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Paragonite eclogites from Dabie Shan, China: re-equilibration during exhumation?

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ABSTRACT Paragonite in textural equilibrium with garnet, omphacite and kyanite is found in two eclogites in the ultrahigh-pressure metamorphic terrane in Dabie Shan, China. Equilibrium reactions between paragonite, omphacite and kyanite indicate a pressure of about 19 kbar at *c.* 700° C. However, one of the paragonite eclogites also contains clear quartz pseudomorphs after coesite as inclusions in garnet, suggesting minimum pressures of 27 kbar at the same temperature. The disparate pressure estimates from the same rock suggest that the matrix minerals in the ultrahigh-pressure eclogites have recrystallized at lower pressures and do not represent the peak ultrahigh-pressure assemblages. This hypothesis is tested by calibrating a garnet + zoisite/clinozoisite + kyanite + quartz/coesite geobarometer and applying it to the appropriate eclogite facies rocks from ultrahigh- and high-pressure terranes. These four minerals coexist from 10 to 60 kbar and in this wide pressure range the grossular content of garnet reflects the equilibrium pressure on the basis of the reaction zoisite/clinozoisite = grossular + kyanite + quartz/coesite + H_2O. The results of the geobarometer agree well with independent pressure estimates from eclogites from other orogenic belts. For the paragonite eclogites in Dabie Shan the geobarometer indicates pressures in the quartz stability field, confirming that the former coesite-bearing paragonite–eclogite has re-equilibrated at lower pressures. On the other hand, garnets from other coesite-bearing but paragonite-free kyanite–zoisite eclogites show a very wide variation in grossular content, corresponding to a pressure variation from coesite into the quartz field. This wide variation, partly due to a rimward decrease in grossular component in garnet, is caused by partial equilibration of the mineral assemblage during the exhumation.

Key words: China; coesite; eclogite; geobarometer; paragonite.

INTRODUCTION

The burial of continental crust to depths of over 100 km and its subsequent exhumation during orogeny constitutes one of the significant recent discoveries in geology. The evidence for this process is largely the presence of ultrahigh-pressure minerals, coesite and diamond, as inclusions in silicates in metamorphic rocks (e.g. Chopin, 1984; Smith, 1984; Okay *et al.*, 1989; Wang *et al.*, 1989; Sobolev & Shatsky, 1990; Reinecke, 1991; Xu *et al.*, 1992; Caby, 1994). In the absence of these minerals, the estimation of ultrahigh-pressure conditions is based on the mineral assemblages and mineral compositions in eclogite facies rocks. An important question in this context is to what extent do the mineral assemblages and compositions in coesite-bearing eclogites reflect the ultrahigh pressures. The relevance of this question was brought up by the discovery of coarse paragonite crystals in apparent textural equilibrium with omphacite and garnet in a kyanite eclogite from Dabie Shan, China; garnet from the same rock also contains quartz pseudomorphs after coesite as inclusions. A similar paragonite eclogite with coesite as inclusions in garnet was recently described from west of Dabie Shan in the Henan province (Zhang & Liou, 1994). These eclogites contain evidence for two distinctly separate metamorphic pressures in the eclogite facies. Another paragonite eclogite in Dabie Shan does not contain coesite or its pseudomorphs, and in this case it is not clear whether this rock has been to the coesite field or not. Here, I describe these paragonite eclogites from Dabie Shan, and interpret the coexistence of coesite and paragonite in the rock. In the second part of the paper a new geobarometer involving zoisite/clinozoisite–garnet–kyanite–quartz/coesite is applied to a suite of rocks from Dabie Shan and other eclogite facies terranes to determine the extent of the equilibration in the eclogite facies during the exhumation.

PARAGONITE ECLOGITES FROM DABIE SHAN, CHINA

Geological setting

The Dabie Shan region in central China comprises probably the largest tract of ultrahigh-pressure metamorphic rocks in the world. These ultrahigh-pressure metamorphic rocks occur in a crystalline tectonic slice, termed the eclogite zone, which is sandwiched between

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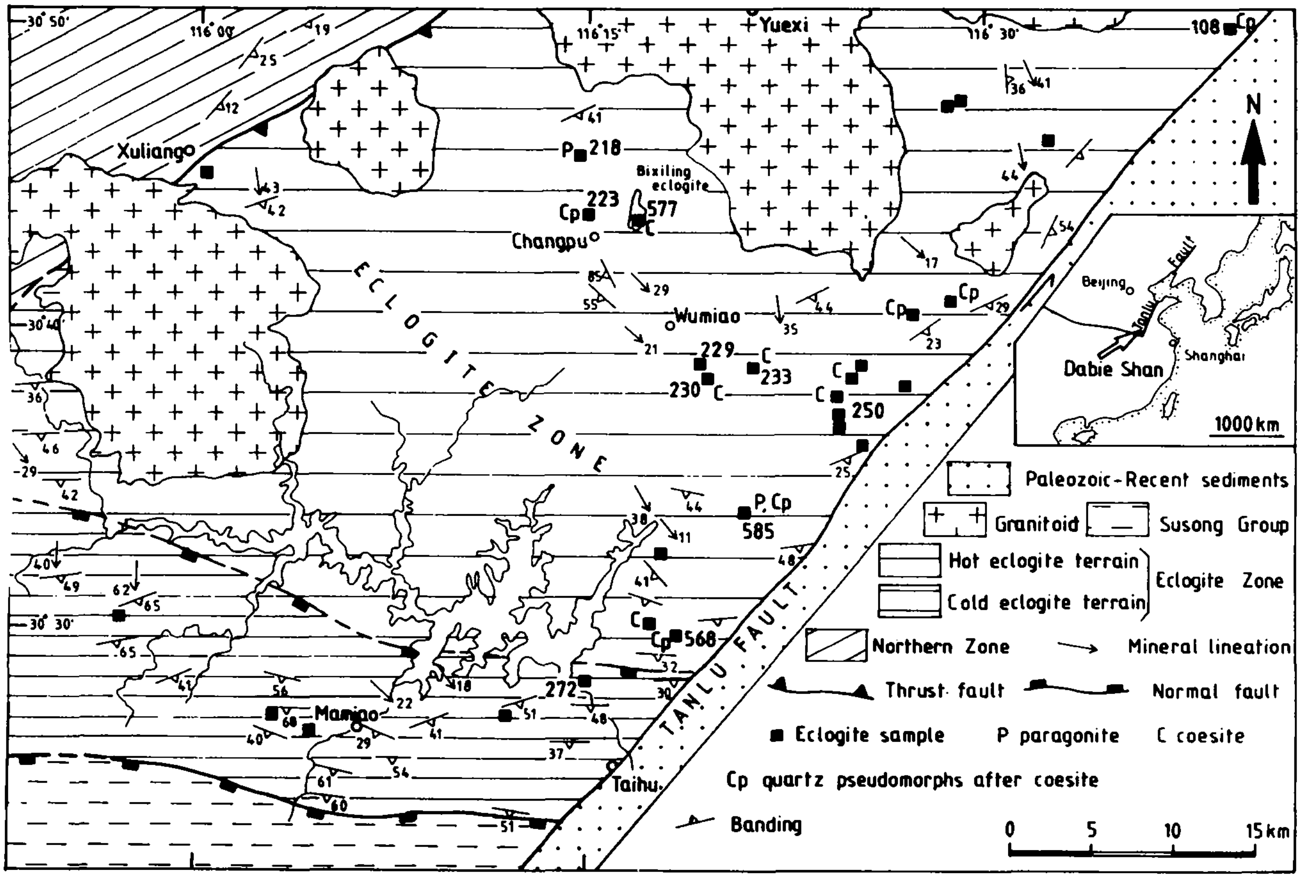

Fig. 1. Geological map of part of the Dabie Shan region showing the locations of eclogite samples. The numbers denote the eclogites described here and in Okay (1993). Letters P and C indicate paragonite- and coesite-bearing eclogites, respectively.

two amphibolite facies gneiss slices (the Northern Zone and the Susong Group of Fig. 1, Okay *et al.*, 1993). The eclogite zone consists mainly of felsic gneiss with a large number of eclogite bands and boudins. There are also rare marble bands with Ca-rich eclogite layers and blocks, and small ultramafic lenses. The structure of the eclogite zone is dominated by a consistent S- to SE-dipping compositional layering and a S- to SE-plunging mineral lineation. Isoclinal folds locally with isolated fold hinges have completely transposed the layering so that the apparent thickness of the eclogite zone is over 20 km.

Coesite occurs widely in certain regions in the eclogite zone as inclusions in garnet, clinopyroxene and dolomite (Fig. 1, Okay *et al.*, 1989; Wang *et al.*, 1989; Schertl & Okay, 1994). Diamond as inclusions in garnet is much rarer and is reported only in a very few localities (Xu *et al.*, 1992). Based on the absence of coesite inclusions in the southern sector of the eclogite zone, Okay (1993) distinguished an upper 'cold eclogite terrane' without coesite but with glaucophane-bearing eclogites in the south, which tectonically overlies the coesite-bearing 'hot eclogite terrane' in the north (Fig. 1). On the other hand, Wang *et al.* (1992) have claimed that in the eclogite zone there is a progressive southward decrease in the metamorphic grade.

Two lenses of paragonite–kyanite-bearing eclogite are found in the gneisses of the 'hot eclogite terrane' (Fig. 1). The first paragonite eclogite (sample 218C) occurs north of Changpu structurally at the base of the eclogite zone. It forms a 1.5-m-thick eclogite band surrounded by felsic gneiss. The eclogite band also contains a 3-cm-thick, continuous gneissic layer of quartz, phengite, clinozoisite, garnet, kyanite and rutile (sample 218A). A large, coesite-bearing eclogite–ultramafic lens, the Bixiling body, occurs 4 km to the south-east and structurally 2.8 km above this paragonite eclogite (Fig. 1). The second paragonite eclogite (585) is a 14-m-thick, banded eclogite in the felsic gneiss. The banding is characterized by alternating 1–40-cm-thick layers rich in garnet + quartz + zoisite/clinozoisite and garnet + omphacite. The eclogite also contains 'nests' several centimetres across of coarse idioblastic zoisite and quartz. Coesite-bearing eclogites occur structurally both above and below this paragonite eclogite (Fig. 1).

Analytical method

Mineral compositions were analysed for 12 elements with an SX-50 Cameca electron microprobe using wavelength-dispersive spectrometers. Operating conditions were generally 15-kV accelerating voltage, 15-nA beam current and 10-μm beam size. Mica analyses were obtained using a lower beam current (10 nA) and a larger beam size.

The structural formulae for sodic pyroxene were calculated on the basis of four cations. The jadeite component is taken to be equal to Al^{VI}, the aegirine component equals Na–Al^{VI}–Ti–Cr. The rest is assigned to the augite component. The ferric ion in amphibole was estimated assuming Σ Si, Ti, Al, Cr, Fe^{3+}, Fe^{2+}, Mg, Mn = 13.00, and a total ionic charge of 46.

Petrography and mineral chemistry

The paragonite eclogites consist of garnet, omphacite, kyanite, zoisite/clinozoisite, colourless amphibole, phengite, paragonite, quartz and rutile, which texturally form an equilibrium assemblage. The secondary minerals include bluish-green amphibole, margarite, plagioclase and symplectites after omphacite, phengite and paragonite; the estimated modal amounts and representative compositions are given in Tables 1 and 2, respectively.

Eclogite sample 585 has a granoblastic texture dominated by *c.* 0.5-mm-large idioblastic garnet grains. Garnet ($grs_{22}alm_{48}prp_{29}sps_1$) contains rare phengite, colourless amphibole and quartz inclusions. One garnet grain has a 0.03-mm inclusion of polycrystalline feathery quartz with radial cracks in garnet around the inclusion (Fig. 2a). Such quartz inclusions are characteristic for the former presence of coesite in the rock (e.g. Chopin, 1984; Gillet *et al.*, 1984). Omphacite ($jd_{43}aug_{44}aeg_{13}$, Fig. 3b) is almost completely replaced by a very fine-grained dark symplectite of diopside and plagioclase. Both zoisite (X_{Ps} = Fe/(Fe + Al) = 0.03–0.08) and clinozoisite (X_{Ps} = 0.11–0.19) are present in apparent mutual equilibrium, forming coarse prismatic crystals with garnet, omphacite and quartz inclusions (Fig. 2a,c). A systematic compositional gap between coexisting zoisite and clinozoisite (e.g. Enami & Banno, 1980; Franz & Selverstone, 1992) is supported by the compositions of adjoining zoisite (X_{Ps} = 0.05) and clinozoisite (X_{Ps} = 0.14) crystals (Fig. 4). Kyanite as a primary phase occurs as up to 1-mm crystals with late albite rims (Fig. 2a); it is generally associated with zoisite and mica. Paragonite forms up to 1-mm grains partially to completely replaced by very fine-grained dark albite (an_1) + Al_2SiO_5 (most probably kyanite) symplectites with minor muscovite and biotite, as determined by the electron probe analysis (Fig. 2c,d); such symplectites after paragonite have to my knowledge not been described before. Paragonite is close to end-member composition with 4–7% muscovite and 1–4% margarite components (Fig. 3d, Table 2). The coexisting phengite with a maximum Si per formula unit (p.f.u.) of 3.55 has 4–8% paragonite and up to 1% margarite component. In contrast to the highly asymmetric solvus between muscovite and paragonite which allows 58 mol% paragonite substitution in muscovite at 700° C and 7 kbar (Chatterjee & Flux 1986; Guidotti *et al.*, 1994), the phengite–paragonite solvus at the same temperature but at 19 kbar appears to be symmetric with only 5–10% substitution of each end-member (Fig. 3d). Phengite is partially replaced by a symplectite of brown to green biotite + plagioclase and is thus easily distinguished from paragonite. Colourless amphibole of an intermediate composition between glaucophane and magnesio-hornblende (Table 2, Fig. 3c) forms poikiloblastic grains enclosing garnet. Quartz is a common interstitial phase and also occurs as inclusions in zoisite, clinozoisite, kyanite and garnet.

Table 1. Estimated modal amounts of the analysed eclogite facies rock from Dabie Shan, China. The numbers in parentheses indicate the modes of plagioclase + diopside symplectite in the omphacite line, biotite + plagioclase symplectite in the phengite line, and kyanite + albite symplectite in the paragonite line.

	Paragonite eclogite		Kyanite gneiss			Coesite eclogite	
	218C	585	218A	250G	577I	577L	108F
Garnet	19	43	21	5	13	51	43
Omphacite	3 (37)	1 (10)	–	1 (4)	2 (14)	35	36 (2)
Kyanite	4	4	6	6	7	1	1
Amphibole	3	3	–	2	–	–	–
Zoisite	–	11	–	51	17	3	–
Clinozoisite	13	6	8	–	–	–	1
Phengite	3 (1)	3 (2)	18	4	tr.	1	2 (1)
Paragonite	2	1 (2)	–	–	–	–	–
Quartz	8	14	46	26	47	7	12
Coesite	–	tr., p.	–	–	–	tr.	tr., p.
Rutile	1	1	1	1	2	1	2
Opaque	–	tr., ilm.	–	–	tr., py.	1, py.	–
Late amph.	2	tr.	4	tr.	tr.	–	–
Total	100	100	100	100	100	100	100

p denotes pseudomorphs after coesite. All samples contain trace amounts of zircon and apatite, additionally sample 218C contains trace amounts of secondary margarite, tr. $<1\%$; ilm., ilmenite; py., pyrite.

The second eclogite sample (218C) has a strongly banded and schistose texture defined by the parallel aligned elongate clinozoisite (X_{Fe} = 0.12–0.19, Fig. 4) and omphacite ($jd_{46}aug_{50}aeg_4$, Fig. 3b) grains, and by millimetre-thick quartz layers (Fig. 2b). Garnet ($grs_{20}alm_{51}prp_{30}$) forms 0.5–1.0-mm poikiloblasts with clinozoisite, omphacite, phengite, amphibole, quartz and rutile inclusions. It shows a slight zoning involving a minor decrease in grossular at the expense of almandine and pyrope components towards the rim. However, the compositional variation among the garnet grains in the probe section is greater than the variation introduced by zoning (Fig. 3a). Paragonite forms up to 1-mm grains associated with phengite (max. Si p.f.u. of 3.42) and kyanite (Fig. 2b). Kyanite is frequently partially replaced by globular aggregates of margarite (Fig. 2b), a retrograde feature common in ultrahigh-pressure eclogites in Dabie Shan and Dora Maira (e.g. Schertl *et al.*, 1991; Wang *et al.*, 1992; Zhang & Liou, 1994) and in the high-pressure metasediments in the Tauern Window (Spear & Franz, 1986). Colourless, prismatic amphibole crystals commonly have dark green pargasitic rims (Fig. 3c); similar rims also occur as kelyphitic coronas around garnets.

Paragonite appears texturally to be a stable phase in both eclogites coexisting with the other eclogite facies minerals (Fig. 2). The symplectitic replacement of paragonite by very fine-grained albite + kyanite through the reaction:

$$\text{paragonite} + \text{quartz} = \text{albite} + \text{kyanite} + H_2O \quad (1)$$

Table 2. Mineral compositions from the paragonite eclogites in Dabie Shan.

	218C							585B						
	gt	amp	czo	cpx	ph	par	marg	gt	amp	zo	czo	cpx	ph	pa
SiO_2	38.87	50.48	38.17	56.37	50.21	46.58	29.77	38.83	50.85	38.86	38.36	56.02	53.05	45.83
TiO_2	0.05	0.02	0.06	0.00	0.06	0.11	0.02	0.06	0.19	0.06	0.18	0.00	0.27	0.10
Al_2O_3	21.97	10.51	28.35	11.51	27.03	40.02	50.68	21.83	10.48	31.93	28.20	9.84	23.56	39.73
Cr_2O_3	0.03	0.07	0.03	0.07	0.04	0.09	0.02	0.05	0.00	0.02	0.00	0.03	0.00	0.00
FeO	23.09	9.64	6.57	5.45	1.71	0.35	0.35	22.90	8.29	2.27	6.66	7.03	1.35	0.53
MgO	7.83	14.12	0.14	7.40	3.93	0.21	0.51	7.90	15.36	0.05	0.27	7.42	4.78	0.20
MnO	0.46	0.16	0.01	0.05	0.05	0.03	0.00	0.79	0.03	0.01	0.08	0.00	0.00	0.03
CaO	7.35	7.07	23.21	11.61	0.02	0.48	11.40	7.74	7.93	24.45	23.42	11.71	0.00	0.60
Na_2O	0.01	3.40	0.00	7.80	0.60	6.82	1.51	0.02	3.19	0.02	0.01	7.85	0.44	7.14
K_2O	0.00	0.22	0.00	0.03	10.21	0.77	0.02	0.00	0.18	0.03	0.01	0.00	9.93	0.72
Total	99.66	95.71	97.28	100.29	93.87	95.47	94.30	100.20	96.56	97.80	97.20	99.90	93.41	94.88
Structural formula based on:														
	12 ox	23 ox	12.5ox	4 cat	11 ox	11 ox	11 ox	12 ox	23 ox	12.5ox	12.5ox	4 cat	11 ox	11 ox
Si	2.99	7.12	2.98	1.99	3.39	2.97	2.00	2.98	7.09	2.97	2.99	1.99	3.58	2.95
Al^4	0.01	0.88	0.02	0.01	0.61	1.03	2.00	0.02	0.91	0.03	0.01	0.01	0.42	1.05
Σ	3.00	8.00	3.00	2.00	4.00	4.00	4.00	3.00	8.00	3.00	3.00	2.00	4.00	4.00
Al^6	1.98	0.86	2.59	0.47	1.54	1.98	2.01	1.95	0.81	2.85	2.57	0.41	1.45	1.97
Ti	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.01	0.00	0.01	0.01
Cr	0.00	0.01	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^{3+}	0.02	0.85	0.43	0.06				0.05	0.74	0.14	0.43	0.13		
Σ	2.00		3.02					2.00		2.99	3.01			
Fe^{2+}	1.46	0.29		0.10	0.10	0.02	0.02	1.42	0.23			0.08	0.08	0.03
Mg	0.90	2.97	0.02	0.39	0.40	0.02	0.05	0.90	3.19	0.01	0.03	0.39	0.48	0.02
Mn	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.01	0.00	0.00	0.00
Σ		5.00		1.03	2.05	2.03	2.08		4.99			1.01	2.02	2.02
Ca	0.61	1.09	1.94	0.44	0.00	0.03	0.82	0.64	1.21	2.00	1.95	0.45	0.00	0.04
Na	0.00	0.95	0.00	0.53	0.08	0.85	0.20	0.00	0.88	0.00	0.00	0.54	0.06	0.89
K	0.00	0.04	0.00	0.01	0.88	0.06	0.00	0.00	0.03	0.00	0.00	0.00	0.85	0.06
Σ	3.00	2.08	1.96	0.97	0.96	0.94	1.02	3.01	2.12	2.01	1.99	0.99	0.91	0.99
Total	8.00	15.08	7.98	4.00	7.01	6.97	7.10	8.01	15.12	8.00	8.00	4.00	6.93	7.01
alm	48.7		jd	47		alm		47.2			jd	41		
prp	30.0		aeg	6		prp		29.9			aeg	13		
sps	1.0		aug	47		sps		1.7			aug	46		
grs + adr	20.3					grs + adr		21.3						

must have occurred during a dry exhumation under very low H_2O activities (Fig. 5). This indicates that paragonite was not formed during the low-pressure (*c.* 8 kbar) retrograde partial hydration of the rock when margarite rims around kyanite, and pargasitic amphibole around garnet have developed, but was part of the eclogite mineral assemblage. Thus, the latest equilibrium mineral assemblage in these eclogites must have been omphacite + garnet + kyanite + paragonite + clinozoisite/zoisite + phengite + amphibole + quartz + rutile. The equilibrium assemblage paragonite + omphacite + kyanite is rare in eclogites, requiring aluminous basic rock compositions and high pressures; it was previously described from the Tauern Window in the Austrian Alps (Miller, 1977; Holland, 1979a). In China paragonite has been described as inclusions in garnets and as a late phase in the eclogites (Hirajima *et al.*, 1992; Wang *et al.*, 1992; Enami *et al.*, 1993; Zhang & Liou, 1994). In the ultrahigh-pressure metamorphic terrane of the Dora Maira massif, paragonite occurs as inclusions in the garnet porphyroblasts in the metapelites (Chopin *et al.*, 1991; Schertl *et al.*, 1991).

Peak *P–T* conditions or re-equilibration during exhumation?

Fe^{2+}–Mg partitioning between 15 adjoining garnet–omphacite pairs from the two samples yield similar K_D values between 7 and 10 giving an average metamorphic temperature of $710 \pm 40°$ C at a reference pressure of 19 kbar using the Ellis & Green (1979) calibration. The biggest uncertainty in the K_D values lies in the recalculation of the Fe^{2+} and Fe^{3+} in omphacite. The recalculation scheme adopted here (Fe^{3+} = Na–Al–Cr–Ti in a 4-cation omphacite formula) was shown to yield the most consistent results (e.g. Selverstone *et al.*, 1992).

The paragonite + kyanite + quartz + omphacite assemblage allows the estimation of pressure on the basis of the reactions:

$$\text{paragonite} = \text{jadeite} + \text{kyanite} + H_2O, \quad (2)$$

$$\text{albite} = \text{jadeite} + \text{quartz}. \quad (3)$$

Both of these reactions are reliable geobarometers as they are experimentally determined (Holland, 1979b, 1980), the paragonite is nearly pure end-member, and the activity–composition relations of omphacite are well defined above 600° C (Holland, 1990). Reaction (2) gives a pressure estimate of 19 kbar for H_2O activity equal to unity, and reaction (3) a minimum pressure of 14.2 kbar at 710° C for the analysed paragonite and omphacite compositions with the maximum jadeite content (0.48), and using the THERMOCALC software of Holland & Powell (1990) (Fig. 5). There is no evidence that sample 218C was subjected to higher pressures than 19 kbar. On the other

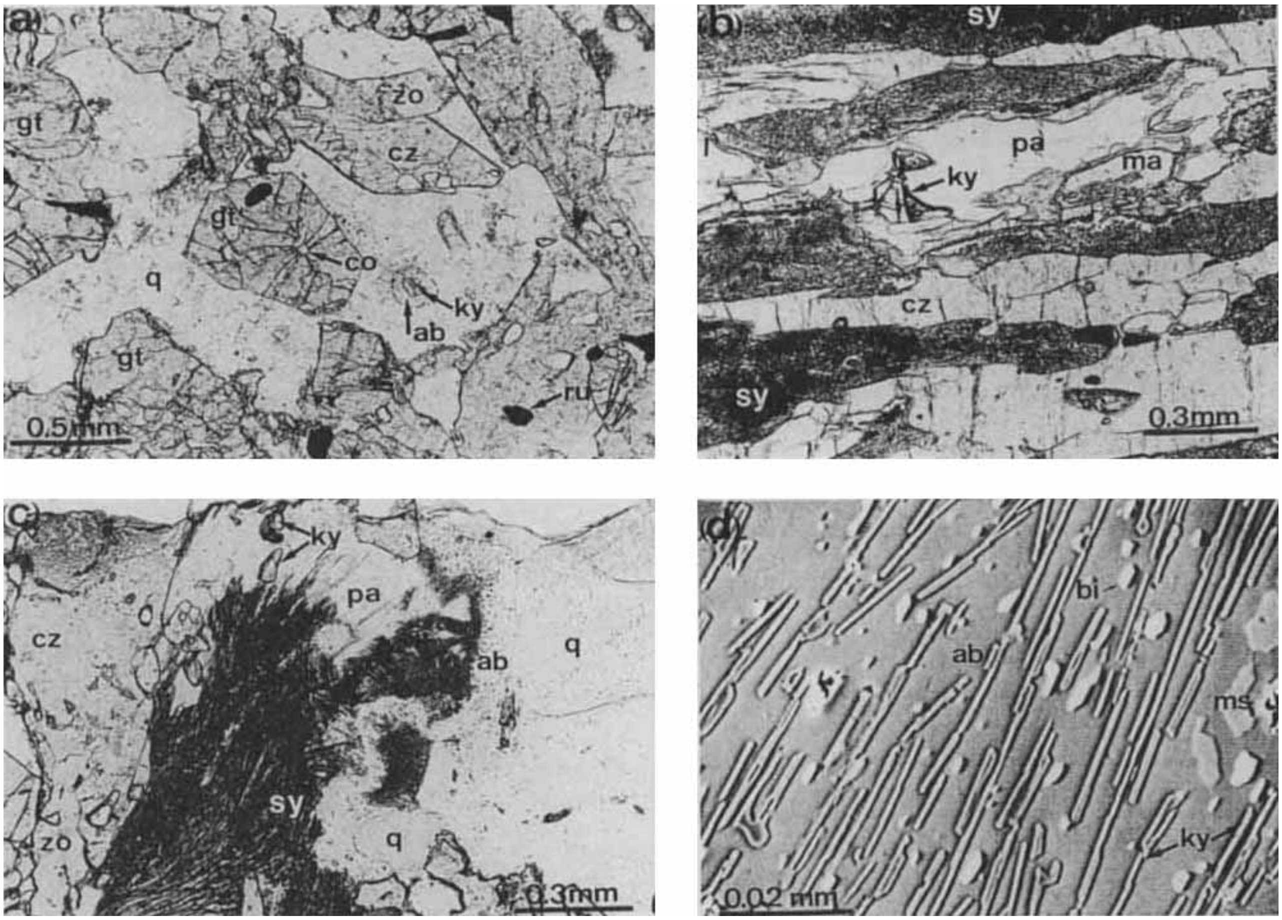

Fig. 2. Photomicrographs from the paragonite eclogites. (a) Eclogite (sample 585) with garnet (gt), zoisite (zo), clinozoisite (cz), kyanite (ky), quartz and rutile (ru). Notice the quartz pseudomorphs after coesite (co) in garnet with radial fractures around it, and the albite rim (ab) around kyanite. Micrograph with plane polarized light. (b) Eclogite (sample 218C) with diopside + plagioclase symplectite after omphacite (sy), clinozoisite (cz), kyanite (ky) and paragonite (pa). Kyanite has a thin reaction rim of margarite; larger margarite crystals (ma) to the right are probably also after kyanite. Micrograph with plane polarized light. (c) Paragonite (pa), which is partially replaced by an albite + kyanite symplectite (sy), is associated with quartz (q), kyanite (ky), clinozoisite (cz) and zoisite. Notice the albite (ab) reaction rim between quartz and paragonite (eclogite sample 585). Micrograph with plane polarized light. (d) Back-scattered electron image of the albite (ab) + kyanite (ky) symplectite with minor muscovite (ms) and biotite (bi) after paragonite (eclogite sample 585).

hand, the quartz pseudomorph after coesite in garnet in sample 585 indicates minimum pressures of 27 kbar at 710° C (Fig. 5). The higher Si p.f.u. in the phengites from this sample as compared to those from sample 218C (Fig. 3d) also suggests higher peak pressures for this rock based on reactions involving garnet, omphacite and phengite (reactions (1) and (2) in Okay, 1993). The most plausible explanation for this discrepancy in pressure estimates in this rock is that coesite formed early in the metamorphic history and the matrix minerals have equilibrated during the exhumation, while a fluid phase was still present. One way of testing whether the suggested equilibration during exhumation is a general phenomenon in the ultrahigh-pressure rocks is to apply other geobarometers to the equilibrium assemblages from ultrahigh-pressure and high-pressure eclogites. Any systematic difference in critical mineral compositions would be indicative of frozen equilibrium at ultrahigh pressures.

A ZOISITE–GARNET–KYANITE–QUARTZ/COESITE GEOBAROMETER

One important equilibrium in kyanite eclogites that is frequently used for geobarometry (e.g. Chopin *et al.*, 1991; Okay, 1993; O'Brien, 1993) is

$$\text{zoisite/clinozoisite} = 4\text{grossular} + 5\text{kyanite} + \text{quartz} + 3H_2O. \quad (4)$$

This reaction is particularly useful for the estimation of the metamorphic pressures or H_2O activities as it has a flat slope in the $P-T$ field and the four phases of the reaction coexist over a wide pressure range with garnet becoming richer in grossular component with increasing pressure. In the case of reduced H_2O activity, reaction (4) gives maximum pressures. Recent experimental work on the high-pressure stability limit of zoisite (Schmidt & Poli, 1994; B. Wunder, pers. comm., 1994) indicates that zoisite

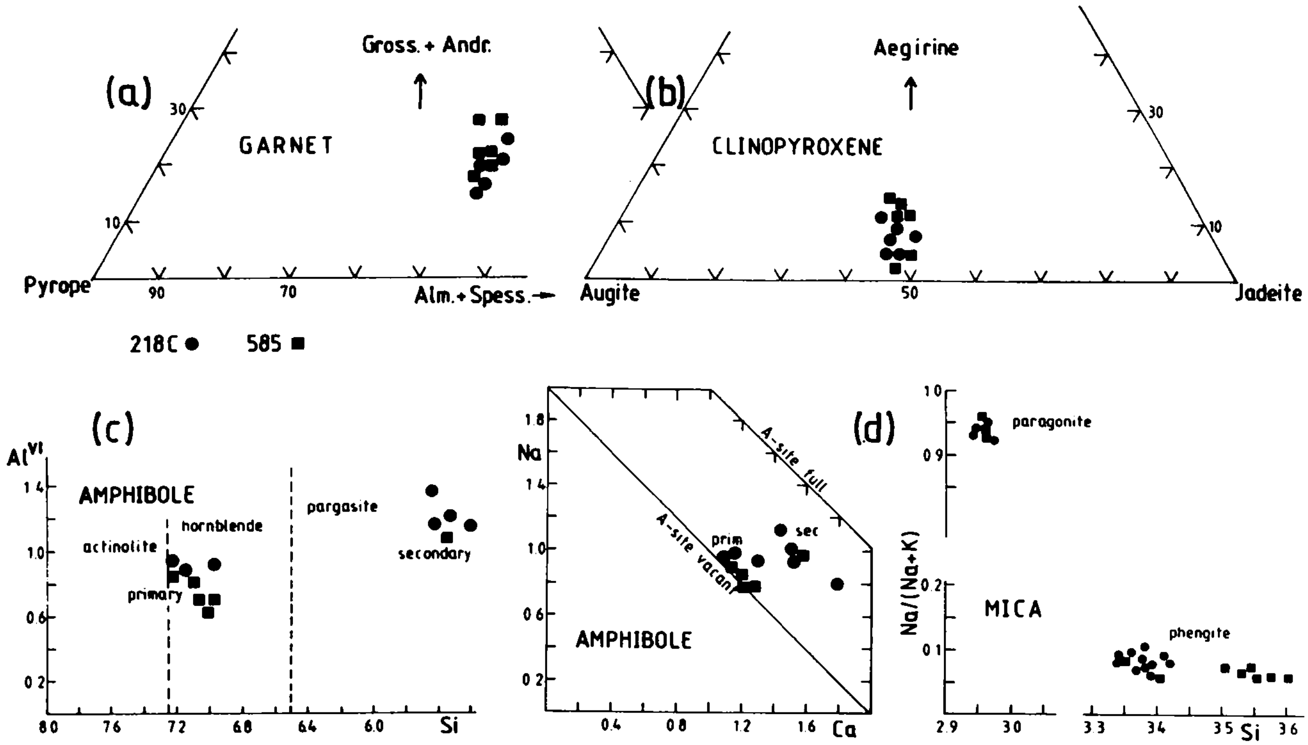

Fig. 3. Representative (a) garnet, (b) clinopyroxene, (c) primary and secondary amphibole, and (d) mica compositions from the paragonite eclogites from Dabie Shan.

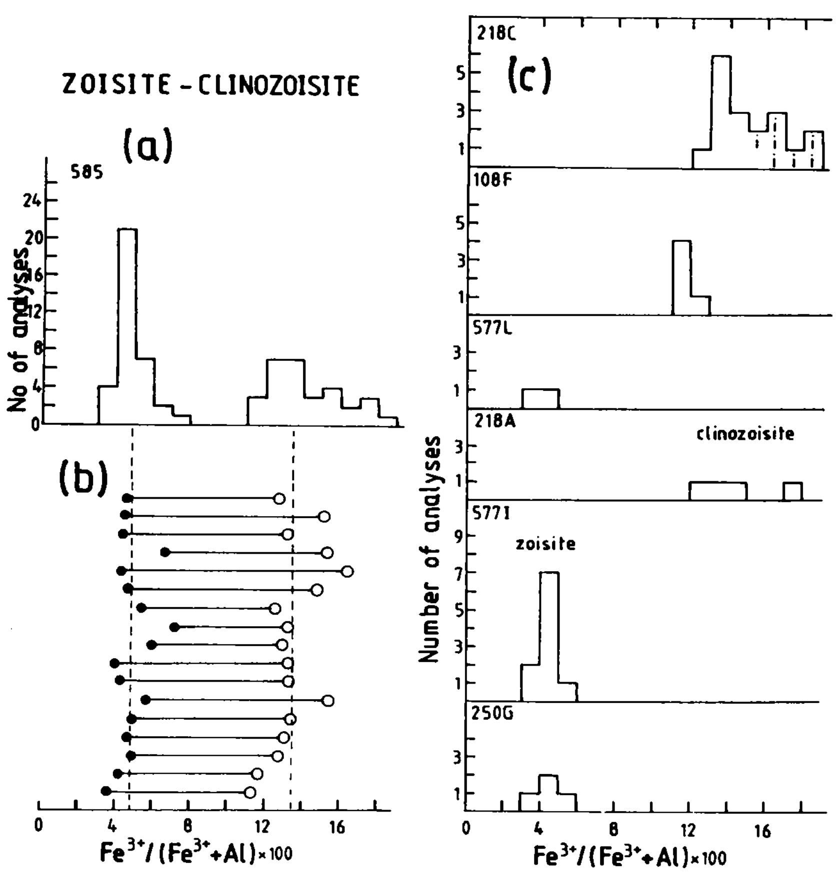

Fig. 4. Compositions of zoisite and clinozoisite that coexist with garnet, kyanite and quartz/coesite in the eclogite facies rocks from Dabie Shan. (a) Histogram of zoisite ($X_{Fe} < 0.09$) and clinozoisite compositions from the paragonite eclogite sample 585. (b) Compositions of adjoining zoisite and clinozoisite grains from sample 585. The dashed line indicates the average adjoining zoisite ($X_{Fe} = 0.049$) and clinozoisite ($X_{Fe} = 0.135$) compositions. (c) Histograms of zoisite and clinozoisite compositions from kyanite–garnet–quartz/coesite-bearing eclogite facies rocks from Dabie Shan. Clinozoisite compositions from the inclusions in garnet in sample 218C are denoted by 'I'.

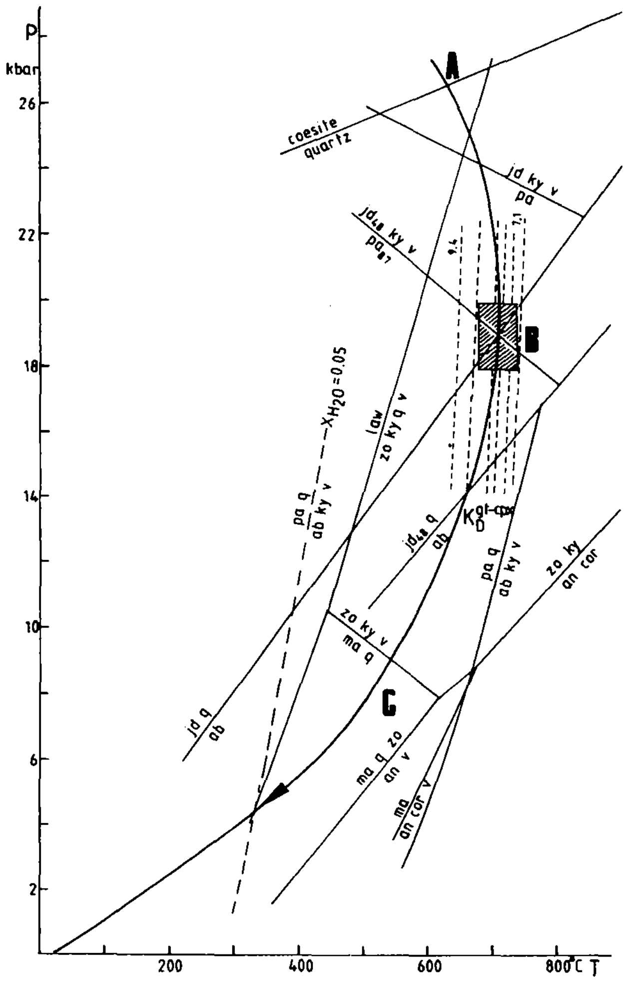

Fig. 5. Relevant $P-T$ equilibria and a speculative exhumation $P-T$ path for the paragonite eclogites. Stage **A** is the ultrahigh-pressure metamorphic event with the formation of coesite in the eclogite. Eclogite mineral assemblage equilibrates during the fluid-present-exhumation with the formation of paragonite until stage **B**, when the fluid phase leaves the rock. The dry exhumation from stage **B** to **C** is evidenced by the symplectitic replacement of paragonite by albite + kyanite, and of omphacite by diopside + plagioclase. The replacement of kyanite by margarite, and calcic amphibole rims around garnet indicate partial hydration of the rock during stage **C**. Garnet–clinopyroxene equilibria (thin dashed lines) are after Ellis & Green (1979); all other reaction lines are calculated using THERMOCALC software (Holland & Powell, 1990). Abbreviations: ab, albite; an, anorthite; cor, corundum; jd, jadeite; ky, kyanite; law, lawsonite; ma, margarite; pa, paragonite; q, quartz; v, H_2O; zo, zoisite.

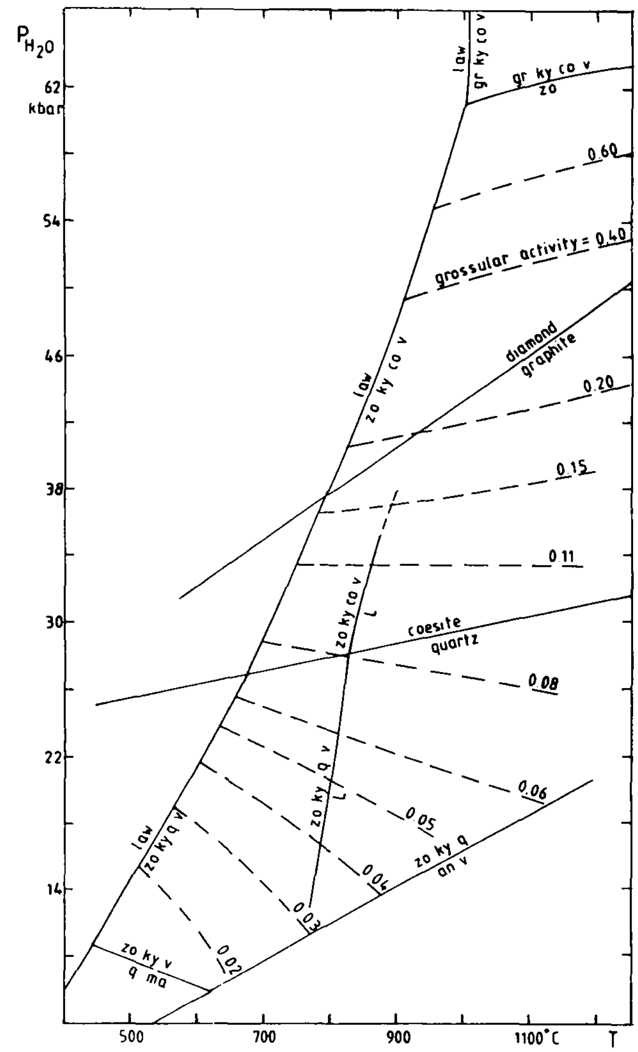

Fig. 6. $P-T$ diagram showing the stability field of garnet + zoisite + kyanite + quartz/coesite assemblage. Dashed lines indicate the grossular activities that are in equilibrium with end-member zoisite, kyanite and quartz/coesite. The liquidus line is after Boettcher (1970); all other reactions are calculated using THERMOCALC software of Holland & Powell (1990). Abbreviations: an, anorthite; co, coesite; ky, kyanite; L, melt; law, lawsonite; ma, margarite; q, quartz; v, H_2O; zo, zoisite.

breaks down to grossular, kyanite and coesite between 60 and 70 kbar at above 1000° C, which is predicted by the THERMOCALC software of Holland & Powell (1990). On the other hand, the GE0-CALC software of Brown *et al.* (1988) with Berman's (1988) data set place the end-member reaction at much lower pressures of about 48 kbar. The limiting reactions for the zoisite–kyanite–quartz assemblage at lower pressures are known from the experimental work of Chatterjee *et al.* (1984). Figure 6 shows the $P-T$ stability field of the zoisite–garnet–kyanite–quartz/coesite assemblage calibrated for different grossular activities using the THERMOCALC program of Holland & Powell (1990). As zoisite in eclogites is usually close to the end-member composition, the metamorphic pressures can ideally be estimated from the composition of the garnet in the four-phase assemblage assuming the presence of an H_2O-rich fluid phase. Pressures calculated from reaction (4) are projected on the garnet ternary compositional field in Fig. 7 using a zoisite activity of 0.86 and garnet activities calculated after Berman (1990). The most uncertain part in this projection is the activity–composition relationships of garnet. The results using garnet activities of Berman (1990) agree better with independent pressure estimates from eclogites (see later). Other garnet activity models (e.g. Newton & Perkins,

1982) result in similar trends for the isobars but the pressures for the same garnet compositions are about 5–8 kbar lower for the common eclogitic garnet compositions as compared to those calculated by the Berman (1990) model. The widely varying pressures obtained from different garnet activity models indicate that at the present stage the geobarometer is probably more useful for comparing relative pressures from different eclogite terranes than obtaining accurate pressure estimates.

Zoisite with usually <5 mol% pistacite end-member is a common mineral in the kyanite eclogites. If an ideal activity model for zoisite and clinozoisite ($a_{zo/czo}$ = Al–2 in 12.5 oxygen formula unit) is assumed, the compositional gap between zoisite and clinozoisite (Fig. 4, see also Enami & Banno, 1980; Franz & Selverstone, 1992) implies that at a temperature of about 700° C a zoisite activity of 0.85 in reaction (3) has the same effect as a clinozoisite activity of 0.60, so that the garnet composition–pressure diagram in Fig. 7 can also be used for the clinozoisite-bearing assemblages, where the clinozoisite activities are about 0.60.

Garnet compositions from eclogite facies rocks with the mineral assemblage garnet + omphacite + kyanite + zoisite/clinozoisite + quartz/coesite from various orogenic belts are plotted in the pressure–composition diagram in Fig. 7(a). Except those from the ultrahigh-pressure terrane of the Dora Maira massif, almost all garnet compositions plot in the quartz stability field. Independent pressure and temperature estimates for the samples from these localities are listed in Table 3. The pressures estimated from the grossular content of the garnet from these rocks agree with these independently established metamorphic pressures (Table 3, Fig. 7a). This agreement also implies high H_2O activities during the eclogite facies metamorphism, which is independently shown to be the case in many regions (e.g. Holland, 1979a; Klemd, 1989). Interestingly, the garnet composition from the eclogite associated with the garnet peridotite in the Alpe Arami in Switzerland (Heinrich, 1986) plots in the coesite field, suggesting an ultrahigh-pressure metamorphic origin for this rock. Also plotted in Fig. 7(a) are garnets from the kyanite–coesite-bearing xenolith from the Roberts Victor kimberlite (Smyth & Hatton, 1977; Sharp *et al.*, 1992). In the absence of zoisite, garnet compositions from this xenolith indicate minimum pressures of about 40 kbar, in agreement with the ultrahigh-pressure origin for this rock. Thus, the zoisite–garnet–kyanite–quartz/coesite geobarometer appears to be promising especially for separating high-pressure and ultrahigh-pressure eclogites.

Garnet compositions from the paragonite eclogites from Dabie Shan are shown in the garnet pressure–composition diagram in Fig. 7(b). They plot in the quartz stability field, suggesting equilibration at pressures of 15–25 kbar in agreement with the presence of paragonite in the rock. Thus, the whole eclogite mineral assemblage in the paragonite eclogites has recrystallized at pressures of about 19 kbar, and the inclusion of quartz pseudomorphs after coesite in garnet is the only evidence for the former ultrahigh-pressures in specimen 585.

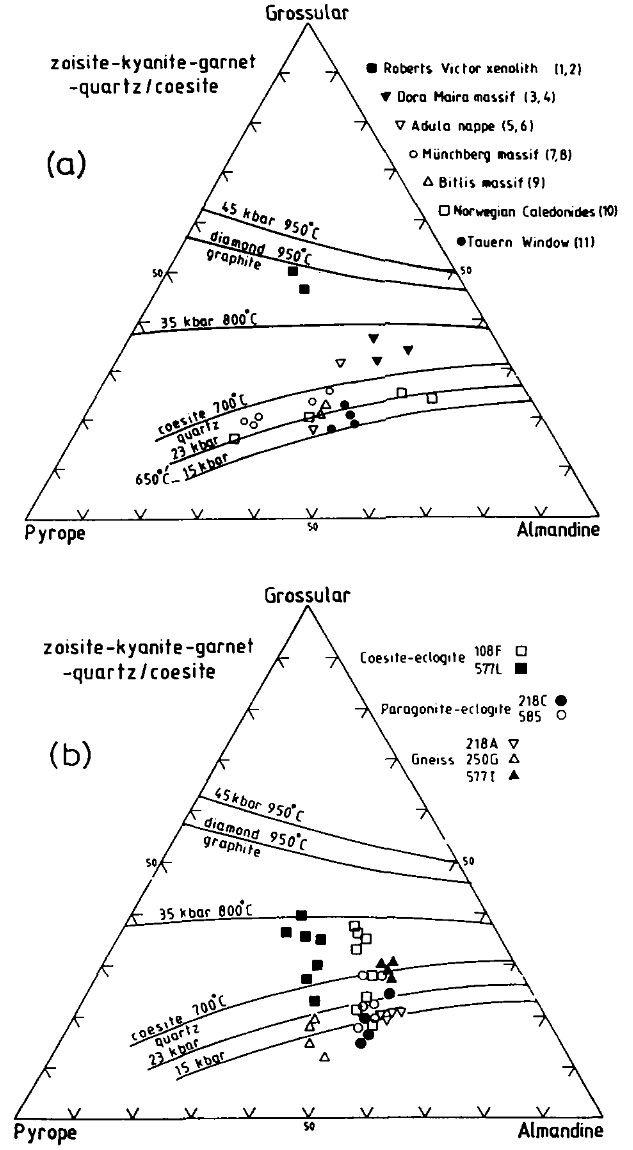

Fig. 7. (a) Garnet composition–pressure diagram showing the 15-, 23-, 35- and 45-kbar isobars and the coesite- and the diamond-in line for garnets in equilibrium with zoisite (activity = 0.86 or clinozoisite with activity *c.* 0.60), kyanite and quartz/coesite. The isobars are constructed using the THERMOCALC software of Holland & Powell (1990) and the garnet activity model of Berman (1990). Garnet compositions from various high-pressure terranes are also shown. The data are from: 1, Smyth & Hatton (1977); 2, Sharp *et al.* (1992); 3, Chopin *et al.* (1991); 4, Kienast *et al.* (1991); 5, Ernst (1977); 6, Heinrich (1986); 7, Klemd (1989); 8, O'Brien (1993); 9, Okay *et al.* (1985); 10, Bryhni & Griffin (1971); 11, Holland (1979) and T. J. B. Holland & K. Eremin pers. comm. (1994). (b) The same diagram as in (a) showing the garnet compositions from critical assemblages from Dabie Shan.

Application of the geobarometer to other eclogite facies rocks from Dabie shan

In the eclogite zone in Dabie Shan there are, apart from the paragonite eclogites, two more rock types with the critical assemblage of zoisite/clinozoisite–garnet–kyanite–quartz/coesite. One is the coesite-bearing eclogite without

Table 3. Data on eclogites with the subassemblage garnet–zoisite/clinozoisite–kyanite–quartz/coesite. Garnet compositions from these eclogites are shown in Fig. 7(a). The pressures are calculated from reaction (4) using the given metamorphic temperatures unless stated otherwise.

Locality	*P,T* given (kbar, °C)	Ref.	a_{grs}, a_{zo}	*P* calculated (kbar)	Samples
Trescolman, Adula nappe	19, 600	(1)	0.035, 0.93	21	Ad25-9-3
Alpe Arami, Adula nappe	27, 825	(1)	0.074, 0.92	29	Mg9-5-12c
Alpe Arami, Adula nappe	40	(2)	0.047, 0.95	22, 725°C	F53
Dora Maira massif, Italy	30, 725	(3)	0.072–0.10, 0.95	28–34	86Dm49
Dora Maira massif, Italy	31, 715	(4)	0.082, 0.95	30	Br22
Tauern Window, Austria	20, 620	(5)	0.022–0.045, 0.95	16–25	
Münchberg Massif, Germany	23, 625	(6)	0.054–0.060, 0.93	26–27	II.1
Münchberg Massif, Germany	26, 650	(7)	0.051–0.059, 0.96	25–26	Bhs66 and Bhs63
Nordfjord, Norway		(8)	0.038–0.043, 0.93	21–23, 650°C	Aep and Vt1
Bitlis Massif, SE Turkey	16, 625	(9)	0.041, 0.90	23	Mu33

References: 1, Heinrich (1986); 2, Ernst (1977); 3, Chopin *et al.* (1991); 4, Kienast *et al.* (1991); 5, Holland (1979) and T. J. B. Holland & K. Eremin, pers. comm. (1994); 6, Klemd (1989); 7, O'Brien (1993); 8, Bryhni & Griffin (1971); 9, Okay *et al.* (1985).

paragonite, and the other is kyanite gneiss that occurs as centimetre-thick bands or segregations in eclogites. Although the kyanite gneiss has a mineral assemblage similar to the eclogite, it is characterized by the volumetric dominance of zoisite/clinozoisite, quartz and kyanite, which make up over 60 vol.% of the rock (Okay, 1993). Two eclogites (samples 108F & 577 L), one with coesite and the other with quartz pseudomorphs after coesite as inclusions in omphacite, and three kyanite gneisses (samples 218 A, 250G & 577 L) were analysed with the electron microprobe. The garnet–clinopyroxene Fe^{2+}–Mg geothermometer of Ellis & Green (1979) indicates temperatures between 700 and 800°C at 20–30 kbar for these rocks. The modal amounts of these specimens and selected mineral compositions are given in Tables 1 and 4, respectively, and the specimen localities are shown in Fig. 1. Two of the newly analysed samples (577 L & 577I) come from the coesite-bearing Bixiling eclogite, which is the largest single continuous eclogite body in Dabie Shan with a length of 1 km and a maximum width of 400 m (Fig. 1).

Garnets from the Dabie Shan coesite eclogites show a wide compositional variation in grossular component corresponding to a pressure variation of above 12 kbar (Fig. 7b). The compositional variation in garnet is largely due to a rimward decrease in grossular component, which in some garnets in sample 108F amounts to over 15 mol% (Table 4). In contrast, garnet compositions from Dabie Shan eclogites without the critical assemblage are much more homogeneous in grossular component (cf. fig. 4 of Okay, 1993), suggesting that the variation in the grossular content of the garnet is caused by reaction (4). The rimward decrease in grossular component at approximately constant Fe/Mg ratio in garnets (Fig. 7b) suggests that the garnets were beginning to equilibrate during isothermal decompression. Garnet zoning involving a rimward decrease in grossular component appears to be a common feature in garnets with the critical assemblage (e.g. Bryhni & Griffin, 1971; Klemd, 1989; Kienast *et al.*, 1991; O'Brien, 1993), suggesting that re-equilibration of garnet compositions during the exhumation is a general feature. In the analysed eclogites the grossular-rich garnets represent part of the ultrahigh-pressure assemblage, whereas those with lesser grossular contents have partially equilibrated during the exhumation. Zoisite, which occurs in amounts <3 vol.% in these rocks (cf. Table 1), has probably formed during the exhumation. In normal basic rock compositions zoisite should not be part of the ultrahigh-pressure mineral assemblage.

Garnet compositions from the kyanite gneisses are more homogeneous as compared to those from the coesite eclogites and plot largely in the quartz stability field (Fig. 7b). The high modal amounts of zoisite/clinozoisite in these rocks (cf. Table 1) suggest that the equivalent assemblages at ultrahigh pressures would have been very grossular-rich garnet–omphacite–kyanite–coesite rocks (meta-anorthosites?), similar to the grospydites described from the kimberlites (e.g. Sobolev *et al.*, 1968; Smyth & Hatton, 1977). In Dabie Shan, garnets with up to 60 mol% grossular end-member but without the accompanying kyanite occur in the 'para-eclogites' in marbles (Okay, 1993). An alternative possibility for the origin of these kyanite gneisses is that they have formed from Ca–Al-rich fluids at pressures of below 25 kbar by metamorphic differentiation from the breakdown of grossular-rich garnets, and do not have sedimentary or magmatic protoliths.

CONCLUSIONS

The eclogite facies encompasses a *P–T* field larger than that of all the other metamorphic facies combined (e.g. Turner, 1968, p. 342; Carswell, 1990). The pressures recorded in crustal metamorphic rocks in the eclogite facies range from above 35 kbar (e.g. Sobolev & Shatsky, 1990; Xu *et al.*, 1992) down to 15 kbar (e.g. Carswell, 1990). The decompression of eclogites over this wide pressure range will not always be obvious because of the modal dominance of garnet and omphacite in metabasic rock compositions throughout the eclogite facies. A consequence of this is that complete recrystallization of ultrahigh-pressure eclogites at lower pressures, but still within the eclogite facies field, may go undetected. This case is illustrated in the one paragonite eclogite from Dabie Shan studied here, which, although it contains quartz pseudomorphs after coesite as inclusions in garnet, is almost completely recrystallized at lower pressures of 19 kbar and 710°C. Other evidence for complete recrystallization at lower pressures is the common granoblastic texture of the quartz crystals in the matrix of the coesite-bearing eclogites in Dabie Shan. Although all

Table 4. Mineral compositions from eclogite facies rocks from Dabie Shan with the mineral assemblage kyanite + zoisite/clinozoisite + garnet + quartz/coesite ± omphacite ± phengite.

	Coesite eclogite 577L					Coesite eclogite 108F					Kyanite gneiss 577I			Kyanite gneiss 218A		
	gt core	gt rim	zo	cpx	ph	gt core	gt rim	cz	cpx	ph	gt	zo	cpx	cz	gt	ph
SiO_2	40.33	39.50	39.16	57.09	52.57	38.79	38.74	38.77	56.61	52.95	38.44	38.92	56.03	38.26	39.20	49.50
TiO_2	0.12	0.00	0.01	0.03	0.00	0.05	0.00	0.04	0.02	0.15	0.09	0.04	0.08	0.11	0.03	0.27
Al_2O_3	22.64	22.08	31.93	11.02	27.66	21.78	21.98	28.17	11.97	27.24	21.99	31.81	12.69	28.22	22.13	27.61
Cr_2O_3	0.07	0.04	0.02	0.05	0.10	0.12	0.08	0.09	0.02	0.04	0.03	0.00	0.03	0.01	0.04	0.00
FeO	15.18	17.43	1.61	1.67	0.75	18.09	21.92	5.28	3.00	1.21	21.43	1.73	3.31	5.70	23.06	1.55
MgO	9.05	9.67	0.00	9.84	4.17	6.24	7.40	0.29	8.21	4.64	5.78	0.04	7.52	0.18	7.33	3.71
MnO	0.40	0.44	0.02	0.05	0.00	0.39	0.49	0.01	0.02	0.00	0.50	0.05	0.00	0.05	1.02	0.02
CaO	13.64	10.36	24.05	13.95	0.20	14.49	8.89	23.37	12.69	0.00	11.36	24.07	11.84	22.98	7.48	0.00
Na_2O	0.09	0.13	0.00	6.78	0.03	0.02	0.00	0.03	7.34	0.12	0.01	0.05	7.64	0.01	0.04	0.56
K_2O	0.00	0.00	0.00	0.01	9.32	0.00	0.00	0.00	0.00	9.40	0.00	0.00	0.02	0.03	0.03	9.35
Total	101.52	99.65	96.80	100.49	94.80	99.97	99.50	96.05	99,88	95.75	99.63	96.71	99.16	95.55	100.36	92.57
Structural formula based on:																
	12 ox	12 ox	12.5ox	4 cat	11 ox	12 ox	12 ox	12.5ox	4 cat	11 ox	12 ox	12.5ox	4 cat	12.5ox	12 ox	11 ox
Si	2.98	2.99	3.01	2.00	3.46	2.97	2.99	3.04	2.00	3.46	2.97	3.00	1.99	3.01	3.00	3.37
Al^4	0.02	0.01	0.00	0.00	0.54	0.03	0.01	0.00	0.00	0.54	0.03	0.00	0.01	0.00	0.00	0.63
Σ	3.00	3.00	3.01	2.00	4.00	3.00	3.00	3.04	2.00	4.00	3.00	3.00	2.00	3.01	3.00	4.00
Al^6	1.96	1.96	2.90	0.45	1.60	1.94	1.98	2.60	0.50	1.55	1.98	2.89	0.53	2.62	2.00	1.59
Ti	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0:00	0.01
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.03	0.04	0.10	0.01		0.06	0.01	0.34	0.00		0.01	0.11	0.00	0.38	0.00	
Σ	2.00	2.00	3.00			2.00	2.00	2.95			2.00	3.00		3.01	2.00	
Fe^{2+}	0.91	1.06		0.04	0.04	1.10	1.40		0.09	0.07	1.37		0.10		1.48	0.09
Mg	1.00	1.09	0.00	0.51	0.41	0.71	0.85	0.03	0.43	0.45	0.67	0.01	0.40	0.02	0.84	0.38
Mn	0.03	0.03	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.07	0.00
Σ				1.01	2.05				1.02	2.08			1.03			2.07
Ca	1.08	0.84	1.98	0.52	0.02	1.19	0.74	1.96	0.48	0.00	0.94	1.99	0.45	1.94	0.61	0.00
Na	0.01	0.02	0.00	0.46	0.00	0.00	0.00	0.00	0.50	0.02	0.00	0.01	0.53	0.00	0.01	0.07
K	0.00	0.00	0.00	0.00	0.78	0.00	0.00	0.00	0.00	0.78	0.00	0.00	0.00	0.00	0.00	0.81
Σ	3.03	3.04	1.98	0.98	0.80	3.02	3.02	1.99	0.98	0.80	3.01	2.01	0.98	1.96	3.00	0.88
Total	8.00	15.08	7.99	3.99	6.90	8.02	8.02	8.00	4.00	6.88	8.01	8.01	4.01	7.98	8.00	6.95
alm	30.1	35.1	jd	46	alm	36.4	46.3	jd	50	alm	45.5	jd	53	alm	49.4	
prp	33.1	36.1	aeg	1	prp	23.5	28.2	aeg	0	prp	22.3	aeg	0	prp	28.0	
sps	1.0	1.0	aug	53	sps	0.7	1.0	aug	50	sps	1.0	aug	47	sps	2.3	
grs + adr	35.8	27.8			grs + adr	39.4	24.5			grs + adr	31.2			grs + adr	20.3	

quartz in the rock must have been coesite at the peak pressure, there is now no textural evidence for this. The extensive recrystallization suggests the presence of a fluid phase during part of the exhumation path and the retention of the ultrahigh-pressure mineral assemblages in the eclogites may be controlled by the depth at which the fluid leaves the rock (Fig. 5). Possible field evidence for the fluid phase in Dabie Shan eclogites comes from 'nests' of coarse idoblastic zoisite, kyanite and quartz that are up to 0.4 m in length (Okay, 1993; Castelli *et al.*, 1994). These minerals must have crystallized from a free fluid phase, which was in equilibrium with the host rock and was acting as a solution and reprecipitation agent for reaction (4) during the exhumation path (see also Selverstone *et al.*, 1992).

There is no evidence for ultrahigh pressures for the second paragonite eclogite studied, which does not contain coesite or its pseudomorphs. Further work is necessary to determine whether the eclogites in this region are re-equilibrated ultrahigh-pressure rocks, or whether there is a tectonic slice of lower pressure eclogite facies rocks structurally below the coesite-bearing 'hot eclogite terrane' (Fig. 1).

A geobarometer for zoisite/clinozoisite–garnet–kyanite–quartz/coesite-bearing assemblages is developed. It is applicable for a very wide pressure range from about 10 to 60 kbar and is particularly useful for the differentiation of high-pressure and ultrahigh-pressure eclogite facies rocks. The geobarometer indicates extensive recrystallization at 15–20 kbar for many ultrahigh-pressure rocks, including the paragonite eclogites, in Dabie Shan.

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REFERENCES

Berman, R.G., 1988. Internally consistent thermodynamic dataset for minerals in the system Na_2O–K_2O–CaO–MgO–FeO–Fe_2O_3–Al_2O_3–SiO_2–TiO_2–H_2O–CO_2. *Journal of Petrology*, **29,** 445–522.

Berman, R.G., 1990. Mixing properties of Ca–Mg–Fe–Mn garnets. *American Mineralogist*, **75,** 328–344.

Boettcher, A.L., 1970. The system CaO–Al_2O_3–SiO_2–H_2O at high pressures and temperatures. *Journal of Petrology*, **11,** 337–379.

Bryhni, I. & Griffin, W.L., 1971. Zoning in eclogite garnets from Nordfjord, west Norway. *Contributions to Mineralogy and Petrology*, **32,** 112–125.

Brown, T.H., Berman, R.G. & Perkins, E.H., 1988. GE0-CALC:

software for calculation and display of pressure–temperature–composition phase diagrams using an IBM or compatible personal computer. *Computer and Geosciences*, **14**, 279–289.

Caby, R., 1994. Precambrian coesite from northern Mali: first record and implications for plate tectonics in the trans-saharan segment of the Pan-African belt. *European Journal of Mineralogy*, **6**, 235–244.

Carswell, D.A., 1990. Eclogites and the eclogite facies: definitions and classification. In: *Eclogite Facies Rocks* (ed. Carswell, D. A.), pp. 1–13. Blackie, Glasgow.

Castelli, D., Compagnoni, R. & Xu, S.T., 1994. Metamorphic veins with kyanite and zoisite megablasts in the ultrahigh-pressure Zhu-jiachong eclogite, Dabie Shan, China. *Abstracts, 16th General Meeting of the International Mineralogical Association*, pp. 65–66.

Chatterjee, N.D. & Flux, S., 1986. Thermodynamic mixing properties of muscovite–paragonite crystalline solutions at high temperatures and pressures and their geological applications. *Journal of Petrology*, **27**, 677–693.

Chatterjee, N.D., Johannes, W. & Leistner, H., 1984. The system $CaO–Al_2O_3–SiO_2–H_2O$: new phase equilibria data, some calculated phase relations, and their petrological applications. *Contributions to Mineralogy and Petrology*, **88**, 1–13.

Chopin, C., 1984. Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first record and some consequences. *Contributions to Mineralogy and Petrology*, **86**, 107–118.

Chopin, C., Henry, C. & Michard, A., 1991. Geology and petrology of the coesite-bearing terrain, Dora Maira massif, Western Alps. *European Journal of Mineralogy*, **3**, 263–291.

Ellis, D.J. & Green, D.H., 1979. An experimental study of the effect of Ca upon garnet–clinopyroxene Fe–Mg exchange equilibria. *Contributions to Mineralogy and Petrology*, **71**, 13–22.

Enami, M. & Banno, S., 1980. Zoisite–clinozoisite relations in low- to medium-grade high-pressure metamorphic rocks and their implications. *Mineralogical Magazine*, **43**, 1005–1013.

Enami, M., Zang, Q.J. & Yin, Y.J., 1993. High-pressure eclogites in northern Jiangsu – southern Shandong province, eastern China. *Journal of Metamorphic Geology*, **11**, 589–603.

Ernst, W.G., 1977. Mineralogic study of eclogitic rocks from Alpe Arami, Lepontine Alps, southern Switzerland. *Journal. Petrology*, **18**, 371–398.

Fockenberg, T., Schreyer, W., Skrok, V. & Wunder, B., 1994. Experimental studies relevant to ultra-high-pressure metamorphism. *16th Meeting of the International Mineralogical Association, Abstract*, p. 121.

Franz, G. & Selverstone, J., 1992. An emperical phase diagram for the clinozoisite–zoisite transformation in the system $Ca_2Al_3Si_3O_{12}$ (OH)–$Ca_2Al_2Fe^{3+}Si_3O_{12}$ (OH). *American Mineralogist*, **77**, 631–642.

Gillet, P., Ingrin, J. & Chopin, C., 1984, Coesite in subducted continental crust: *P–T* history deduced from an elastic model. *Earth and Planetary Science Letters*, **70**, 426–436.

Guidotti, C.V., Sassi, F.P., Blencoe, J.G. & Selverstone, J., 1994. The paragonite–muscovite solvus: I. P–T–X limits derived from the Na–K compositions of natural, quasibinary paragonite–muscovite pairs: *Geochimica et Cosmochimica Acta*, **58**, 2269–2275.

Heinrich, C.A., 1986. Eclogite facies regional metamorphism of hydrous mafic rocks in the Central Alpine Adula Nappe. *Journal of Petrology*, **27**, 123–154.

Hirajima, T., Zhang, R., Li, J. & Cong, B., 1992. Petrology of the nyböite-bearing eclogite in the Donghai area, Jiangsu province, eastern China. *Mineralogical. Magazine*, **56**, 37–46.

Holland, T.J.B., 1979a. High-water activities in the generation of high-pressure kyanite eclogites of the Tauern Window, Austria. *Journal of Geology*, **87**, 1–27.

Holland, T.J.B., 1979b. Experimental determination of the reaction paragonite = jadeite + kyanite + water, and an internally consistent thermodynamic data for part of the system $Na_2O–Al_2O_3–SiO_2–H_2O$, with application to eclogites and blueschists. *Contributions to Mineralogy and Petrology*, **68**, 293–301.

Holland, T.J.B., 1980. The reaction albite = jadeite + quartz determined experimentally in the range 600–1200° C. *American Mineralogist*, **65**, 129–134.

Holland, T.J.B., 1990. Activities of components in omphacitic solid solutions. *Contributions to Mineralogy and Petrology*, **105**, 446–453.

Holland, T.J.B. & Powell, R., 1990. An enlarged and updated internally consistent thermodynamic dataset with uncertainties and correlations: the system $K_2O–Na_2O–CaO–MgO–MnO–FeO–Fe_2O_3–Al_2O_3–TiO_2–SiO_2–C–H_2O–O_2$. *Journal of Metamorphic Geology*, **8**, 89–124.

Kienast, J.R., Lombardo, B., Biino, G. & Pinardon, J.L., 1991. Petrology of very-high-pressure eclogitic rocks from the Brossasco–Isasca Complex, Dora-Maira Massif, Italian Western Alps. *Journal of Metamorphic Geology*, **9**, 19–34.

Klemd, R., 1989. P-T evolution and fluid inclusion characteristics of retrograded eclogites, Münchberg Gneiss Complex, Germany. *Contributions to Mineralogy and Petrology*, **102**, 221–229.

Miller, Ch., 1977. Mineral parageneses recording the P,T history of Alpine eclogites in the Tauern Window, Austria. *Neues Jahrbuch der Mineralogie, Abhandlungen*, **130**, 69–77.

Newton, R.C. & Perkins, D., 1982. Thermodynamic calibration of geobarometers based on the assemblages garnet–plagioclase–orthopyroxene (clinopyroxene)–quartz. *American Mineralogist*, **67**, 203–222.

O'Brien, P.J., 1993. Partially retrograded eclogites of the Münchberg Massif, Germany: records of a multistage Variscan uplift history in the Bohemian Massif. *Journal of Metamorphic Geology*, **11**, 241–260.

Okay, A.I., 1993. Petrology of a diamond and coesite-bearing metamorphic terrain: Dabie Shan, China. *European Journal of Mineralogy*, **5**, 659–675.

Okay, A.I., Arman, M.B. & Göncüoğlu, M.C., 1985. Petrology and phase relations of the kyanite-eclogites from eastern Turkey. *Contributions to Mineralogy and Petrology*, **91**, 196–204.

Okay, A.I., Xu, S.T. & Sengör, A.M.C., 1989. Coesite from the Dabie Shan eclogites, central China. *European Journal of Mineralogy*, **1**, 595–598.

Okay, A.I., Sengör, A.M.C. & Satir, M., 1993. Tectonics of an ultrahigh-pressure metamorphic terrane: the Dabie Shan/Tongbai Shan orogen, China. *Tectonics*, **12**, 1320–1334.

Reinecke, T., 1991. Very-high pressure metamorphism and uplift of coesite-bearing metasediments from the Zermatt-Saas zone, Western Alps. *European Journal of Mineralogy*, **3**, 7–17.

Schertl, H.P. & Okay, A.I., 1994. A coesite inclusion in dolomite in Dabie Shan, China: petrological and rheological significance. *European Journal of Mineralogy*, **6**, 995–1000.

Schertl, H.P., Schreyer, W. & Chopin, C., 1991. The pyrope–quartzite rocks and their country rocks at Parigi, Dora Maira Massif, Western Alps: detailed petrography, mineral chemistry and PT-path. *Contributions to Mineralogy and Petrology*, **108**, 1–21.

Schmidt, M.W. & Poli, S., 1994. The stability of lawsonite and zoisite at high pressures: experiments in CASH to 92 kbar and implications for the presence of hdrous phases in subducted lithosphere. *Earth and Planetary Science Letters*, **124**, 105–118.

Selverstone, J., Franz, G., Thomas, S. & Getty, S., 1992. Fluid variability in 2 GPa eclogites as an indicator of fluid behaviour during subduction. *Contributions to Mineralogy and Petrology*, **112**, 341–357.

Sharp, Z.D., Essene, E.J. & Smyth, J.R., 1992. Ultra-high temperatures from oxygen isotope thermometry of a coesite–sanidine grospydite. *Contributions to Mineralogy and Petrology*, **112**, 358–370.

Smith, D.C., 1984. Coesite in clinopyroxene in the Caledonides and its implication for geodynamics. *Nature*, **310**, 641–644.

Smyth, J.R. & Hatton, C.J., 1977, A coesite–sanidine grospydite from the Robert Victor kimberlite. *Earth and Planetary Science Letters*, **34**, 284–290.

Sobolev, N.V.jr., Kuznetsova, I.K. & Zyuzin, N.I., 1968. The petrology of grospydite xenoliths from the Zağadochnaya kimberlite pipe in Yakutia. *Journal of Petrology*, **9**, 253–280.

Sobolev, N.V. & Shatsky, V.S., 1990. Diamond inclusions in garnets from metamorphic rocks: a new environment for diamond formation. *Nature*, **343**, 742–746.

Spear, F.S. & Franz, G., 1986, P–T evolution of metasediments from the Eclogite Zone, south-central Tauern Window, Austria. *Lithos*, **19**, 219–234.

Turner, F.J., 1968. *Metamorphic Petrology*. McGraw-Hill, New York.

Wang, X., Liou, J.G. & Mao, H.K., 1989. Coesite-bearing eclogite from the Dabie Mountains in central China. *Geology*, **17**, 1085–1088.

Wang, X., Liou, J.G. & Maruyama, S., 1992. Coesite-bearing eclogites from the Dabie Mountains, central China: petrogenesis, P–T paths and implications for regional tectonics. *Journal of Geology*, **100**, 231–250.

Xu, S.T., Okay, A.I., Ji, S.Y., Sengor, A.M.C., Su, W., Liu, Y.C. & Jiang, L.L., 1992. Diamond from the Dabie Shan metamorphic rocks and its implication for tectonic setting. *Science*, **256**, 80–82.

Zhang, R., & Liou, J.G., 1994, Coesite-bearing eclogite in Henan Province, central China: detailed petrography, glaucophane stability and PT-path. *European Journal of Mineralogy*, **6**, 217–233.

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