with meta-ophiolites (dark grey). Austroalpine Domain: DB = Dent Blanche nappe; ME = Monte Emilius klippe; SZ = Sesia-Lanzo zone. SA = Southern Alps; EU = Embrunais-Ubaye flysch nappe; PF = Penninic thrust front; SVL = Sestri-Voltaggio line. B. Enlargement of the southern Dora-Maira Massif. Tectonic units of the Massif are listed from the structurally lowest Pinerolo Unit to the structurally highest Dronero-Sampeyre Unit.

Recently, the P-T pseudosection approach has been successfully used to model metamorphic conditions and to estimate the metamorphic evolution of natural rocks of either pelitic (Zeh, 2001; Proyer, 2003a, 2003b; Wei and Powell, 2003, 2004; Wei et al., 2004; Groppo et al., 2006), or mafic compositions (Carson et al., 1999; Lopez et al., 2003; Wei et al., 2003; Štípská and Powell, 2005). Comparing modeled phase compositions to actual mineral compositions allows obtaining P-T data independently from conventional thermobarometry.

In this paper, we report the results of a detailed mineral-chemical and petrological study on a representative phengite-amphibole eclogite from the UHP Brossasco-Isasca Unit. The eclogite paragenesis is well preserved in this sample, but both omphacite and phengite are partially replaced by retrograde symplectites; hence a combination of pseudosection analysis with conventional thermobarometric methods allows reconstruction of the

entire evolution from UHP peak metamorphic conditions at nearly 40 kbar down to about 12 kbar.

Geological Setting

The coesite-bearing Brossasco-Isasca Unit (BIU) is a coherent thrust sheet of Penninic continental crust belonging to the southern Dora-Maira Massif. The BIU is tectonically sandwiched between two units, both recrystallized in quartz-eclogite facies at ~550°C and 15 kbar (Chopin et al., 1991; Schertl et al., 1991; Sharp et al., 1993; Compagnoni et al., 1994; Matsumoto and Hirajima, 2000; Compagnoni and Rolfo, 2003; Hermann, 2003) (Fig. 1). The BIU, originally a Variscan amphibolite-facies metamorphic basement (Compagnoni et al., 1995), was intruded at 275 Ma by porphyritic granitoids (Gebauer et al., 1997), as shown by local preservation of relict pre-Alpine igneous and metamorphic structures (Biino and Compagnoni, 1991; Compag-

noni et al., 1994, 1995; Compagnoni and Rolfo, 2003). During the Alpine orogeny, the BIU was subjected to pervasive recrystallization in the coesite-eclogite field (Chopin, 1984, 1987; Chopin et al., 1991; Kienast et al., 1991; Schertl et al., 1991; Sharp et al., 1993; Compagnoni et al., 1995; Gebauer et al., 1997; Rubatto and Hermann, 2001; Hermann, 2003), followed by partial re-equilibration in the quartz-eclogite field and local greenschist-facies recrystallization. The Variscan amphibolite-facies basement rocks and the late-Variscan granitoids were converted into the present "Polymetamorphic Complex" and "Monometamorphic Complex," respectively (Compagnoni et al., 1995) (Fig. 1).

The Polymetamorphic Complex mainly consists of Grt-Phe-Ky-Jd paragneiss and paraschist with marble and eclogite intercalations (Chopin et al., 1991; Compagnoni et al., 1994, 1995; Compagnoni and Rolfo, 2003). The paraschists contain rare textural and/or mineralogical relics of the pre-Alpine amphibolite-facies regional metamorphism (Biino and Compagnoni, 1991; Compagnoni et al., 1994, 1995; Compagnoni and Rolfo, 2003). The Monometamorphic Complex consists of medium- to fine-grained, typically mylonitic orthogneiss, with local augen structure and locally preserved relict metagranitoids. Layers of pyrope-bearing white-schist, derived from the metasomatic transformation of the granitoid protolith along ductile shear zones in the presence of a hydrous fluid phase (Chopin, 1984; Compagnoni and Hirajima, 2001; Simon and Chopin, 2001), are locally included in the orthogneiss.

Petrography and Mineral Chemistry

The studied eclogite (Br2F) was collected from an eclogite boudin a few meters long exposed at Casale Faggeri, near Brossasco, within the polymetamorphic paragneiss of the central portion of the BIU (Fig. 1). This eclogite was described by Kienast et al. (1991). It shows a weak foliation mainly defined by the preferred orientation of phengite flakes and by the alignment of elongated omphacite crystals (Fig. 2A). Small isoclinal folds, resulting from the syneclogitic ductile deformation responsible for the main foliation development, are locally preserved.

Eclogite Br2F is fine-grained and mainly consists of omphacite, garnet, phengite, and quartz; porphyroblasts of blue-green amphibole statically

overgrow the eclogitic foliation (Fig. 2B), and abundant accessory rutile occurs in the rock matrix. Both omphacite and phengite are partially replaced by fine-grained symplectites, consisting of clinopyroxene + albite and biotite + oligoclase, respectively.

Omphacite, garnet, phengite, and the symplectites were analyzed with a Cambridge Stereoscan 360 SEM equipped with an EDS Energy 200 and a Pentafet detector (Oxford Instruments) at the Department of Mineralogical and Petrological Sciences, University of Torino. The operating conditions were: 50 seconds counting time, 15 kV accelerating voltage, and 2.70–2.80 A beam current. SEM-EDS quantitative data (spot size = 2 μ m) were acquired and managed using the Microanalysis Suite Issue 12, INCA Suite version 4.01; the raw data were calibrated on natural mineral standards and the $\phi\rho Z$ correction (Pouchou and Pichoir, 1988) was applied. Representative SEM-EDS analyses of clinopyroxene, garnet, phengite, and amphibole are reported in Tables 1–4.

Omphacite and symplectite clinopyroxene

Idioblastic omphacite (average size 50–200 μ m) locally includes small grains of garnet and rutile. Omphacite is strongly zoned and, on the basis of the Na/(Na+Ca) ratio and backscattered electron images (Figs. 3A, 3C, and 3D), a core with jadeite contents from Jd₅₅ to Jd₅₀, a mantle from Jd₅₀ to Jd₄₅, and a discontinuous rim from Jd₄₀ to Jd₃₅ may be distinguished. The Fe/(Fe+Mg) ratio progressively increases outward from 0.14–0.20 in the core, to 0.20–0.24 in the mantle, and 0.24–0.28 in the rim (Figs. 4 and 5).

Omphacite is partly replaced by a symplectite mainly consisting of a less sodic clinopyroxene and plagioclase (Figs. 2D, 2E, 3A, 3B, 3E, and 3F). Symplectitic clinopyroxene fingers are broader at the original grain boundary and become thinner toward the present location of the reaction front (Waters, 2002) (Figs. 2E and 3E). Symplectitic clinopyroxene fingers are generally oriented perpendicular to the original omphacite margins and are weakly zoned, being more jadeitic (Jd₂₃) in the proximity of the unaltered omphacite and more diopsidic at the contact with the quartz grains (Jd₇) (Figs. 3E, 3F, and 5). Symplectitic plagioclase is quite homogeneous and its anorthite content is invariably less than 10 mol%. Small grains of Ca-Na amphibole are locally intergrown in the symplectite (Fig. 3F). Microstructural observations suggest that amphibole is the first product of omphacite retro-

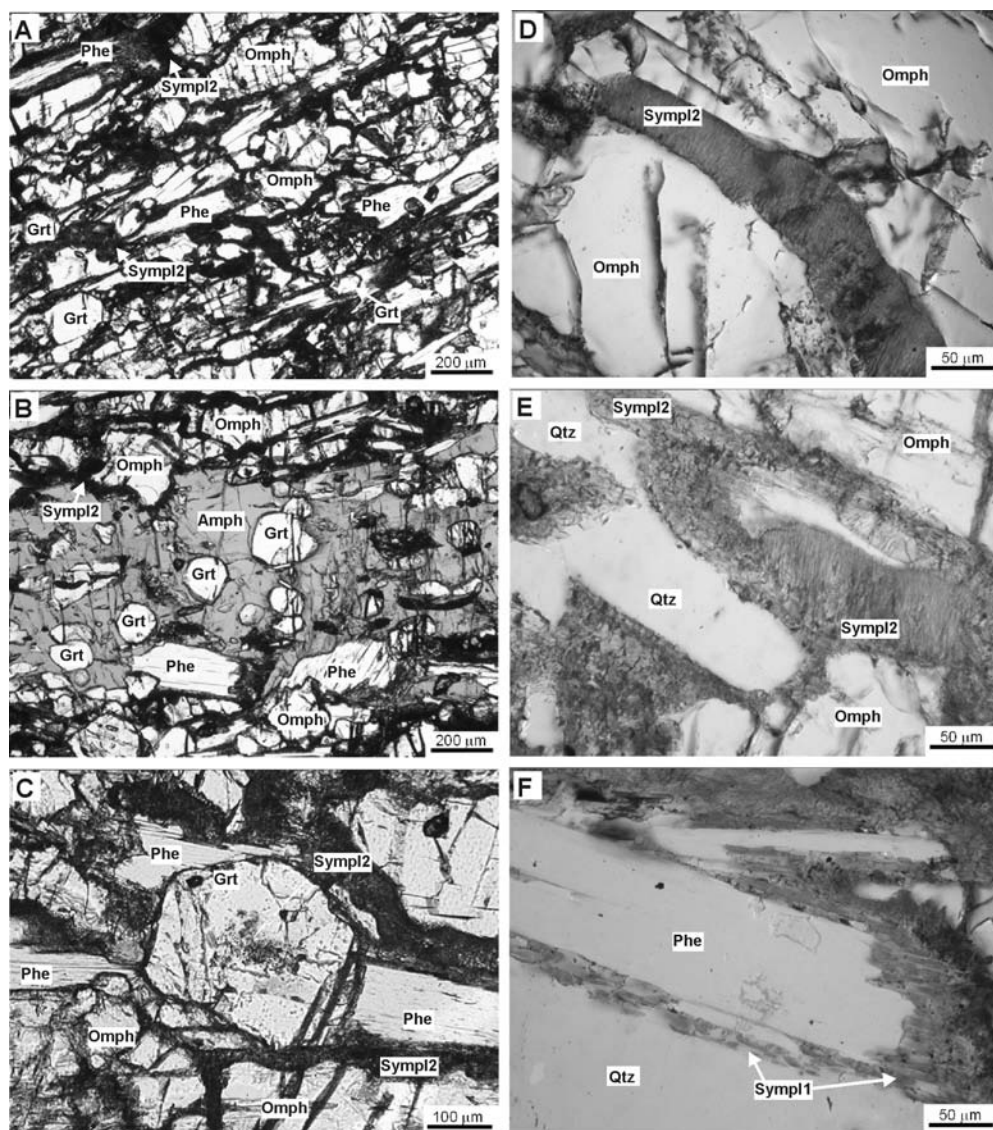


FIG. 2. Representative microstructures of eclogite Br2F as seen under the optical microscope. A. Eclogite foliation, mainly defined by the preferred orientation of phengite flakes and lineation of omphacite crystals. B. Porphyroblastic Na-Ca amphibole with inclusions of omphacite, garnet, and phengite. C. Idioblastic garnet showing a core crowded with very small rutile inclusions. D and E. Na-clinopyroxene + albite symplectite after omphacite. Note that symplectite fingers are coarser at the original grain boundary and finer toward the reaction front. F. Biotite + oligoclase symplectite after phengite. Omph = omphacite; Grt = garnet; Phe = phengite; Qtz = quartz; Amph = amphibole; Sympl 1 = biotite + oligoclase symplectite after phengite; Sympl 2 = Na-clinopyroxene + albite symplectite after omphacite.

gression, followed by the Na-clinopyroxene + albite intergrowths. Chemical analyses of the symplectite amphibole plot in the edenite-pargasite compositional fields of Leake et al. (1997).

Garnet

Small garnet grains (averaging 100 µm across), typically partially corroded, locally show an asymmetric core crowded with very small inclusions of

TABLE 1. Representative SEM-EDS Analyses of Omphacite and Na-Clinopyroxene in Symplectite

Point analysis	Crystal A					Omphacite					Crystal B					Na-Clinopyroxene in symplectite				
	3.21	3.22	3.23	3.24	3.25	7.7	7.8	7.9	7.10	7.11	3.15	3.16	9.22	9.28	10.9	10.1				
SiO ₂	56.34	56.48	56.02	55.60	54.55	56.87	56.55	56.28	55.24	54.89	51.76	52.13	52.8165	52.4705	53.26	52.947				
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Al ₂ O ₃	13.05	13.18	11.78	11.84	10.18	13.47	13.37	12.75	11.73	10.77	5.34	1.30	6.05	5.13	6.26	6.59				
FeO	2.84	2.70	4.24	4.07	4.92	2.50	2.63	3.28	4.07	4.63	7.18	8.94	6.19	6.51	7.01	6.75				
MgO	7.47	7.26	8.05	8.06	8.64	7.55	7.34	7.52	7.59	8.30	12.02	11.85	11.39	11.58	10.00	10.20				
CaO	12.20	12.11	13.47	13.63	15.61	12.07	12.48	12.43	13.39	14.47	21.38	23.91	20.67	21.58	20.11	20.33				
Na ₂ O	7.69	7.78	6.89	7.00	5.81	8.01	7.89	7.62	7.08	6.41	2.13	1.05	2.86	2.39	3.28	3.20				
Total	99.57	99.51	100.45	100.21	99.71	100.47	100.26	99.88	99.10	99.48	99.80	99.18	99.98	99.66	99.92	100.01				
Si	1.99	2.00	1.98	1.97	1.96	1.99	1.98	1.99	1.98	1.96	1.90	1.96	1.92	1.93	1.95	1.93				
Al ^{IV}	0.01	0.00	0.02	0.03	0.04	0.01	0.02	0.01	0.02	0.04	0.10	0.04	0.08	0.07	0.05	0.07				
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Sum T	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00				
Al ^{VI}	0.53	0.55	0.47	0.46	0.39	0.54	0.53	0.52	0.47	0.42	0.13	0.02	0.18	0.15	0.22	0.22				
Fe ³⁺	0.00	0.00	0.02	0.06	0.06	0.02	0.02	0.02	0.05	0.06	0.12	0.10	0.09	0.10	0.06	0.08				
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Mg	0.39	0.38	0.42	0.42	0.46	0.39	0.38	0.40	0.40	0.44	0.66	0.66	0.62	0.63	0.55	0.56				
Fe ²⁺	0.08	0.08	0.10	0.06	0.09	0.06	0.06	0.08	0.08	0.08	0.10	0.18	0.09	0.10	0.15	0.13				
Sum M1	1.01	1.01	1.02	1.00	1.00	1.01	0.99	1.01	1.00	1.00	1.01	0.96	0.99	0.98	0.98	0.98				
Ca	0.46	0.46	0.51	0.52	0.60	0.45	0.47	0.47	0.51	0.55	0.84	0.96	0.81	0.85	0.79	0.80				
Na	0.53	0.53	0.47	0.48	0.40	0.54	0.54	0.52	0.49	0.44	0.15	0.08	0.20	0.17	0.23	0.23				
Sum M2	0.99	0.99	0.98	1.00	1.00	0.99	1.01	0.99	1.00	1.00	0.99	1.04	1.01	1.02	1.02	1.02				
X _{Na}	0.53	0.54	0.48	0.48	0.40	0.55	0.53	0.53	0.49	0.44	0.15	0.07	0.20	0.17	0.23	0.22				
X _{Fe}	0.18	0.17	0.23	0.22	0.24	0.16	0.17	0.20	0.23	0.24	0.25	0.30	0.23	0.24	0.28	0.27				

TABLE 2. Representative SEM-EDS Analyses of Garnet

Point analysis	Crystal A							Crystal B										
	4.3	4.4	4.5	4.6	4.7	4.8	4.9	4.37	4.27	4.28	4.29	4.30	4.31	4.32	4.33	4.34	4.35	4.36
SiO ₂	38.68	38.87	37.89	38.68	38.25	38.06	38.05	37.50	38.07	38.14	38.19	38.23	37.79	36.88	37.63	37.88	38.60	37.58
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	21.56	21.68	21.55	21.79	21.83	21.53	21.52	21.29	21.44	21.11	21.46	21.59	20.86	21.19	21.00	21.20	21.60	21.40
FeO	22.77	21.93	23.25	23.68	21.43	24.08	26.40	24.81	24.15	24.04	23.23	22.03	26.86	26.39	26.38	23.56	23.51	26.05
MnO	0.00	0.57	0.53	0.00	0.68	0.49	0.82	1.13	0.52	0.55	0.50	0.51	0.76	1.15	0.81	0.44	0.44	1.22
MgO	6.00	5.95	5.33	5.91	6.36	5.97	5.35	3.39	5.91	5.89	5.85	5.96	4.59	3.98	4.15	5.73	5.96	3.60
CaO	11.07	11.65	11.25	10.51	11.86	9.69	8.08	11.56	9.52	10.16	10.56	11.76	9.08	10.28	9.47	10.28	9.83	10.68
Total	100.08	100.64	99.79	100.57	100.41	99.82	100.22	99.67	99.60	99.89	99.79	100.07	99.93	99.87	99.44	99.08	99.94	100.52
Si	2.99	2.99	2.96	2.98	2.95	2.97	2.97	2.97	2.97	2.98	2.97	2.96	2.98	2.93	2.98	2.97	2.99	2.96
Al	1.96	1.96	1.98	1.98	1.98	1.98	1.98	1.98	1.97	1.94	1.97	1.97	1.94	1.98	1.96	1.96	1.97	1.98
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	1.47	1.41	1.52	1.52	1.38	1.57	1.72	1.64	1.58	1.57	1.51	1.43	1.77	1.75	1.75	1.55	1.52	1.71
Mn	0.00	0.04	0.03	0.00	0.04	0.03	0.05	0.08	0.03	0.04	0.03	0.03	0.05	0.08	0.05	0.03	0.03	0.08
Mg	0.69	0.68	0.62	0.68	0.73	0.69	0.62	0.40	0.69	0.68	0.68	0.69	0.54	0.47	0.49	0.67	0.69	0.42
Ca	0.92	0.96	0.94	0.87	0.98	0.81	0.68	0.98	0.80	0.85	0.88	0.98	0.77	0.87	0.80	0.86	0.82	0.90
Grs	0.31	0.32	0.31	0.29	0.33	0.27	0.23	0.33	0.27	0.28	0.29	0.33	0.26	0.29	0.27	0.29	0.27	0.30
Alm	0.49	0.47	0.51	0.51	0.46	0.52	0.57	0.55	0.53	0.52	0.50	0.48	0.59	0.58	0.58	0.52	0.51	0.57
Pyr	0.23	0.23	0.21	0.23	0.24	0.23	0.21	0.13	0.23	0.23	0.23	0.23	0.18	0.16	0.16	0.22	0.23	0.14
Sps	0.00	0.01	0.01	0.00	0.01	0.01	0.02	0.03	0.01	0.01	0.01	0.01	0.02	0.03	0.02	0.01	0.01	0.03
X _{Mg}	0.32	0.33	0.29	0.31	0.35	0.31	0.27	0.20	0.30	0.30	0.31	0.33	0.23	0.21	0.22	0.30	0.31	0.20
X _{Ca}	0.30	0.31	0.31	0.28	0.32	0.26	0.22	0.32	0.26	0.27	0.29	0.32	0.25	0.28	0.26	0.28	0.27	0.30

TABLE 3. Representative SEM-EDS Analyses of Amphibole

Point analysis	Porphyrroblastic amphibole							Amph around Grt			Amph in symplectite after Omph		
	Crystal A			Crystal B				3.13		3.14	9.23		9.24
	7.2	7.3	7.4	8.1	8.2	8.3	8.4	8.5					
SiO ₂	43.62	44.15	42.71	45.58	47.04	46.44	44.74	43.70	37.41	36.77	44.09	41.41	
TiO ₂	0.51	0.65	0.69	0.63	0.63	0.53	0.43	0.70	0.00	0.00	0.38	0.38	
Al ₂ O ₃	14.92	14.43	14.70	14.54	13.44	13.44	14.69	15.54	19.22	20.06	11.77	12.94	
Fe ₂ O ₃	2.05	1.72	1.35	2.72	2.83	2.93	1.57	2.83	2.61	1.88	1.43	4.26	
FeO*	10.16	10.38	11.89	8.73	8.63	8.20	10.70	9.57	15.54	15.86	12.28	11.56	
MgO	10.73	10.92	10.37	11.49	12.26	11.96	10.45	10.89	6.44	5.90	11.60	9.78	
CaO	9.63	9.86	10.83	8.44	8.45	8.28	9.03	9.27	11.67	11.48	11.96	12.39	
Na ₂ O	3.69	3.52	3.02	4.16	4.41	4.04	4.11	3.82	2.67	2.23	2.28	2.19	
K ₂ O	0.56	0.63	1.02	0.70	0.50	0.56	0.62	0.70	1.67	1.89	0.95	1.32	
Total	95.87	96.26	96.58	96.99	98.19	96.38	96.34	97.02	97.23	96.07	96.74	96.23	
Si	6.45	6.51	6.36	6.60	6.72	6.74	6.58	6.38	5.72	5.68	6.57	6.28	
Al ^{IV}	1.55	1.49	1.65	1.40	1.29	1.26	1.42	1.62	2.28	2.32	1.43	1.72	
Al ^{VI}	1.06	1.01	0.93	1.08	0.98	1.03	1.12	1.06	1.18	1.34	0.64	0.60	
Ti	0.06	0.07	0.08	0.07	0.07	0.06	0.05	0.08	0.00	0.00	0.04	0.04	
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Fe ²⁺	0.23	0.19	0.15	0.30	0.31	0.32	0.17	0.31	0.30	0.22	0.16	0.49	
Fe ³⁺	1.26	1.28	1.48	1.06	1.03	0.99	1.32	1.17	1.99	2.05	1.53	1.47	
Mg	2.37	2.40	2.30	2.48	2.61	2.59	2.29	2.37	1.47	1.36	2.58	2.21	
Ca	1.53	1.56	1.73	1.31	1.29	1.29	1.42	1.45	1.91	1.90	1.91	2.02	
Na(M4)	0.47	0.44	0.27	0.69	0.71	0.71	0.58	0.55	0.09	0.10	0.09	0.00	
Sum M													
Na(A)	0.59	0.56	0.60	0.48	0.51	0.42	0.59	0.53	0.70	0.57	0.57	0.64	
K	0.11	0.12	0.19	0.13	0.09	0.10	0.12	0.13	0.33	0.37	0.18	0.26	
Sum A	0.69	0.68	0.79	0.61	0.60	0.53	0.71	0.66	1.03	0.94	0.75	0.90	
X _{Na}	0.41	0.39	0.34	0.47	0.49	0.47	0.45	0.43	0.29	0.26	0.26	0.24	
X _{Fe}	0.09	0.07	0.06	0.11	0.10	0.11	0.07	0.12	0.17	0.14	0.06	0.18	

*Ferric iron was estimated with the procedure proposed by Holland and Blundy, 1994, using their program for hornblende-plagioclase thermometry.

TABLE 4. Representative SEM-EDS Analyses of Phengite

Point analysis	Crystal A					Crystal B					Crystal C				
	1.8	1.9	1.10	1.11	1.12	1.13	2.28	2.29	2.30	2.31	2.32	4.53	4.54	4.55	4.57
SiO ₂	50.45	50.31	48.42	51.32	50.27	49.36	51.38	50.53	50.58	50.50	50.59	47.78	48.36	48.61	48.66
TiO ₂	0.63	0.44	0.66	0.00	0.51	0.63	0.46	0.37	0.41	0.44	0.44	0.88	0.72	0.70	0.69
Al ₂ O ₃	24.82	24.48	25.35	22.81	24.47	25.20	23.24	23.57	22.56	23.29	23.86	27.34	26.29	26.92	26.51
FeO	2.10	2.22	1.77	1.82	1.81	1.81	1.42	1.56	1.43	1.45	1.64	2.18	2.10	2.08	2.23
MgO	4.07	3.82	3.44	4.64	4.06	3.73	4.56	4.34	4.61	4.44	4.34	2.90	3.30	3.34	3.58
Na ₂ O	0.65	0.75	0.71	0.41	0.45	0.65	0.00	0.00	0.00	0.00	0.40	0.85	0.72	0.83	0.70
K ₂ O	10.71	10.43	10.42	11.04	11.01	10.21	11.04	10.92	11.04	10.90	10.75	10.38	10.14	10.47	10.45
Total	93.43	92.44	90.76	92.04	92.59	91.59	92.09	91.29	90.64	91.01	92.02	92.31	91.62	92.94	92.82
Si	3.45	3.47	3.40	3.55	3.47	3.43	3.54	3.52	3.55	3.52	3.50	3.31	3.36	3.34	3.35
Al ^{IV}	0.55	0.53	0.60	0.45	0.53	0.57	0.46	0.48	0.45	0.48	0.50	0.69	0.64	0.66	0.65
Al ^{VI}	1.45	1.46	1.50	1.42	1.45	1.49	1.43	1.45	1.41	1.44	1.44	1.54	1.52	1.52	1.50
Ti	0.03	0.02	0.04	0.00	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.05	0.04	0.04	0.04
Fe ²⁺	0.12	0.13	0.10	0.11	0.10	0.11	0.08	0.09	0.08	0.08	0.09	0.13	0.12	0.12	0.13
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.41	0.39	0.36	0.48	0.42	0.39	0.47	0.45	0.48	0.46	0.45	0.30	0.34	0.34	0.37
Na	0.09	0.10	0.10	0.05	0.06	0.09	0.00	0.00	0.00	0.00	0.05	0.11	0.10	0.11	0.09
K	0.93	0.92	0.93	0.97	0.97	0.90	0.97	0.97	0.99	0.97	0.95	0.92	0.90	0.92	0.92

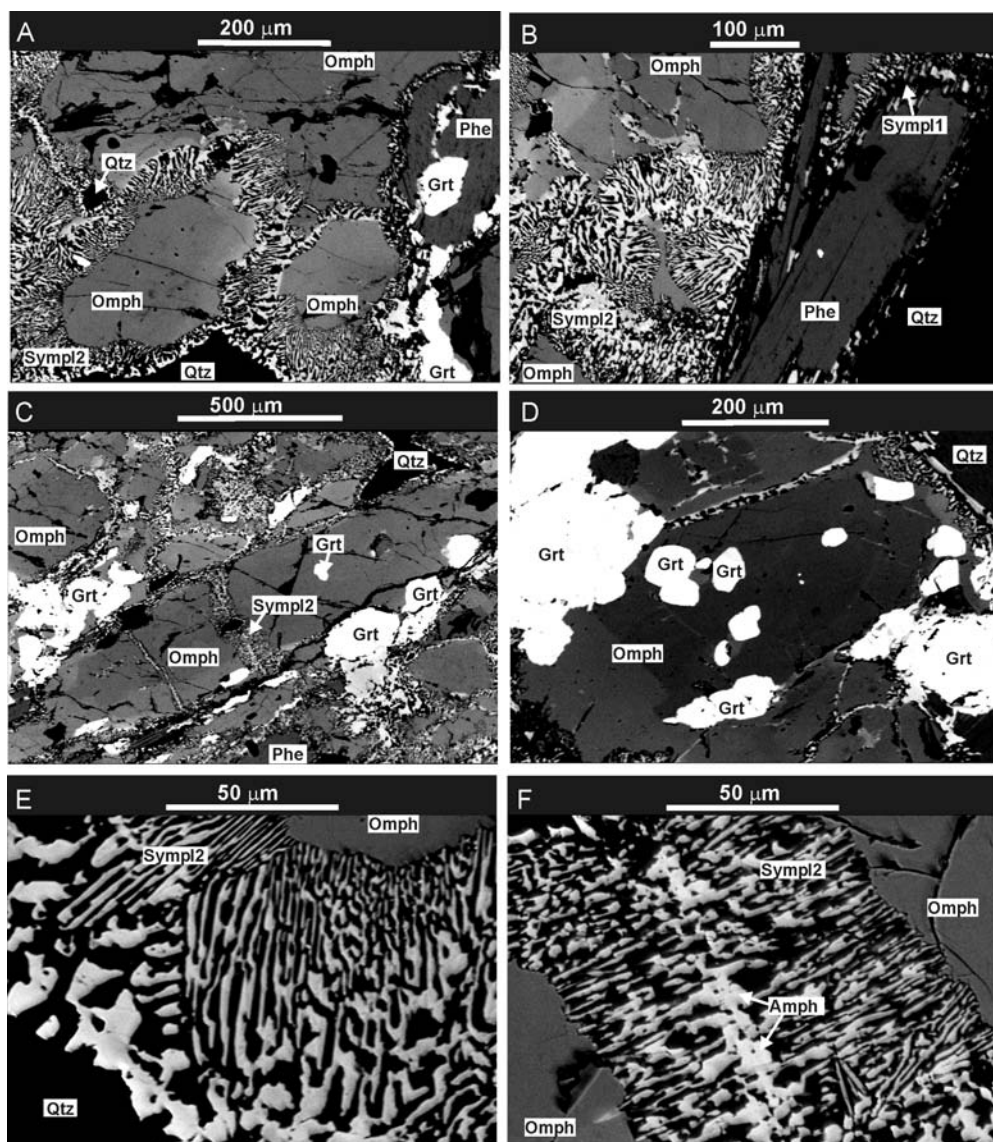


FIG. 3. Backscattered electron images of eclogite Br2F. A. Zoned omphacites, partially replaced by a symplectite of Na-clinopyroxene + albite, idioblastic garnets, and phengite flakes. B. Na-clinopyroxene + albite symplectite after omphacite and biotite + oligoclase symplectite after phengite. C. Zoned omphacite idioblast including a small idioblastic garnet. Omphacite is partially replaced by the Na-clinopyroxene + albite symplectite. D. Detail of a zoned omphacite with inclusions of small idioblastic garnets. E. Detail of the Na-clinopyroxene + albite symplectite after omphacite (see Figs. 2D and 2E). Na-clinopyroxene, oriented perpendicular to the omphacite margins, is weakly zoned, being more Na-rich in the proximity of the omphacite and more diopsidic at the contact with quartz. F. Detail of the Na-clinopyroxene + albite symplectite after omphacite, showing small grains of early amphibole. Mineral abbreviations are the same as in Figure 2.

rutile (Fig. 2C). Unlike omphacite, garnet is only weakly zoned, and its Ca content gradually decreases from Grs₃₂ in the core to Grs₂₆ in the man-

tle. A thin and discontinuous corona, characterized by a sharp Ca and Fe increase (up to Grs₃₃ and Alm₅₇, respectively), is locally present (Fig. 6A).

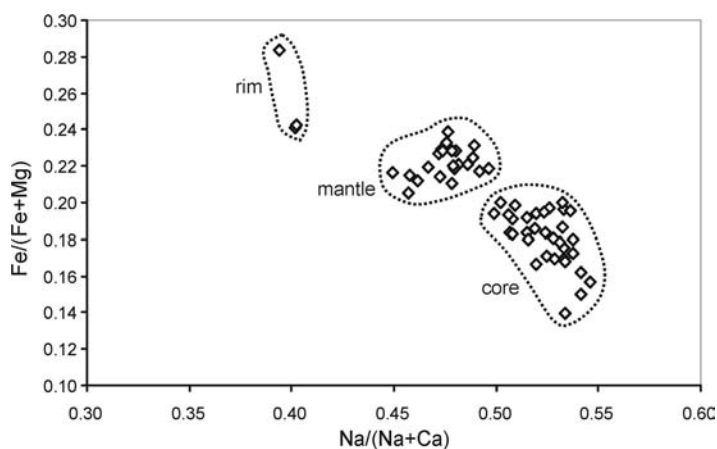


FIG. 4. Compositions of omphacite plotted in the $\text{Fe}/(\text{Fe}+\text{Mg})$ vs. $\text{Na}/(\text{Na}+\text{Ca})$ diagram. Three distinct compositional fields (core, mantle, and rim) may be recognized.

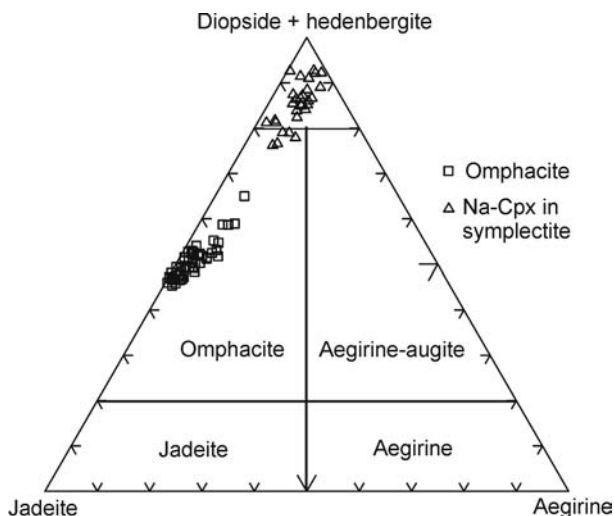


FIG. 5. Omphacite and Na-clinopyroxene compositions plotted in the jadeite–(diopside + hedenbergite)–aegirine diagram of Morimoto (1988). Omphacite mantle and rim are enriched in diopsidic and aegirinic components relative to the core compositions. Na-clinopyroxene in symplectite after omphacite mainly plots in the diopside + hedenbergite field.

The asymmetrically zoned core crowded with rutile inclusions shows local re-equilibration along fractures, characterized by Ca decrease and Mg increase (Figs. 6A, 6B, and 7), such as described by Erambert and Austrheim (1993), Hames and Menard (1993), Pennacchioni (1996), Whitney (1996), and Straume and Austrheim (1999). A retro-

gressive blue-green ferro-pargasite (Leake et al., 1997) locally surrounds garnet idiomblasts (Fig. 9).

Phengite

Phengite flakes, with a strong preferred orientation, although more abundant in the quartz-rich domains, occur throughout the rock matrix. The

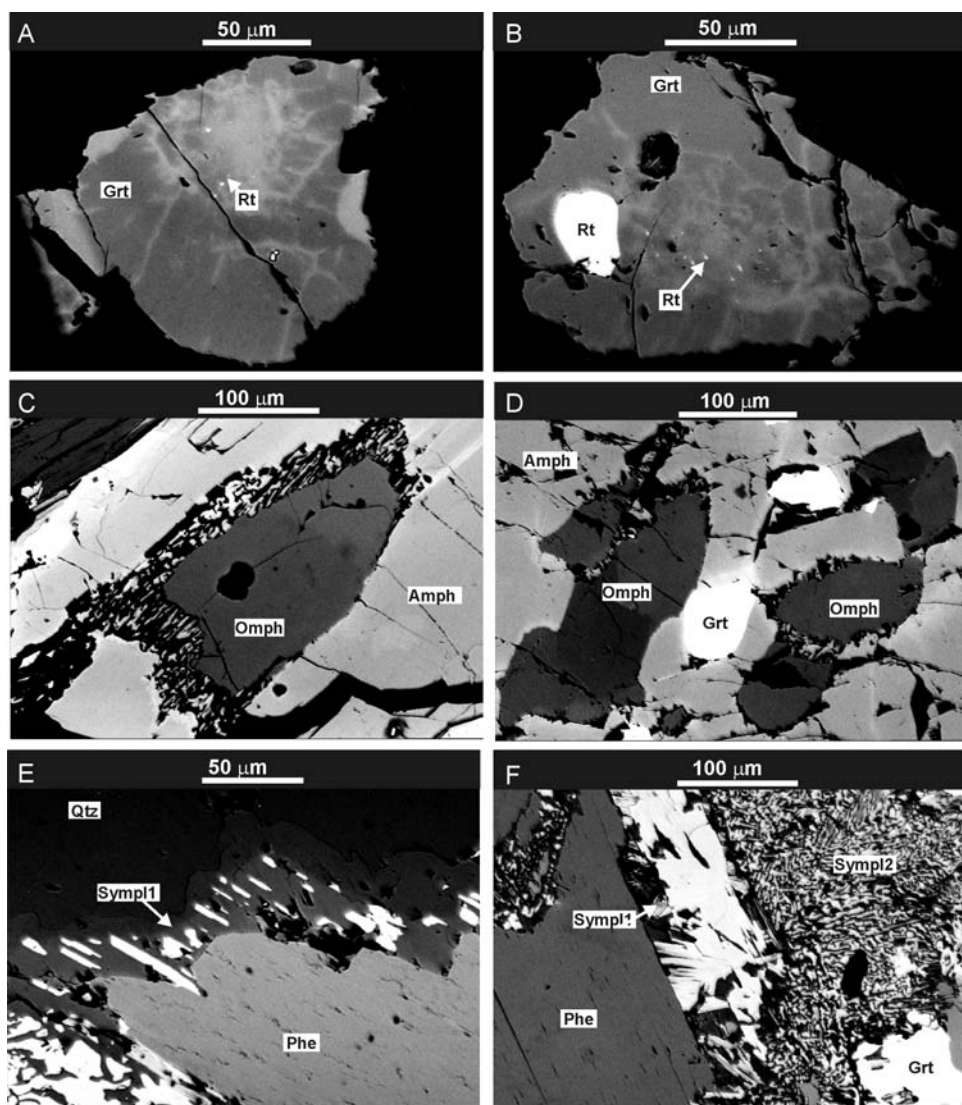


FIG. 6. Backscattered electron images of eclogite Br2F. A and B. Small garnets partially corroded at the rim, with a core crowded with very small rutile inclusions. The lighter vein network in the garnet core shows chemical re-equilibration (decrease in Ca and enrichment in Fe). In (A), a thin and discontinuous rim enriched in Ca and Fe is also evident. C and D. Omphacite and garnet inclusions in a porphyroblastic amphibole. The omphacite zoning is clearly earlier than the amphibole growth. E and F. Biotite + oligoclase symplectite after phengite (Symp1), formed both at the contact phengite-quartz (E) and at the contact phengite-omphacite (F), now replaced by clinopyroxene + albite symplectite (Symp2). Mineral abbreviations are the same as in Figure 2.

highest Si content, observed in the core of the largest flakes (Si = 3.55 atoms p.f.u. on the basis of 11 oxygen), decreases toward the rim (down to 3.35 a.p.f.u.). Smaller phengite flakes, clearly derived from recrystallization of high-Si phengite, have

lower Si contents (in the range Si = 3.38 to Si = 3.25 a.p.f.u.) (Fig. 8). Phengite is partially replaced by a fine-grained symplectite consisting of biotite and plagioclase (Figs. 2F, 3B, 6E, and 6F). Biotite flakes are generally oriented parallel to the basal (001)

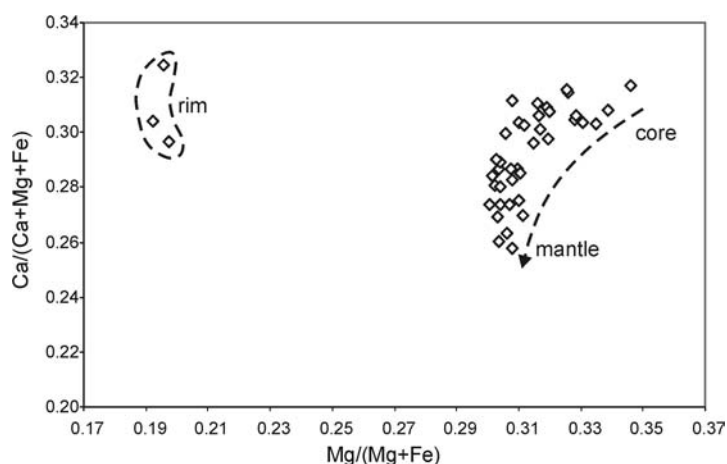


FIG. 7. Garnet compositions plotted in the $\text{Ca}/(\text{Ca}+\text{Mg}+\text{Fe})$ vs. $\text{Mg}/(\text{Mg}+\text{Fe})$ diagram. Garnet is weakly zoned, with Ca-rich cores and Fe-rich mantles. Late discontinuous rims are characterized by enrichment in both Ca and Fe.

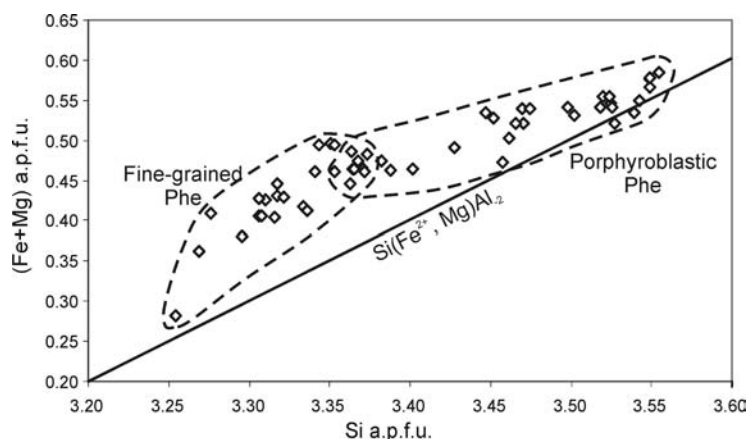


FIG. 8. Phengite compositions plotted in the Si vs. $(\text{Fe}+\text{Mg})$ diagram. The line represents the ideal celadonic substitution. Si is given as a.p.f.u. on the basis of 11 oxygens.

planes of phengite and are intergrown with oligoclase ($X_{\text{An}} = 0.20\text{--}0.30$).

Amphibole

Porphyroblasts of blue-green amphibole statically overgrow the main foliation and host roundish garnets and less abundant zoned omphacite relics (Fig. 2B, Fig. 6C, and 6D). Textural observations show that the amphibole most likely grew at the expense of both omphacite and garnet (they are both corroded), earlier than the development of the symplectite after omphacite. Blue-green amphibole is

weakly zoned from Na-Ca cores (Mg-katophorite according to the nomenclature of Leake et al., 1997) to Ca rims (pargasite) (Figs. 9 and 10); Fe content progressively increases toward the rim.

Reconstruction of P-T Metamorphic Evolution

The metamorphic evolution of eclogite Br2F has been reconstructed combining microstructural observations, conventional thermobarometry and the pseudosection analysis.

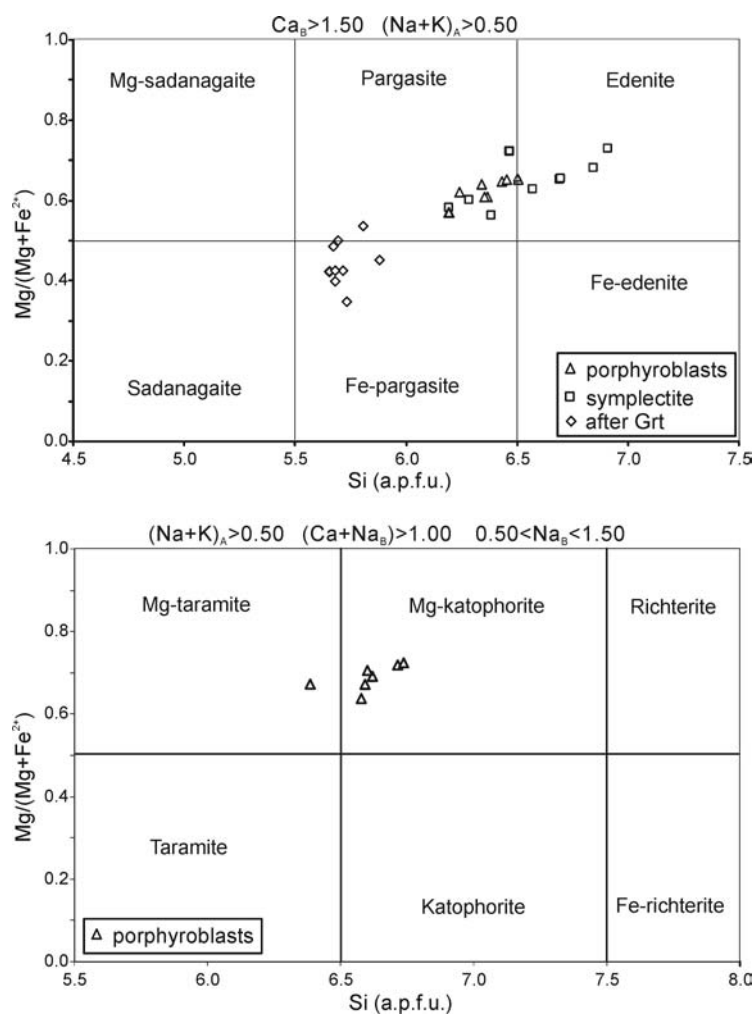


FIG. 9. Compositional diagrams for the Na-Ca amphiboles (Leake et al., 1997). Porphyroblastic amphibole ranges in composition from Mg-katophorite to pargasite; amphibole in symplectites after omphacite is mainly edenite and pargasite. The Fe-rich and Si-poor amphibole around garnet is ferro-pargasite.

Thermobarometry

For the thermobarometry of the eclogite assemblages, the Krogh Ravna and Terry (2004) method for kyanite-free eclogite was used. This method combines reactions 1a and 1b of Krogh Ravna and Terry [$6\text{di} + 3\text{mu} = 2\text{grs} + 1\text{prp} + 3\text{cel}$] with the garnet-clinopyroxene Fe-Mg thermometer of Ravna (2000). Based on the calibrations of Krogh Ravna and Terry (2004), the averaged standard deviations are $\pm 45^\circ\text{C}$ in temperature and ± 3.2 kbar in pressure estimates. Peak P-T conditions were estimated using core compositions of garnet, omphacite, and

phengite, which correspond to the highest values of $X_{\text{Jd}}(\text{Omph})$, $X_{\text{Grs}}(\text{Grt})$, and $\text{Si}(\text{Phe})$ (Figs. 4, 7, and 8).

Growth of a second generation of fine-grained phengite, mostly recrystallized from porphyroblastic phengite, is a significant event in the retrograde evolution of eclogite Br2F. The two phengite generations are characterized by different amounts of celadonic substitution, with Si content in the range 3.55–3.36 and 3.38–3.25 a.p.f.u. in porphyroblastic and fine-grained phengite, respectively (Fig. 8). Therefore, to estimate the P-T conditions during the

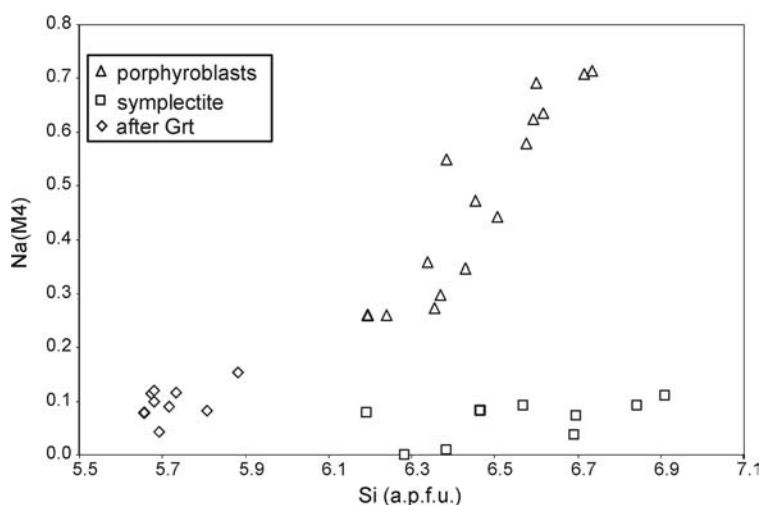


FIG. 10. Amphibole compositions plotted in the Na(M4) vs. Si (a.p.f.u.) diagram.

retrograde evolution, mantle compositions of garnet and omphacite (modeled to occur in equilibrium with a Si = 3.36–3.40 phengite on the basis of the pseudosection analysis discussed below) and the rim compositions of porphyroblastic phengite have been selected.

Average P-T conditions for peak and retrogressive metamorphic events are $T = 732^{\circ}\text{C}$ at $P = 37.7$ kbar, and $T = 656^{\circ}\text{C}$ at $P = 27.1$ kbar, respectively (Table 5). The entire set of P-T estimates is shown in Figure 14.

P-T pseudosections

To model peak metamorphic conditions and part of the exhumation path, a P-T pseudosection (pseudosection 1) was calculated at fixed bulk-rock composition (e.g., Hensen, 1971; Zeh, 2001). The effective bulk-rock composition, calculated in the model system NCKFMASH, was obtained as the average of SEM-EDS analyses on ten 4.70×3.20 mm areas randomly chosen in the sample (see, e.g., Groppo et al., 2006 for a discussion of the method). This choice was made on the base of the assumption that all the eclogite minerals were involved during the post-peak equilibration, at least until porphyroblastic amphibole growth. This assumption is confirmed by the zoning of omphacite, garnet, and phengite crystals, which suggests that the three minerals were all involved in continuous retrogressive reactions. The growth of porphyroblastic Na-Ca amphibole also implies the involvement of the entire

bulk-rock composition, inasmuch as it developed at the expense of both omphacite and garnet, as suggested by microstructural relationships.

To model the growth of the late Na-clinopyroxene + albite symplectite after omphacite, the chemical composition of the microdomain effectively reacting was considered (Evans, 2004). In fact, the symplectite after omphacite appears to have formed through a reaction such as: $\text{Omph} + \text{Qtz} = \text{Na-Cpx} + \text{Pl}$ (Heinrich, 1982; O'Brien, 1989; Rubie, 1990; Smelov and Beryozkin, 1993; Moller, 1998). Taking into consideration the average composition of omphacite $\text{OMPH} = [\text{Na}_{0.50} \text{Ca}_{0.50}](\text{Mg}_{0.40} \text{Al}_{0.51} \text{Fe}_{0.09})(\text{Al}_{0.02} \text{Si}_{1.98})\text{O}_6$, symplectitic Na-clinopyroxene $\text{Na-CPX} = [(\text{Na}_{0.15} \text{Ca}_{0.88})(\text{Mg}_{0.69} \text{Al}_{0.12} \text{Fe}^{2+}_{0.07} \text{Fe}^{+3}_{0.09})(\text{Al}_{0.07} \text{Si}_{1.93})\text{O}_6]$, and plagioclase $\text{PLAG} = [(\text{Na}_{0.93} \text{Ca}_{0.07})\text{Al}(\text{Si}_{2.93} \text{Al}_{0.07})\text{O}_8]$, the amount of SiO_2 required to balance the reaction was calculated as: $\text{OMPH} + 0.09 \text{Qtz} = 0.54 \text{Na-CPX} + 0.54 \text{PLAG}$. A second pseudosection (referred to in the following as pseudosection 2) was therefore calculated in the model system NCFMASH using a bulk composition obtained by adding 0.09 moles of SiO_2 to the omphacite composition.

Both pseudosections were calculated following the approach of Connolly (1990) using the internally consistent thermodynamic data set and equation of state for H_2O of Holland and Powell (1998, revised 2002). Because epidote was not present in the mineral assemblage and the calculated amount of Fe^{+3} in both omphacite and phengite is very low, Fe_2O_3

TABLE 5. Thermobarometric Estimates of the Peak and Early Retrograde P-T Conditions

	Peak P-T conditions						Retrograde P-T conditions									
	Set 1		Set 2		Set 3		Set 1		Set 2		Set 3		Set 4		Set 5	
Analyses	Omph	Grt	Phe	Omph	Grt	Phe	Omph	Grt	Phe	Omph	Grt	Phe	Omph	Grt	Phe	Omph
	6.1	4.7	2.30	7.7	4.2	1.11	6.2	4.41	4.14	4.19	3.5	4.23	2.3	2.19	4.12	3.21
SiO ₂	56.42	38.35	50.58	56.24	38.53	51.32	56.30	38.37	50.56	57.00	39.29	49.07	56.57	38.72	48.98	56.34
TiO ₂	0.00	0.00	0.41	0.00	0.00	0.51	0.00	0.00	0.51	0.00	0.00	0.75	0.00	0.00	0.50	0.00
Al ₂ O ₃	13.35	21.83	22.56	13.21	21.70	22.81	13.35	21.71	22.76	12.93	21.69	26.89	12.87	21.66	26.34	13.05
FeO	2.35	21.43	1.43	2.45	21.62	1.82	2.55	21.95	1.60	2.84	23.74	2.09	2.72	23.78	1.83	2.84
MnO	0.00	0.68	0.00	0.00	0.68	0.00	0.00	0.56	0.00	0.00	0.54	0.00	0.00	0.45	0.00	0.00
MgO	7.47	6.36	4.61	7.40	6.18	4.64	7.38	6.31	4.62	7.35	6.22	3.36	7.49	6.08	3.59	7.47
CaO	11.97	11.86	0.00	11.83	11.37	0.00	12.02	11.54	0.00	12.36	9.89	0.00	12.25	10.24	0.00	12.20
Na ₂ O	7.82	0.00	0.00	7.85	0.00	0.41	7.84	0.00	0.00	7.82	0.00	0.50	7.73	0.00	0.59	7.69
K ₂ O	0.00	0.00	11.04	0.00	0.00	11.04	0.00	0.00	11.25	0.00	0.00	10.70	0.00	0.00	10.34	0.00
Total	99.38	100.51	90.63	98.98	100.08	92.55	99.44	100.44	91.30	100.30	101.37	93.35	99.63	100.93	92.17	99.59
	1	2	3								1	2	3	4	5	
X _{Na} (Omph)	0.55	0.54	0.54						X _{Na} (Omph)	0.53	0.53	0.53	0.53	0.53	0.52	
X _{Ca} (Grt)	0.31	0.30	0.30						X _{Ca} (Grt)	0.26	0.27	0.27	0.27	0.28	0.27	
Si(Phe)	3.55	3.54	3.53						Si(Phe)	3.36	3.36	3.38	3.40	3.37	3.39	
P (kbar)	38.06	37.58	37.32						P(kbar)	26.76	27.75	28.23	27.37	27.65	27.6 ±0.5	
T(°C)	736	730	729						T(°C)	668	656	659.00	640	666	658 ±11	

TABLE 6. Solid Solution Models and Mixing Parameters Used in the Pseudosection Calculations¹

Phase solution models	End members	References
Omphacite (o) $\text{Na}_{1-y}\text{Ca}_y\text{Mg}_{8xy}\text{Fe}_{(1-x)y}\text{Al}_y\text{Si}_2\text{O}_6$	Diopside $\text{CaMgSi}_2\text{O}_6$ Hedenbergite $\text{CaFeSi}_2\text{O}_6$ Jadeite $\text{NaAlSi}_2\text{O}_6$	Holland and Powell, 1996
Garnet (g) $\text{Fe}_{3x}\text{Ca}_y\text{Mg}_z\text{Mn}_{3(1-x-y-z)}\text{Al}_2\text{Si}_3\text{O}_{12}$ $x + y + z \leq 1$	Spessartine $\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ Almandine $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ Pyrope $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ Grossular $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	Holland and Powell, 1998
Phengite (ph) $\text{K}_x\text{Na}_{1-x}\text{Mg}_y\text{Fe}_z\text{Al}_{3-2(y+z)}\text{Si}_{3+y+z}\text{O}_{10}(\text{OH})_2$	Celadonite $\text{KMgAlSi}_4\text{O}_{10}(\text{OH})_2$ Fe-celadonite $\text{KFeAlSi}_4\text{O}_{10}(\text{OH})_2$ Muscovite $\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$ Paragonite $\text{NaAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$	Holland and Powell, 1998
Amphibole (am/gl) $\text{Ca}_{2-2w}\text{Na}_{x+2w}\text{[Mg}_x\text{Fe}_{1-x}\text{]}_{3+2y+z}\text{Al}_{3-3y-w}\text{Si}_{7+w+y}\text{O}_{22}(\text{OH})_2$ $w + y + z \leq 1$	Tremolite $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ Fe-actinolite $\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ Pargasite $\text{NaCa}_2\text{Mg}_4\text{Al}_3\text{Si}_6\text{O}_{22}(\text{OH})_2$ Tschermakite $\text{Ca}_2\text{Mg}_3\text{Al}_4\text{Si}_6\text{O}_{22}(\text{OH})_2$ Glaucophane $\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$ $\text{fparg}_i = 1 \text{ parg} + 4/5 \text{ ftr} - 4/5 \text{ tr}$ $\text{fts}_i = 1 \text{ ts} + 3/5 \text{ ftr} - 3/5 \text{ tr}$ $\text{fgl}_i = 1 \text{ gl} + 3/5 \text{ ftr} - 3/5 \text{ tr}$	White et al., 2000, 2003 Wei et al., 2003
Plagioclase (pl) $\text{Na}_x\text{Ca}_{1-x}\text{Al}_{2-x}\text{Si}_{2+x}\text{O}_8$	Albite $\text{NaAlSi}_3\text{O}_8$ Anorthite $\text{CaAl}_2\text{Si}_2\text{O}_8$	Newton et al., 1980
Biotite (bt) $\text{KMg}_{(3-w)x}\text{Fe}_{(3-w)y}\text{Mn}_{(3-w)(1-x-y)}\text{Al}_{1+2w}\text{Si}_{3-w}\text{O}_{10}(\text{OH})_2$ $x + y \leq 1$	Annite $\text{KFe}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$ Eastonite $\text{KMg}_2\text{Al}_3\text{Si}_2\text{O}_{10}(\text{OH})_2$ Mn-biotite $\text{KMn}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$ Phlogopite $\text{KMg}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$ $\text{mnts}_i = 1 \text{ east} + 2/3 \text{ mnbi} - 2/3 \text{ phl}$ $\text{sdph}_i = 1 \text{ east} + 2/3 \text{ ann} - 2/3 \text{ phl}$	Powell and Holland, 1999
Chlorite (ch) $\text{Mg}_{(5-y+z)x}\text{Fe}_{(5-y+z)w}\text{Mn}_{(5-y+z)(1-x-w)}\text{Al}_{2(1+y+z)}\text{Si}_{3-y+z}\text{O}_{10}(\text{OH})_8$ $x + w \leq 1$	Clinocllore $\text{Mg}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_4$ Daphnite $\text{Fe}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_4$ Mn-chlorite $\text{Mn}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_4$	Holland et al., 1998

¹mnts = Mn-tschermak; east = eastonite; mnbi = Mn-biotite; phl = phlogopite; sdph = siderophyllite; ann = annite
 fparg = Fe-pargasite; parg = pargasite; ftr = Fe-tremolite; tr = tremolite; fts = Fe-tschermakite; ts = tschermakite; fgl = Fe-glaucophane; gl = glaucophane.

was neglected. The phases considered in the calculation were: garnet, omphacite, phengite, biotite, chlorite, plagioclase, amphibole, kyanite, zoisite, quartz, and coesite. Solid-solution models and mixing parameters used for garnet, omphacite, phengite, biotite, chlorite, plagioclase, and amphibole are briefly described in Table 6. In both pseudosections, H_2O was treated as a perfectly mobile or satu-

rated component. Pseudosection 1, used to model peak metamorphic conditions and the first part of the exhumation path, was calculated at both $a\text{H}_2\text{O} = 1.0$ and reduced water activities. The pseudosection obtained at $a\text{H}_2\text{O} = 0.5$ shows, at least for peak conditions, the best correspondence between measured and modeled data. A reduced water activity at peak conditions was also suggested by Kienast et al.

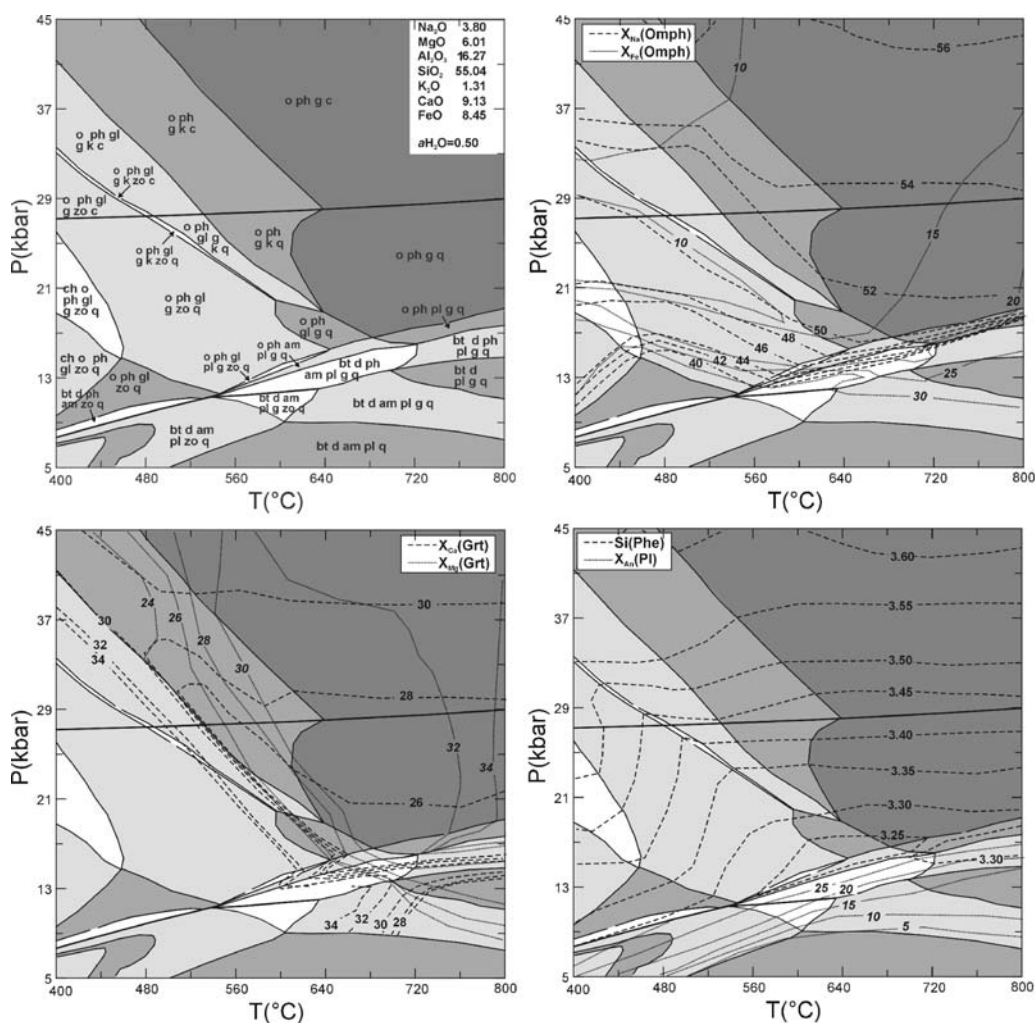


FIG. 11. A. P-T pseudosection for eclogite Br2F calculated at $a\text{H}_2\text{O} = 0.5$ in the NKCFMASH system, using the bulk rock composition reported in the top right inset. White, light grey, medium grey, and dark grey fields are di-, tri-, quadri-, and five-varient fields, respectively. B. X_{Na} ($[\text{Na}/(\text{Na}+\text{Ca}) \cdot 100]$) and X_{Fe} ($[\text{Fe}/(\text{Fe}+\text{Mg}) \cdot 100]$) isopleths for omphacite. C. X_{Ca} ($[\text{Ca}/(\text{Ca}+\text{Mg}+\text{Fe}) \cdot 100]$) and X_{Mg} ($[\text{Mg}/(\text{Mg}+\text{Fe}) \cdot 100]$) isopleths for garnet. D. Si (a.p.f.u.) isopleths for phengite and X_{An} ($[\text{Ca}/(\text{Ca}+\text{Na}) \cdot 100]$) isopleths for plagioclase [am = Na-Ca amphibole; bt = biotite; c = coesite; d = diopside; g = garnet; gl = glaucophane; k = kyanite; o = omphacite; ph = phengite; pl = plagioclase; q = quartz; zo = zoisite].

(1991) and Sharp et al. (1993) for BIU eclogite and whiteschist, respectively. Due to the occurrence of Ca-Na amphibole in the late symplectite after omphacite, pseudosection 2 will be discussed at both $a\text{H}_2\text{O} = 1.0$ and $a\text{H}_2\text{O} = 0.5$.

Peak and early retrogression

Results of pseudosection 1. The peak metamorphic conditions and the first portion of the exhumation

history were modelled by pseudosection 1 in the P-T range 5–45 kbar and 400–800 °C (Fig. 11), using the bulk rock composition previously discussed. A detail of this pseudosection was calculated in the P-T range 5–20 kbar and 500–750 °C (Fig. 12), in order to better model the eclogite exhumation path. The resulting P-T pseudosection is dominated by di-, tri-, and four-varient fields, with only two five-varient fields. In the high pressure

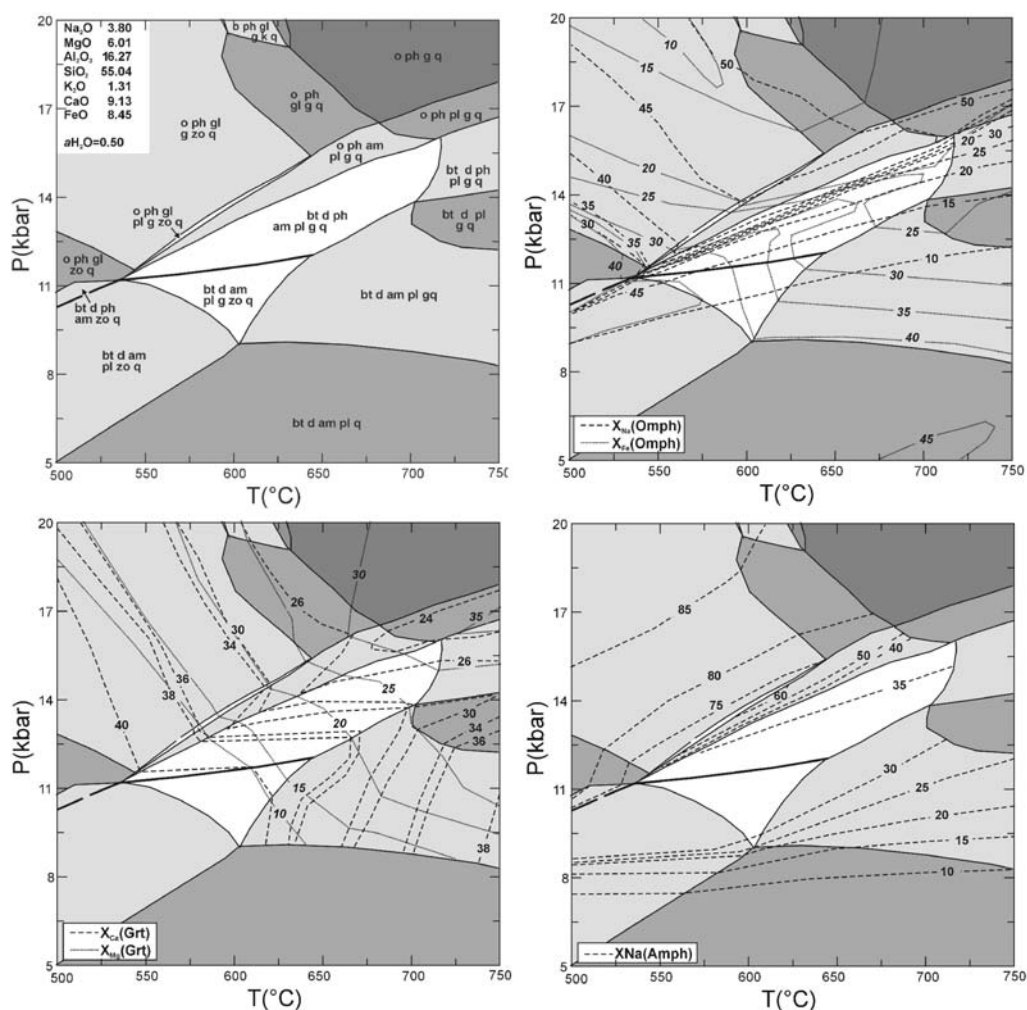


FIG. 12. A. Detail of the P-T pseudosection reported in Figure 11. B. X_{Na} [$Na/(Na+Ca)*100$] and X_{Fe} [$Fe/(Fe+Mg)*100$] isopleths for omphacite. C. X_{Ca} [$Ca/(Ca+Mg+Fe)*100$] and X_{Mg} [$Mg/(Mg+Fe)*100$] isopleths for garnet. D. X_{Na} [$Na/(Na+Ca)*100$] isopleths for glaucophane and Na-Ca amphibole. Mineral abbreviations are the same as those in Figure 11.

portion of the pseudosection (20–45 kbar) three eclogite assemblages are stabilized: i.e., at high T a Phe-bearing eclogite, at medium T a Phe-Ky-bearing eclogite, and at low T a Phe-Gl-Zo-bearing eclogite.

The mineral assemblage Omph + Grt + Phe + Qtz/Cs corresponds to the two five-variant fields of the pseudosection (Fig. 11). Within these two five-variant fields, the location of X_{Na} (Omph), X_{Fe} (Omph), X_{Ca} (Grt), X_{Mg} (Grt), and Si(Phe) isopleths are consistent with the observed mineral composition and zon-

ing. In the Pl-absent fields, the jadeite content of omphacite progressively decreases from $X_{Jd} = 0.56$ to $X_{Jd} = 0.50$ as pressure decreases; omphacite with $X_{Jd} < 0.50$ coexists with oligoclase within narrow di- and tri-variant fields at intermediate pressures between the Pl-absent and the Omph-absent fields. In omphacite the Fe/(Fe+Mg) ratio is T-dependent at pressures greater than 20 kbar, whereas it becomes P-dependent at lower pressures.

In garnet the grossular content shows the same trend as the content of jadeite in omphacite,

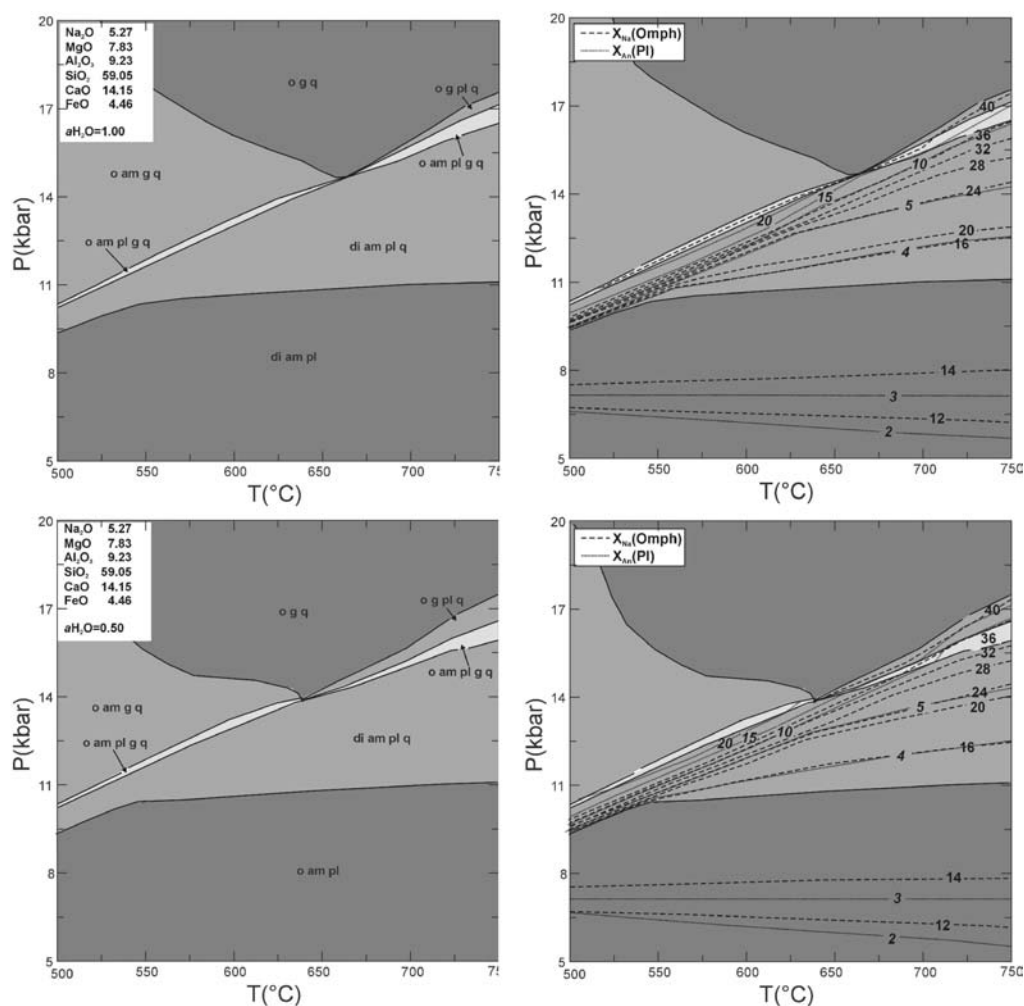


FIG. 13. A. P-T pseudosection calculated at $a_{\text{H}_2\text{O}} = 1.0$ in the NCFMASH system, using the bulk composition obtained by adding 0.09 moles of SiO_2 to the omphacite composition (top left inset). Light grey, medium grey, and dark grey fields are tri-, four-, and five-variant fields, respectively. B. $X_{\text{Na}}[\text{Na}/(\text{Na}+\text{Ca}) \cdot 100]$ isopleths for omphacite and $X_{\text{An}}[\text{Ca}/(\text{Ca}+\text{Na}) \cdot 100]$ isopleths for plagioclase. C. P-T pseudosection calculated at $a_{\text{H}_2\text{O}} = 0.5$ in the NCFMASH system, using the same composition as in A. D. $X_{\text{Na}}[\text{Na}/(\text{Na}+\text{Ca}) \cdot 100]$ isopleths for omphacite and $X_{\text{An}}[\text{Ca}/(\text{Ca}+\text{Na}) \cdot 100]$ isopleths for plagioclase. Mineral abbreviations are the same as those in Figure 11.

decreasing progressively from $X_{\text{Ca}} = 0.30$ to $X_{\text{Ca}} = 0.26$ as pressure decreases. In the plagioclase stability fields, the $X_{\text{Ca}}(\text{Grt})$ isopleths invert their trend and indicate that a Grs-rich garnet becomes more stable at low pressures. In garnet the $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio is temperature dependent only in the Pl-absent field, whereas in Pl-bearing fields it is P-dependent. The maximum and minimum Si contents in phengite stabilized in the P-T pseudosection are $\text{Si} = 3.60$

a.p.f.u. (on the basis of 11 oxygens) at about 45 kbar and $\text{Si} = 3.25$ a.p.f.u. at about 16 kbar, respectively.

The $X_{\text{Ca}}(\text{Pl})$ isopleths suggest that the first plagioclase formed along the decompression path is oligoclase, with X_{An} ranging from 0.30 to 0.20. In plagioclase, the Ca content progressively decreases with decreasing pressure toward pure albite. Two different types of amphibole are stable in the P-T pseudosection: Na-amphibole (X_{Na} from 0.75 to

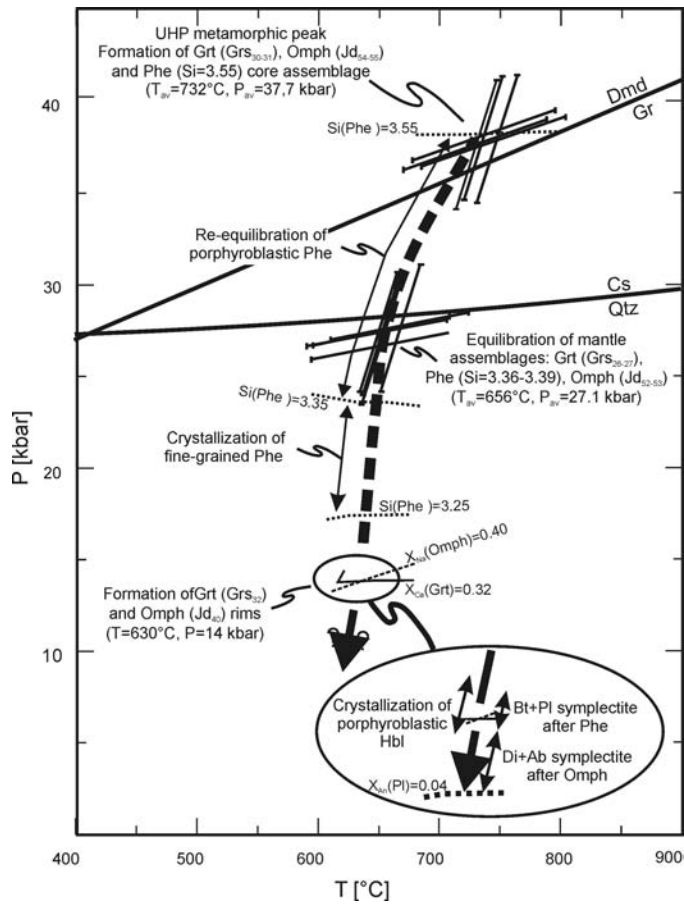


FIG. 14. P-T path of the eclogite Br2F as inferred from the pseudosection analysis and thermobarometric data. P-T estimates for the peak and early retrograde events, obtained by the thermobarometric method of Krogh Ravna and Terry (2004), are reported with the error bars suggested by Krogh Ravna and Terry. An additional constraint is given by the intersection point between the $X_{\text{Na}}(\text{Omph}) = 0.40$ and $X_{\text{Ca}}(\text{Grt}) = 0.32$ isopleths, which model the omphacite and garnet rim compositions, respectively.

0.90) is modeled in the plagioclase-absent fields, whereas Ca-Na amphibole (X_{Na} from 0.50 to 0.10) is modeled in the plagioclase stability field.

Discussion. The topology of the P-T pseudosection and the patterns of the Omph, Grt, Phe, Pl, and Amph isopleths closely constrain the peak and early retrogressive pressure conditions of the studied eclogite, but give only loose temperature constraints. The maximum X_{Jd} , X_{Grs} , and Si contents measured in omphacite, garnet, and phengite respectively, suggest peak metamorphic pressures of 35–40 kbar on the basis of the modelled P-T pseudosection. These estimates are in agreement with the thermobarometric data previously discussed

(see Fig. 14), obtained using compositions of garnet, omphacite, and phengite cores (average $T = 732^{\circ}\text{C}$, average $P = 37.7$ kbar, see point 1 in Fig. 15).

Thermobarometric estimates obtained from garnet, omphacite, and phengite mantle compositions indicate average P-T conditions of $T = 656^{\circ}\text{C}$ and $P = 27.1$ kbar for the earlier decompressional path (Table 5; see Fig. 14); this result is consistent with the modeled isopleths (see point 2 in Fig. 15). An additional constraint along the exhumation P-T path can be obtained by considering the compositions of rim omphacite and garnet. These compositions are, in fact, modeled in the pseudosection and the intersection between the $X_{\text{ca}}(\text{Grt}) = 0.30$ and the

$X_{\text{Na}}(\text{Omph}) = 0.40$ isopleth occurs at $T = 630^\circ\text{C}$ and $P = 14$ kbar (see point 3 in Fig. 15).

On the basis of the calculated P-T pseudosection and using the three points previously discussed, the following conclusions may be drawn for the eclogite Br2F:

1. Metamorphic peak occurred at $P = 37.7 \pm 0.4$ kbar and $T = 732 \pm 4^\circ\text{C}$ —i.e., in the diamond stability field, the paragenesis being omphacite ($X_{\text{Jd}} = 0.55$), garnet ($X_{\text{GrS}} = 0.30\text{--}0.32$), phengite ($\text{Si} = 3.55$ a.p.f.u.), rutile, and coesite.

2. Early decompression was accompanied by a temperature decrease of about 80°C from $P = 37.7$ kbar to $P = 27.1$ kbar. During this part of the P-T path the peak assemblage remained stable, but cation exchanges were active, resulting in a significant zoning of omphacite, garnet, and phengite. At pressure of about 27 kbar (see point 2 in Fig. 15), i.e. approximately at the coesite-quartz transition, porphyroblastic phengite ceased to re-equilibrate and a new generation of fine-grained phengite crystallized. At this time, both garnet and omphacite continued to re-equilibrate as a function of decreasing temperature and pressure.

3. At about 14 kbar, metamorphic reactions ceased to be continuous and became discontinuous, as evident from pseudosection 2 (Fig. 13). Evidence for discontinuous reactions is the development—at about 14 kbar and 630°C —of thin rims around omphacite and garnet, which are characterized, respectively, by abrupt decrease in jadeite content and by abrupt increases in grossular and almandine contents. Unlike the gradual and continuous zoning from core to mantle of both omphacite and garnet, mantle-rim boundary is sharp. At the same time, the porphyroblastic amphibole started to grow, probably at the expense of omphacite, garnet, and phengite, according to a reaction such as: $\text{Omph1} + \text{Grt1} + \text{Phe1} = \text{Amph} + \text{Omph2} + \text{Grt2} + \text{Phe2}$, where Omph1, Grt1, and Phe1 are zoned minerals of the eclogitic assemblage and Omph2, Grt2, and Phe2 are the late rim compositions of the same phases. Approximately at this time, phengite started to be replaced by a biotite + oligoclase symplectite.

4. At pressures just below 14 kbar, omphacite was replaced by the Na-clinopyroxene + albite symplectite (see pseudosection 2).

5. The P-T path resulting from the above considerations would pass through the small four-variant omphacite + phengite + glaucophane + garnet + quartz field, in which an amount of 2.6 vol% of glaucophane with $X_{\text{Na}} = 0.80\text{--}0.85$ has been modeled in

the pseudosection. However, glaucophane has not been identified either in eclogite Br2F or in other eclogites from the same unit (Kienast et al., 1991; Nowlan, 1998; Nowlan et al., 2000). The absence of glaucophane in eclogite Br2F could be due to the fact that: (a) the rock did not have sufficient time to equilibrate in this narrow P-T field; and (b) the position of the omphacite + phengite + glaucophane + garnet + quartz field is strongly affected by modeling of glaucophane in the amphibole solid solution.

Na-clinopyroxene + albite symplectite after omphacite

Results of pseudosection 2. To model the Na-clinopyroxene + albite symplectite after omphacite, a second pseudosection (pseudosection 2) was calculated in the model system NCFMASH using the bulk composition previously discussed, in the P-T range 5–20 kbar and $500\text{--}750^\circ\text{C}$ at two different water activities ($a_{\text{H}_2\text{O}} = 1.0$ and $a_{\text{H}_2\text{O}} = 0.5$) (Fig. 13). The resulting P-T pseudosection consists of two five-variant, four-variant, and two tri-variant fields. The observed symplectite assemblage consisting of Na-clinopyroxene + albite $\pm$ amphibole $\pm$ quartz corresponds to the five-variant field occurring in the pressure interval 10–16 kbar.

The $X_{\text{Ca}}(\text{Pl})$ isopleths are pressure dependent and range from $X_{\text{An}} = 0.20$ at $P = 15$ kbar to $X_{\text{An}} = 0.04$ at $P = 10$ kbar. The Na content in clinopyroxene strongly decreases with decreasing pressure, from $X_{\text{Na}} = 0.40$ at $P = 15$ kbar to $X_{\text{Na}} = 0.15$ at $P = 10$ kbar. At reduced water activity ($a_{\text{H}_2\text{O}} = 0.5$), the topology of the pseudosection and the position of the clinopyroxene and garnet isopleths do not change significantly.

Discussion. Combining the measured composition of clinopyroxene and plagioclase in the symplectite [$X_{\text{Na}}(\text{Cpx})$ from 0.23 to 0.13 and $X_{\text{Ca}}(\text{Pl})$ from 0.10 to 0.04] with the P-T pseudosection data, it can be concluded that the symplectite grew at pressures of 10–13 kbar, i.e., later than the growth of the porphyroblastic Na-Ca amphibole at about 14 kbar. Because the isopleths of both clinopyroxene and plagioclase are essentially independent of temperature, it cannot be constrained (see also Štířská and Powell, 2005). As previously discussed, Na-clinopyroxene in the symplectite is zoned, showing a more diopsidic composition at the contact with quartz. This zoning could be modeled assuming a bulk composition locally richer in SiO_2 , which results in a shift of the $X_{\text{Na}}(\text{Cpx})$ isopleths toward higher pressures. In conclusion, the symplectite

development is the lowest-P metamorphic event recorded by the eclogite Br2F.

Discussion: Comparison with P-T Conditions Previously Estimated for the BIU

P-T estimates obtained using thermobarometric methods and the pseudosection analysis are summarized in Figure 14, which details the proposed decompressional P-T path from peak conditions to ~12 kbar. Estimated average peak metamorphic conditions are $P = 37.7$ kbar and $T = 732^{\circ}\text{C}$. The decompressional P-T path followed by the studied eclogite involves cooling from about 730°C at 38 kbar to 630°C at 14 kbar (Fig. 14). During the earliest exhumation history, the minerals of the peak assemblage gradually changed composition, resulting in a continuous zoning (Fig. 14). At about 15 kbar, the metamorphic reactions became discontinuous and the mineral assemblage abruptly changed: porphyroblastic amphibole grew at the expense of omphacite and garnet, and a new discontinuous rim in both garnet and omphacite developed outside amphibole porphyroblasts (Fig. 14). Phengite and omphacite were replaced by biotite + oligoclase and clinopyroxene + albite symplectites, respectively.

Peak and retrogressive metamorphic conditions of the BIU, discussed by several authors who used different approaches and model chemical systems, are summarized in Table 7 and Figure 15. The mafic system of the BIU was studied in detail by Kienast et al. (1991), Nowlan et al. (2000), and Chopin and Schertl (2000). In these works, the P-T conditions were estimated on the basis of different thermobarometers applied to unaltered omphacite, garnet, and phengite. Symplectite intergrowths after omphacite and/or phengite were never used to model the decompressional P-T path.

Kienast et al. (1991), from phase relations and the garnet-omphacite (Ellis and Green, 1979) and the garnet-phengite (Green and Hellman, 1982) thermometers, obtained peak conditions of 26–28 to 35 kbar and 680–750°C for eclogites from the BIU. They also suggested that, at peak conditions, the water activity was lower than unity. Nowlan et al. (2000) and Chopin and Schertl (2000) studied in detail several eclogite samples. Their P-T peak estimates were obtained using the Grt–Cpx–Phe geobarometer of Waters and Martin (1993) coupled with the Grt–Cpx geothermometer applied to the rim compositions of matrix phengite and omphacite. In

TABLE 7. Literature Peak and Retrogression P-T Estimates for the BIU

	System	Peak	Retrogression
Schertl et al., 1991	Whiteschist	35 kbar; 800°C	5 kbar; 500°C
Kienast et al., 1991	Eclogite	27–35 kbar; 680–750°C	
Compagnoni et al., 1995	Whiteschist/eclogite	33 kbar; 750°C	
Nowlan, 1998	Eclogite	36 kbar; 720°C	14 kbar; 620°C
Nowlan et al., 2000	Eclogite	36 kbar; 720°C	14 kbar; 620°C
Chopin and Schertl, 2000	Eclogite	38 kbar; 740°C	14 kbar; 620°C
Rubatto and Hermann, 2001	Calc-silicate in marble	35 kbar; 760°C	10 kbar; 550°C
Hermann, 2003	Whiteschist	43 kbar; 730°C	11 kbar; 600°C
Castelli et al., 2004	Marble	39 ± 0.1; 720–730°C	
Groppo et al., 2006	Metapelite	40 kbar; 745°C	10.0–10.6 kbar; 580–590°C

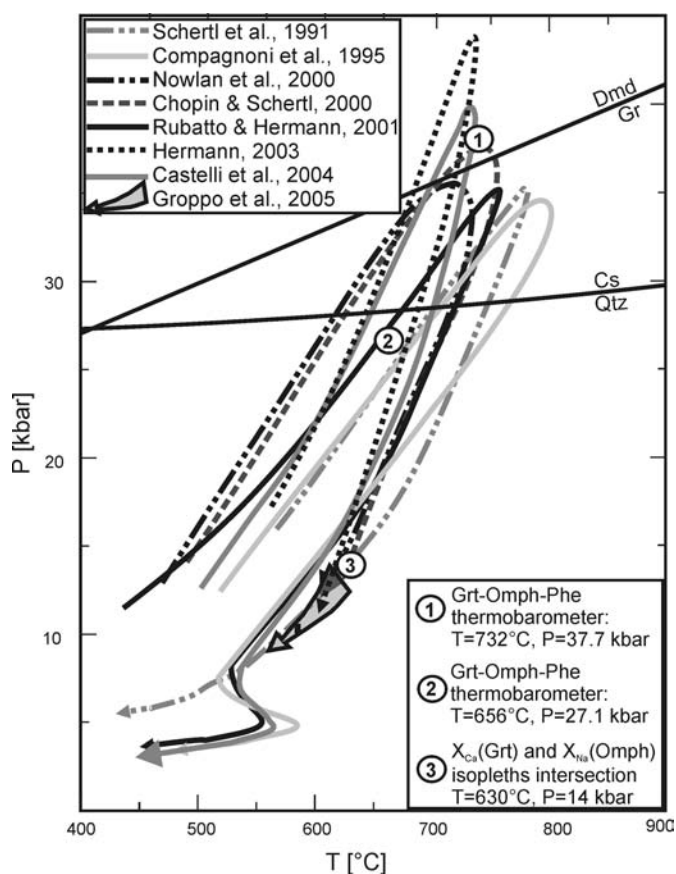


FIG. 15. Comparison between the P-T path modelled for eclogite Br2F (shown by the three piercing points, see text for explanation) and that obtained by Nowlan et al. (2000) from a study of several eclogite bodies of the entire BIU. The BIU paths obtained from other lithologies by Schertl et al. (1991), Compagnoni et al. (1995), Chopin and Schertl (2000), Rubatto and Hermann (2001), Hermann (2003), Castelli et al. (2004), and Groppo et al. (2006) are also shown. Points 1 and 2 represent average P-T conditions obtained from thermobarometry on garnet-, omphacite- and phengite core and mantle, respectively.

their P-T path, resulting from the interpolation of widely scattered P-T points, Nowlan et al. (2000) described three main stages: a prograde stage (I) at 25 kbar and 570°C; a peak stage (II) at 36 kbar and 720°C; and a retrograde stage (III) at 24 kbar and 680°C. The P-T path proposed by Chopin and Schertl (2000) on the base of the data of Nowlan (1998) only differs for slightly higher peak conditions (38 kbar and 740°C). The decompressional path connecting stage II and stage III is characterized by moderate cooling.

Peak conditions were estimated by Kienast et al. (1991), Schertl et al. (1991), and Compagnoni et al. (1995) from whiteschists and by Rubatto and Hermann (2001) from a calc-silicate nodule in a

marble. Their peak estimates lie outside the diamond stability field, whereas more recent data of Hermann (2003) and Castelli et al. (2004) from whiteschist, and marble, respectively, suggest that BIU experienced peak pressures within the diamond stability field.

The exhumation P-T path of the BIU was constrained by Rubatto and Hermann (2001) using geochronological and mineral data from a calc-silicate nodule in marble. They recognized an initial stage of rapid exhumation from 35 to 10 kbar, followed by a second stage of decompression and slight heating from 10 to 5 kbar (Fig. 15). A later stage of slower exhumation was coupled with cooling to 250°C. The exhumation path of the BIU from

about $T = 700^{\circ}\text{C}$ at $P = 18$ kbar to $T = 500^{\circ}\text{C}$ at $P = 6$ kbar was also constrained by Groppo et al. (2006), who applied the pseudosection analysis to a late chloritoid + staurolite assemblage in a metapelite from the polymetamorphic complex of the BIU unit.

Comparing our results from eclogite Br2F with earlier P-T estimates (Fig. 15), the peak metamorphic conditions inferred from the P-T pseudosection calculated for Br2F are in agreement with the experimental results of Hermann (2003) and the thermobarometric estimates of Castelli et al. (2004), both suggesting diamond-eclogite facies conditions. The retrograde P-T path obtained from Br2F is in agreement with the P-T path given by Hermann (2003) and Castelli et al. (2004), the only difference being slightly lower peak pressure conditions (Fig. 15). The P-T paths proposed by Schertl et al. (1991), Compagnoni et al. (1995), Nowlan et al. (2000), Chopin and Schertl (2000), and Rubatto and Hermann (2001) are all characterized by the most rapid cooling rates during decompression, because of the higher peak temperatures. Nevertheless, the last portion of our P-T trajectory, calculated on the basis of the composition of garnet and omphacite discontinuous rims, porphyroblastic amphibole, and Na-clinopyroxene + albite symplectite after omphacite, is consistent with the data of Schertl et al. (1991), Nowlan et al. (2000), and Chopin and Schertl (2000). Our trajectory is also consistent with the P-T path proposed by Groppo et al. (2006), this latter being an approximation to the lower P-T portion of the path recorded in the BIU (Fig. 15).

Acknowledgments

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