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Petrology of a diamond and coesite-bearing metamorphic terrain: Dabie Shan, China

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Abstract: The Dabie Shan Complex with the ultra-high pressure rocks is a large gneiss-granite terrain in the eastern part of the Qinling orogen in central China. It represents part of the lower continental crust of the Yangtze Plate that was subducted during the Triassic continental collision and consists of several welded gneiss terrains with different metamorphic grades. The eclogite zone, one of these, is sandwiched between two amphibolite-facies gneiss terrains, and consists of an over 25 km thick, regularly southward dipping sequence of leucocratic, granoblastic gneiss with eclogite, marble and minor ultramafic bands and lenses. Two subzones with different P-T regimes are tentatively differentiated in the eclogite zone. In the hot eclogite terrain in the north the eclogites in the gneiss have the common mineral assemblage of garnet + omphacite + zoisite + kyanite + phengite ± Ca-amphibole ± quartz + rutile and very rarely coesite as inclusions in garnet. Eclogites also occur in marble bands as blocks; they are characterised by the absence of kyanite, the presence of diopside-rich pyroxene and grossular-rich garnet with coesite, K-feldspar and diamond inclusions. The eclogite mineral assemblages record temperatures of 800±50°C ($K_{Dgt\text{-}cpx} \approx 6$) and pressures ranging from 18 to 34 kbar while the presence of coesite and diamond at these temperatures indicates minimum pressures of 29 and 38 kbar respectively. The lower pressures recorded by the mineral assemblage is probably due to reequilibration during the uplift. The mineral assemblage in the gneiss, that forms the bulk of the eclogite zone, is quartz + plagioclase + garnet + phengite + epidote ± biotite ± microcline ± opaque ± titanite. Phengite inclusions in garnets in the gneiss with up to 3.56 Si p.f.u. and the rare presence of jadeite-gneiss with quartz + jadeite + garnet indicate minimum pressures of 17 and 22 kbar respectively and point to an early high-pressure metamorphic history. It is likely that the ultra-high-pressure metamorphism was regional and has affected both the eclogites and the host gneisses.

The coesite and diamond-free cold eclogite terrain in the south tectonically overlies the hot eclogite terrain, and is characterised by the absence of marble-eclogite horizons and by the presence of sodic amphibole-bearing eclogites. Otherwise it is lithologically similar to the hot eclogite terrain. The mineral assemblage in the eclogite is garnet + clinopyroxene + epidote + sodic amphibole + kyanite + quartz + rutile, which record temperatures of 635±40°C ($K_{Dgt\text{-}cpx} \approx 9$) and pressures of 18 to 26 kbar. The retrograde P-T path of the hot eclogite terrain appears to be very steep down to pressures of below 10 kbar where it was juxtaposed with the cold eclogite terrain. This was probably contemporaneous with the dominant structural imprint that obliterated any structural discordances that may have been present between the different tectonic units.

Key-words: metamorphism, eclogite, diamond, coesite, Dabie Shan, China.

Introduction

The description of ultra-high pressure minerals such as coesite and diamond in crustal rocks, with implications of burial of continental crust to depths of over 100 km, constitutes one of the major discoveries in geology in the 1980's (*e.g.* Chopin, 1984; Sobolev & Shatsky, 1990; Xu *et al.*, 1992). Detailed petrological studies of these metamorphic terrains are important to understand the regional extent of the ultra-high pressure metamorphism, the P-T path followed by these

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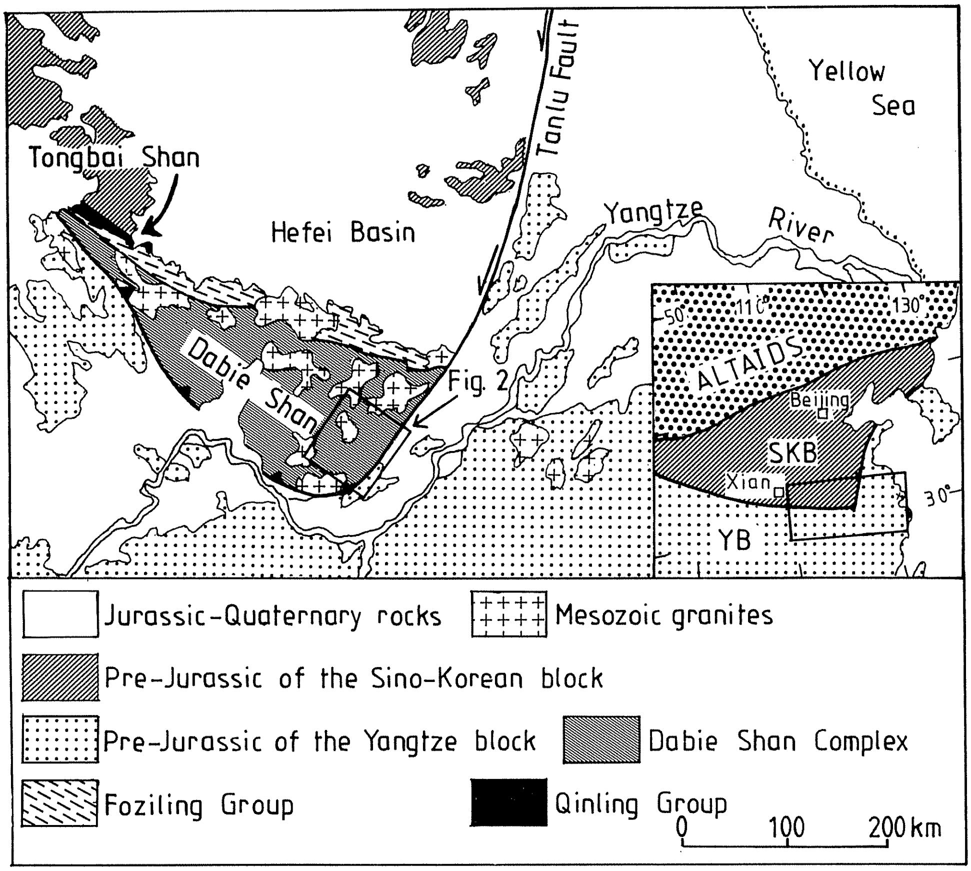

Fig. 1. Simplified tectonic map of the eastern Qinling orogen in China. The inset shows the Sino-Korean (SKB) and Yangtze blocks (YB).

rocks and phase relations under these extreme P-T conditions. One such large terrain with well-preserved ultra-high pressure metamorphic rocks is in Dabie Shan, China (Okay *et al.*, 1989; Wang *et al.*, 1989). Here I describe the petrology of this metamorphic terrain following four months field-work in the area in 1988 and 1990. The emphasis in the paper is on the characterisation of the peak metamorphic assemblages and peak metamorphic conditions.

Geological setting

Dabie Shan (Fig. 1) constitutes the eastern end of the Qinling orogen, which was produced during the Triassic continental collision between the Sino-Korean and Yangtze plates (*e.g.* Mattauer *et al.*, 1985). The Qinling orogen is characterised by E-W trending tectonic zones separated by steeply dipping faults. In the north in Tongbai Shan there are the Paleozoic arc and fore-arc sequences of the active margin of the Sino-Korean Block. These are in contact in the south with a steeply dipping belt of granulite-facies rocks with ultramafic slivers called the Qinling Group, which represents the suture root zone (Fig. 1). Farther south is a belt of fine-grained metaclastic rocks in greenschist facies called the Foziling Group. In the Dabie Shan region this monotonous metaclastic sequence is in steep tectonic contact in the south with a 150 km wide crystalline belt with the ultra-high pressure metamorphic rocks. This Dabie Shan Complex is thought to represent the subducted lower continental crust of the Yangtze Block. Preliminary isotopic data on eclogites indicate Triassic high-pressure metamorphism of a Precambrian crystal-

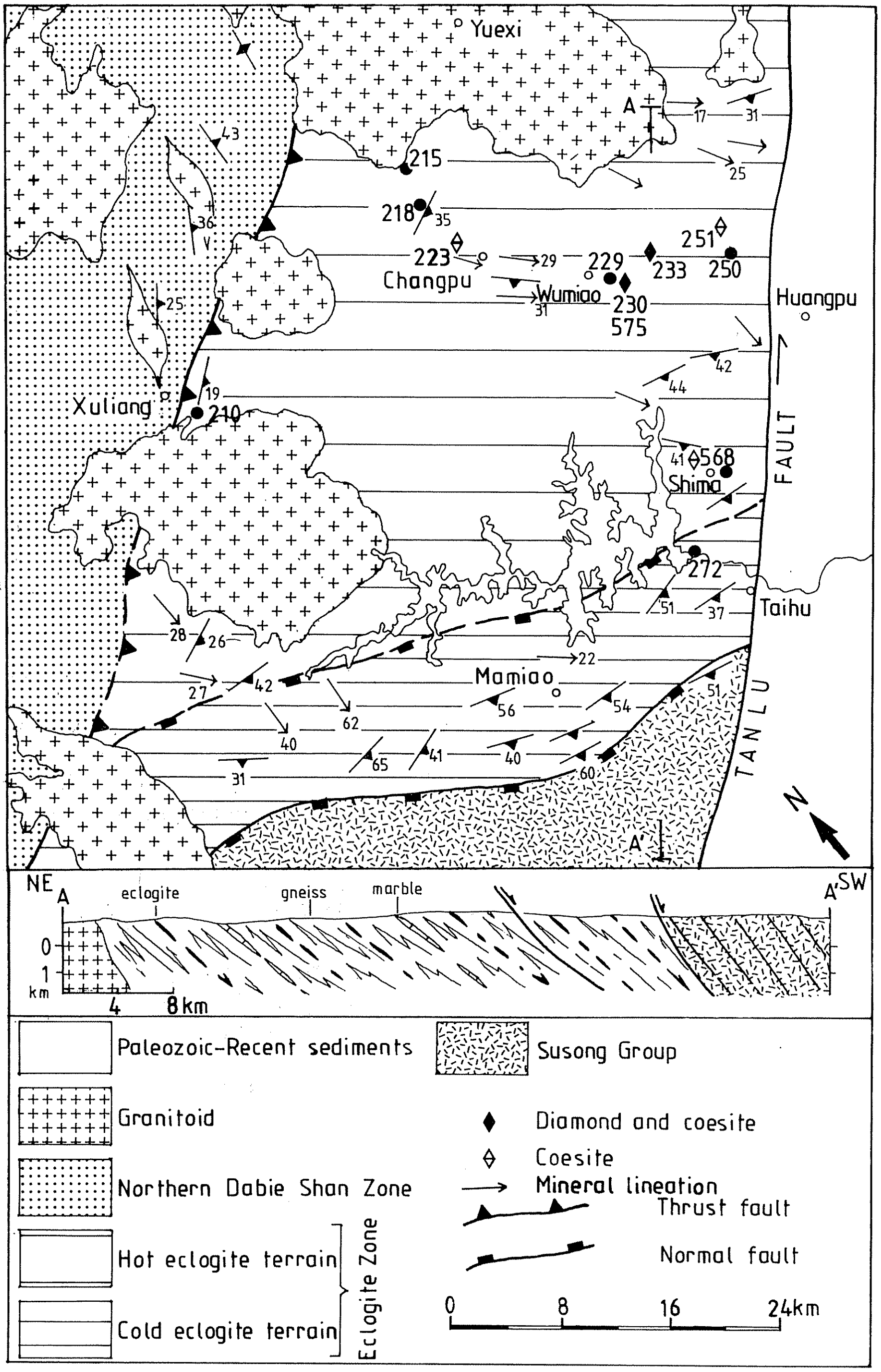

Fig. 2. Geological map and schematic cross-section of the eclogite zone in Dabie Shan. For location see Fig. 1. The locality numbers of the analysed samples are indicated.

line basement (Li *et al.*, 1989; M. Satır, pers. comm., 1992). The Dabie Shan Complex is in fault contact in the south with a Triassic foreland fold belt whose structurally lower levels show a Triassic high-pressure greenschist-facies metamorphism (Mattauer *et al.*, 1985).

The Dabie Shan Complex is subdivided into several tectonic terrains with different metamorphic grades all intruded by voluminous Mesozoic granitic bodies (Fig. 2). The *northern zone* comprises gneiss, augen-gneiss, migmatite and minor calc-silicate and basic granulite. It is characterised by high-grade amphibolite facies and associated partial melting that has largely overprinted an early granulite-facies event. The *eclogite zone* is made up of acidic gneiss with eclogite lenses and bands and rare marble layers. To the south the *Susong Group* comprises gneiss, micaschist, amphibolite and metaphosporite horizons. All the three terrains contain rare ultramafic bodies.

Eclogite zone

Field relations

The eclogite zone occupies an area of about 750 km^2 and forms a regularly south to southeast dipping gneiss-rich sequence cut by granitic bodies (Fig. 2). It is tectonically underlain by the sheared and foliated metagranites of the northern Dabie Shan zone and is tectonically overlain by the Susong Group. The southern Dabie terrain of Wang *et al.* (1992) includes both the eclogite zone and the Susong Group. The bulk of the Eclogite Zone (> 90 %) consists of white to pale grey, fine-grained, banded acidic gneiss with a granoblastic texture. The 5 to 30-cm-thick banding in the gneiss is due to variation in the mafic mineral content. Intense isoclinal folds with locally isolated fold hinges have completely transposed the banding so that the gneiss sequence has a structural thickness of over 25 kilometres. The gneiss frequently shows a mineral stretching lineation defined generally by quartz with a consistent southeasterly moderate plunge (Fig. 2). Irregular quartz and pegmatitic veins of quartz + K-feldspar, and N-S trending Mesozoic diorite, andesite and aplite dykes cut the gneisses. There is no field evidence for partial melting within the sequence. The gneisses contain frequent, variably amphibolitised eclogite intercalations generally ranging in thickness from 0.2 to several metres. In some cases the small eclogite layers can be followed along strike for over 100 metres; however in most outcrops they form several-metre-large boudins that show amphibolitisation along their contacts with the gneiss. At several locali-

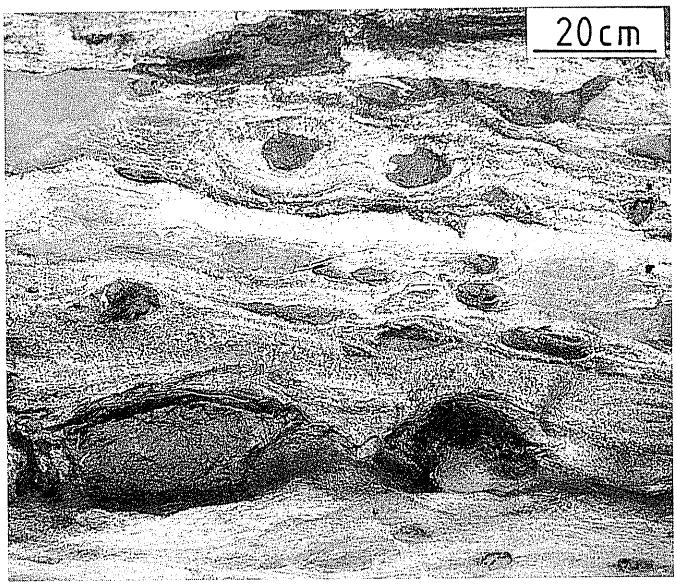

Fig. 3. Diamond and coesite-bearing eclogite blocks in marble (locality 233). The marble forms a 10 m thick band in acidic gneiss with a 0.25 m thick chlorite-quartz band at the contact.

Table 1. Estimated modal amounts of the analysed samples. The numbers in brackets indicate the modes of plagioclase + diopside/amphibole symplectite in the clinopyroxene row, and biotite + feldspar corona in the phengite row.

	eclogite in gneiss			marble	eclogite in marble					gneiss		
	229B	250H	272A	575E	575G	230D	575C	223B	251A	215D	251C	250G
garnet	50	36	18	-	8	47	36	18	52	17	2	5
clinopyroxene	40(2)	34(1)	9(33)	20	(43)	41	42(2)	63(5)	46(2)	-	3(46)	1(4)
amphibole	6	22	8	4	-	-	-	4	-	-	-	2
kyanite	2	-	2	-	-	-	-	-	-	-	-	6
zoisite	-	4	-	-	-	5	2,i	-	-	-	-	51
epidote	-	-	12	-	2	-	-	-	-	3	-	-
phengite	-	3	-	1	5(15)	2	3(2)	-	-	15	-	4
quartz	-	-	15	-	16	-	1	tr	tr	30	40	26
coesite	-	-	-	-	-	-	tr	tr,p	tr,p	-	-	-
calcite	-	-	-	60	2	-	4	3	tr	1	-	-
dolomite	-	-	-	15	-	4	-	-	-	-	-	-
diamond	-	-	-	-	-	tr	-	-	-	-	-	-
rutile	tr	tr	1	-	tr	tr	2	-	tr	1	tr	1
K-feldspar	-	-	-	-	-	-	-	tr	-	-	-	-
apatite	-	-	-	-	tr	-	1	-	-	tr	1	tr
opaque	-	-	-	-	1 py	-	2 py	-	-	3 il	1 il	-
titanite	-	-	-	-	tr	-	-	3	tr	2	tr	-
late amphibole	-	-	2	-	5	-	3	4	-	-	7	-
biotite	-	-	-	-	3	-	-	-	-	12	-	-
chlorite	-	-	-	-	-	-	-	-	-	2	-	-
plagioclase	-	-	-	-	-	-	-	-	-	14	-	-

p denotes pseudomorphs after coesite. All samples contain trace amounts of anhedral to subhedral zircon, tr < 1%; il, ilmenite; py, pyrite; i, inclusion.

ties centimetre-thick gneiss bands with high-pressure parageneses occur between thicker eclogite layers. Up to 30-40 cm large nests composed of 10-15 cm long kyanite, zoisite and quartz crystals occur in several eclogites. Some eclogite bodies show a weak mineral lineation defined by zoisite and/or late hornblende crystals that is subparallel to the more conspicuous lineation in the gneiss.

A spectacular lithology in the gneisses of the eclogite zone is 0.2 to several metres thick discontinuous impure marble layers that frequently contain lensoid eclogite blocks (Fig. 3), which may represent original marly layers in limestone. This marble-calcsilicate-eclogite association is similar to those described from the Tauern Window in the Eastern Alps (*e.g.* Holland, 1979). The impure marble is greenish grey, white, medium-grained, irregularly banded and locally shows a strong mineral lineation that is subparallel to the lineation in the gneiss. There is a continuous petrographic transition from essentially pure marble through calc-silicate to eclogite which also occurs as 0.5 cm to 2 m large, rotated, ellipsoidal, distinct blocks in the carbonates (Fig. 3).

Partially to completely serpentinised garnet-peridotites, often closely associated with the eclogites, occur as rare, structurally conformable small lenses in the gneiss. Most lenses are a few metres thick and a few ten metres long antigorite-serpentinites.

Based on petrological studies the eclogite zone is provisionally subdivided into two terrains; a northern hot eclogite terrain characterised by higher-temperature eclogites and marble-eclogite association, and a southern coesite- and diamond-free cold eclogite terrain with lower-temperature, sodic- amphibole-bearing eclogites.

Analytical techniques

Minerals from 12 selected samples (Table 1) were analysed under standard conditions with wavelength-dispersive techniques using the Jeol electron microprobe in Lamont-Doherty Geological Observatory (samples 229B, 250G,H, 251A,C) and the Cameca SX-50 electron probe in the Department of Earth Sciences in Cambridge (other samples). The pyroxene analyses were calculated for six oxygens. The jadeite content is taken to be equal to octahedral aluminium where Na ≤ Al^6, otherwise the Na content equals the jadeite component. Aegirine component equals Na - Al^6 - Ti - Cr. The rest is assigned to the augite component. The ferric iron in amphibole was estimated by assuming a total charge of 46 and Si + Ti + Al + Fe^{3+} + Fe^{2+} + Mg + Mn = 13.00.

Both conventional mineral thermobarometers and the THERMOCALC program of Holland & Powell (1990) were used in the estimation of the P-T conditions. The mineral compositions used for THERMOCALC are listed in Tables 2 to 4. The activities of mica, amphibole and epidote components are calculated assuming ideal-mixing-on-sites as recommended by Holland & Powell (1990). Garnet activities were calculated from Newton & Haselton (1981) except for grossular where the activity coefficients of Koziol & Newton (1989) were used. There are several versions of the garnet-clinopyroxene Fe^{2+}-Mg geothermometer, which is the main means for estimating metamorphic temperature in the eclogites. The one used here is that of Ellis & Green (1979). It gives reasonable temperature estimates with garnets of low to medium grossular contents (X_{gr} < 0.5) but produces unreasonably high temperature estimates for higher grossular contents. This is due to the reversal of the gradual decrease in the activity coefficient of grossular at above X_{gr} > 0.5 in the Ca-Fe-Mg garnets (Koziol & Newton, 1989). This reversal is partly accounted for in the calibration of Krogh (1988); however, this calibration gives unusually low temperatures for low to medium grossular contents.

Petrography, mineral chemistry and P-T conditions in the "hot" eclogite terrain

Eclogite lenses and bands in the acidic gneiss

Sixtysix metabasite samples from 23 localities were petrographically examined and two were selected for electron probe analysis (Table 1). Even in close proximity the metabasic rocks range from fresh to strongly amphibolitised eclogite. The mineral assemblage in the common

Table 2. Microprobe analyses of minerals from eclogites in gneiss and from the zoisite-gneiss.

	250H eclogite in gneiss					250G zoisite-gneiss					272A glaucophane-eclogite in gneiss				
	gt	am	px	ph	zo	gt core	gt rim	ph	px	zo	gt core	gt rim	am	px	ep
SiO_2	40.76	52.46	55.93	53.24	39.36	40.16	40.79	52.02	56.19	39.65	38.67	38.83	55.38	55.52	37.49
TiO_2	0.00	0.09	0.03	0.26	0.21	0.00	0.00	0.22	0.05	0.04	0.06	0.03	0.05	0.03	0.01
Al_2O_3	22.65	8.44	8.08	26.35	31.73	22.67	22.77	25.35	9.79	31.54	21.57	21.59	9.54	8.93	24.91
Cr_2O_3	0.07	0.01	0.10	0.35	0.07	0.00	0.00	0.00	0.02	0.00	0.01	0.03	0.06	0.08	0.06
FeO	17.66	4.23	2.74	0.88	1.78	22.63	19.61	1.57	4.43	1.92	23.82	24.54	8.55	9.32	10.66
MgO	13.55	18.92	11.18	4.77	0.04	11.15	10.60	4.84	9.22	0.05	8.11	9.53	13.77	6.99	0.28
MnO	0.31	0.00	0.03	0.00	0.04	0.36	0.37	0.01	0.03	0.00	0.84	0.81	0.05	0.05	0.04
CaO	5.11	9.99	16.44	0.00	24.07	4.57	7.37	0.00	14.02	24.34	6.97	4.67	2.67	10.61	22.50
Na_2O	0.01	2.59	4.72	0.18	0.06	0.02	0.00	0.23	6.49	0.06	0.19	0.09	6.21	8.34	0.02
K_2O	0.01	0.30	0.00	9.70	0.00	0.00	0.00	9.15	0.00	0.00	0.01	0.01	0.02	0.00	0.01
Total	100.13	97.15	99.12	95.38	97.19	101.56	101.51	93.39	100.24	97.60	100.25	100.13	96.28	99.87	95.98
	12 Ox	23 Ox	6 Ox	11 Ox	8 cat	12 Ox	12 Ox	11 Ox		8 cat	12 Ox	12 Ox			8 cat
Si	3.010	7.244	2.004	3.484	3.021	2.988	3.015	3.494	2.000	3.029	2.976	2.978	7.622	1.984	2.988
Al^4	0.000	0.756	0.000	0.516	0.000	0.012	0.000	0.506	0.000	0.000	0.024	0.022	0.378	0.016	0.012
Al^6	1.972	0.615	0.341	1.517	2.870	1.976	1.984	1.501	0.411	2.841	1.932	1.930	1.172	0.367	2.328
Ti	0.000	0.009	0.001	0.013	0.002	0.000	0.000	0.011	0.001	0.002	0.004	0.002	0.004	0.001	0.000
Cr	0.004	0.001	0.003	0.019	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.002	0.008	0.002	0.004
Fe^{3+}	0.024	0.389	0.000		0.115	0.024	0.016		0.035	0.123	0.064	0.066	0.706	0.208	0.710
Fe^{2+}	1.065	0.099	0.081	0.048		1.384	1.196	0.088	0.097		1.468	1.508	0.278	0.071	
Mg	1.492	3.886	0.597	0.465	0.004	1.236	1.167	0.484	0.489	0.006	0.930	1.090	2.825	0.373	0.032
Mn	0.020	0.003	0.000	0.000	0.002	0.022	0.023	0.001	0.001	0.000	0.054	0.052	0.006	0.002	0.002
Ca	0.405	1.489	0.631	0.000	1.979	0.364	0.584	0.000	0.535	1.991	0.574	0.384	0.399	0.406	1.922
Na	0.002	0.698	0.328	0.023	0.008	0.000	0.000	0.030	0.448	0.008	0.028	0.012	1.683	0.578	0.002
K	0.001	0.054	0.000	0.810	0.000	0.000	0.000	0.784	0.000	0.000	0.000	0.000	0.004	0.000	0.000
Total	7.995	15.243	3.984	6.876	8.001	8.006	7.970	6.899	4.018	8.000	8.054	8.046	15.085	4.008	8.000
alm	35.7	jd	32.8		alm	46.1	40.2	jd	41.1	alm	48.5	49.7	jd	36.7	
py	50.0	ac	0.0		py	41.1	39.3	ac	3.5	py	30.7	35.9	ac	20.8	
sp	0.7	au	67.2		sp	0.7	0.8	au	55.4	sp	1.8	1.7	au	42.5	
gr+and	13.6				gr+and	12.1	19.7			gr+and	19.0	12.7			

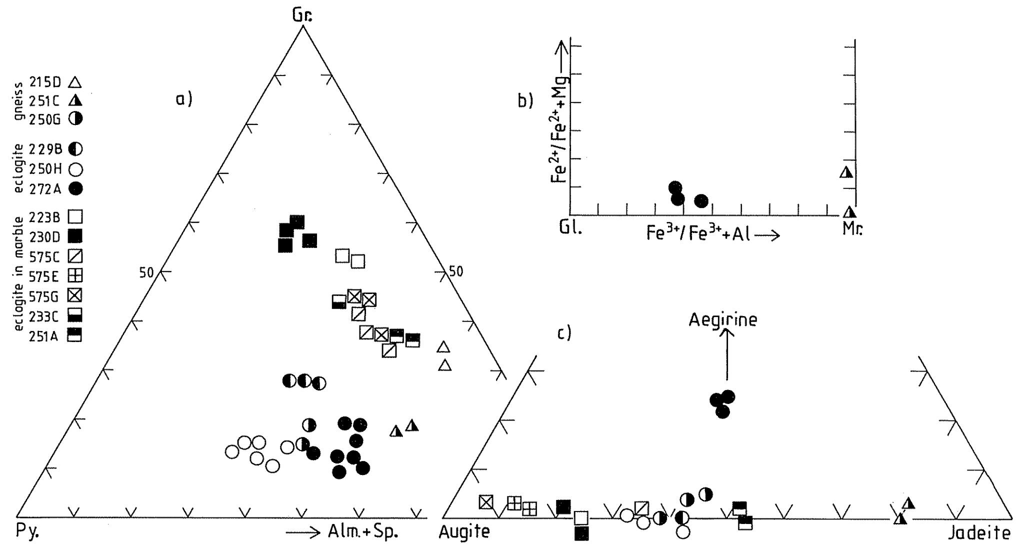

Fig. 4. a) Representative garnet compositions from gneiss (spessartine < 4%), from eclogite in gneiss (sp < 2%), from eclogite and calc-silicate in marble (sp < 1%).

b) Sodic amphibole compositions plotted on part of the Miyashiro diagram (Gl, glaucophane; Mr, magnesioriebeckite).

c) Representative clinopyroxene compositions from various rock types in Dabie Shan plotted on the jadeite-augite-aegirine diagram. Note that the augite compositions from 575C are from the symplectite.

eclogite, as exemplified by sample 250H, is garnet + omphacite + amphibole + zoisite + phengite + rutile (Table 1). The rock has a well developed linear and planar fabric defined by millimetre-size, parallel aligned omphacite and rare acicular zoisite crystals with interstitial garnet. Colourless amphibole occurs as strongly poikilitic, up to one-centimetre-large grains with inclusions of all the anhydrous phases. The amphibole is texturally and chemically quite different from the late green hornblende and is part of the eclogite mineral assemblage, however it is not clear whether it was stable at the peak metamorphic conditions. Garnet ($alm_{33}gr_{14}py_{52}sp_{1}$) and omphacite ($jd_{32}au_{67}aeg_{1}$) do not show any clear zoning (Table 2, Fig. 4). Amphibole is a tremolitic hornblende with a high ferric iron content (Table 2, Fig. 5). Phengite contains a maximum of 3.49 Si p.f.u. (Fig. 6), and zoisite has 4 mol% pistacite component (Table 2).

The other analysed eclogite (229B) is texturally and mineralogically similar to 250H. However, it contains kyanite and no phengite in the primary mineral assemblage (Table 1) and its mineral compositions are somewhat different reflecting a more Mg- and Ca-rich bulk rock composition (Fig. 4, Table 3). Adjoining garnet and omphacite compositions from these two eclogites yield K_D values in the range of 4 to 8 and show the expected positive correlation with the grossular content of garnet (Fig. 7). These K_D values are lower than those from the coesite-bearing eclogites in the Dora Maira in the Alps (K_D 6 to 17, Chopin *et al.*, 1991) but are similar to those from eclogite nodules in kimberlite pipes (*e.g.* Lovering & White, 1969). The average temperature calculated for the two samples 250H and 229B are 788±50°C and 805±20°C respectively for 30 kbar pressure. Two reactions were used for geobarometry (Fig. 8):

6 diopside + 3 muscovite =
pyrope + 2 grossular + 3 celadonite (1)

3 diopside + 3 hedenbergite + 3 muscovite =
2 grossular + almandine + 3 celadonite (2).

Reaction (1) is a particularly good geobarometer as it avoids H_2O and the iron-bearing components, has a very flat slope in the P-T field and the components in the reaction are well represented in the phases. Using the THERMOCALC program, reactions (1) and (2) indicate for a given

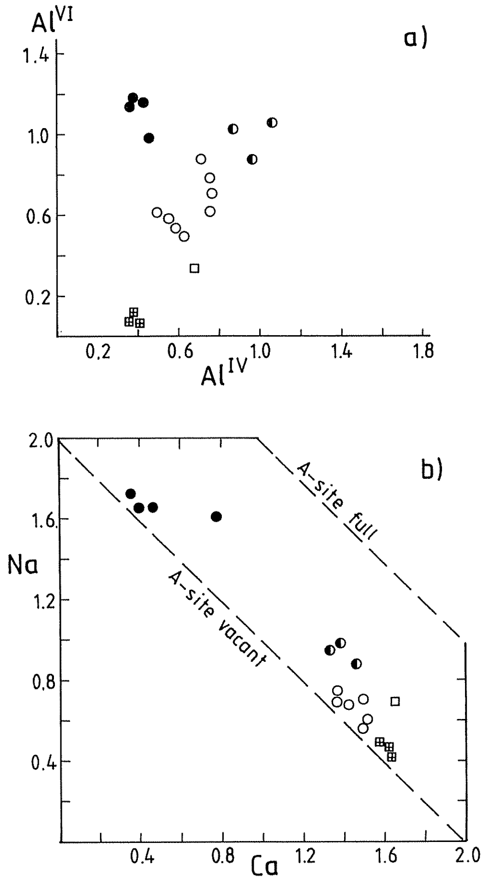

Fig. 5. Eclogitic amphibole compositions from Dabie Shan plotted on a) Al^4-Al^6 and b) Ca-Na diagrams. Symbols as in Fig. 4a.

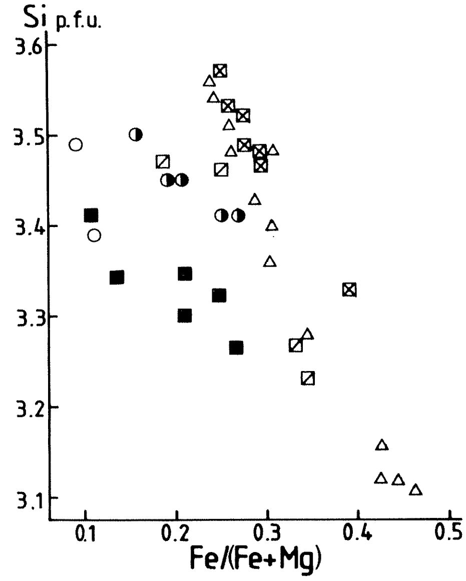

Fig. 6. Phengite compositions from Dabie Shan shown in terms of Si per formula unit against Fe/(Fe+Mg). Symbols as in Fig. 4a.

temperature of 800°C, a pressure of 18±4 kbar for sample 250H (Fig. 8). This pressure is considerably lower than that required for the stabilisation of coesite, which is described from the eclogites in gneiss (Wang *et al.*, 1992), suggesting that the minerals, especially phengite, have equilibrated to lower pressures during the uplift.

Impure marble with eclogite blocks

Out of 64 specimens from ten marble localities that were petrographically examined, seven were chosen for microprobe analysis (Table 1). Most of my diamond and coesite discoveries come from these localities. Compared to the eclogites from the gneiss, eclogites from the marble are characterised by high Ca and low Mg garnets and diopside-rich clinopyroxenes, and by the absence of kyanite in the mineral assemblage. A particularly well-exposed coesite and diamond-bearing marble locality is a road side quarry south of Wumiao (samples 575C, E, G and 230D). The marble contains calc-silicate bands with 3 to 60 cm large eclogite blocks.

The marble assemblage (sample 575E) is calcite + dolomite + tremolite + diopside + phengite (Table 1), similar to that of the siliceous dolomites in the eclogite zone in the Tauern Window in the Alps (Franz & Spear, 1983). Calcite ($Ca_{0.89}Mg_{0.10}Fe_{0.01}CO_3$) and dolomite ($Ca_{0.44}Mg_{0.53}Fe_{0.03}CO_3$) make up over 80% of the rock and form a polygonal mosaic with corroded sodium-rich diopside crystals ($jd_{14}di_{85}aeg_{1}$) rimmed and partially replaced by sodium-rich tremolite (Fig. 4 and 5, Table 3). Tremolite also occurs as prismatic crystals in the matrix. The calcite-dolomite geothermometry (Goldsmith & Newton, 1969) indicates a temperature of 620°C for 15 kbar pressure. As $MgCO_3$ is not soluble in aragonite, this temperature provides a lower limit where the aragonite/calcite reaction curve was crossed on the uplift path.

Table 3. Microprobe analyses of minerals from eclogites in gneiss, in marble and marble matrix.

	229B eclogite in gneiss			575C eclogite in marble				230D eclogite in marble				575E impure marble			
	gt	am	px	am	gt	ph	px	ph	gt	zo	px	am	px	cc	dol
SiO_2	40.06	50.31	56.29	45.70	38.26	50.08	55.40	49.30	39.74	38.41	55.44	55.65	55.70	0.13	0.30
TiO_2	0.06	0.06	0.04	0.43	0.10	0.17	0.04	0.00	0.20	0.13	0.05	0.01	0.02	0.07	0.00
Al_2O_3	22.92	11.06	10.58	12.11	21.98	23.91	8.57	26.07	22.23	32.07	5.66	2.91	3.28	0.07	0.00
Cr_2O_3	0.34	0.39	0.57	0.01	0.03	0.02	0.01	0.00	0.15	0.13	0.13	0.04	0.07	0.00	0.00
FeO	15.51	6.82	1.83	11.11	17.86	1.91	3.19	0.97	8.61	1.32	1.67	2.31	1.75	0.49	1.88
MgO	10.59	15.67	9.56	13.03	5.20	4.72	10.61	4.72	6.23	0.00	13.53	22.71	15.79	3.57	22.21
MnO	0.33	0.02	0.00	0.10	0.60	0.00	0.06	0.01	0.24	0.00	0.21	0.00	0.01	0.00	0.00
CaO	11.18	9.69	14.45	9.90	15.69	0.01	16.72	0.02	21.67	23.29	19.21	10.81	20.51	45.26	25.97
Na_2O	0.00	3.23	6.24	3.45	0.07	0.32	5.46	0.17	0.11	0.00	3.58	1.77	2.25	0.02	0.22
K_2O	0.00	0.15	0.00	0.68	0.01	10.90	0.01	10.39	0.00	0.00	0.00	0.05	0.00	0.00	0.02
Total	100.99	97.40	99.56	96.52	99.80	92.04	100.06	91.65	99.18	91.65	99.48	96.26	99.38	49.61	50.60
	12 Ox	23 Ox	6 Ox	23 Ox	12 Ox	11 Ox	6 Ox	11 Ox	12 Ox	8 cat		23 Ox			
Si	2.964	7.049	1.995	6.668	2.950	3.473	1.981	3.403	2.992	2.999	1.995	7.625	2.007	0.006	0.009
Al^4	0.036	0.951	0.005	1.332	0.050	0.527	0.019	0.597	0.008	0.001	0.005	0.375	0.000	0.003	0.000
Al^6	1.963	0.876	0.437	0.752	1.948	1.428	0.342	1.524	1.966	2.951	0.235	0.094	0.139	0.002	0.000
Ti	0.004	0.006	0.001	0.046	0.006	0.009	0.001	0.000	0.012	0.008	0.001	0.000	0.000		0.000
Cr	0.020	0.043	0.016	0.000	0.002	0.002	0.000	0.000	0.010	0.008	0.004	0.004	0.002	0.000	0.000
Fe^{3+}	0.013	0.187	0.000	0.252	0.044		0.028		0.012	0.085	0.009	0.264	0.016	0.000	0.000
Fe^{2+}	0.946	0.613	0.054	1.105	1.108	0.110	0.067	0.057	0.530		0.041	0.000	0.037	0.015	0.050
Mg	1.168	3.273	0.505	2.835	0.598	0.488	0.566	0.486	0.700	0.000	0.726	4.638	0.848	0.195	1.047
Mn	0.021	0.003	0.000	0.011	0.040	0.000	0.002	0.000	0.016	0.000	0.001	0.000	0.000	0.000	0.000
Ca	0.887	1.462	0.548	1.556	1.296	0.000	0.641	0.004	1.748	1.948	0.741	1.610	0.792	1.778	0.879
Na	0.000	0.882	0.429	0.981	0.010	0.044	0.379	0.022	0.016	0.000	0.249	0.475	0.157	0.001	0.014
K	0.000	0.027	0.000	0.127	0.000	0.965	0.000	0.908	0.000	0.000	0.000	0.008	0.000	0.000	0.001
Total	8.022	15.371		15.665	8.052	7.046	4.026	7.001	8.010	8.000	4.007	15.093	3.998	2.000	2.000
alm	31.3	jd	42.9	alm	36.4	jd	34.2	alm	17.7	jd	23.5		13.9	cc 89.4	44.5
py	38.7	ac	0.0	py	19.7	ac	3.6	py	23.4	ac	0.9		1.6	mg 9.8	53.0
sp	0.7	au	57.1	sp	1.3	au	62.2	sp	0.5	au	75.6		84.5	sid 0.8	2.5
gr+and	29.3			gr+and	42.6			gr+and	58.4						

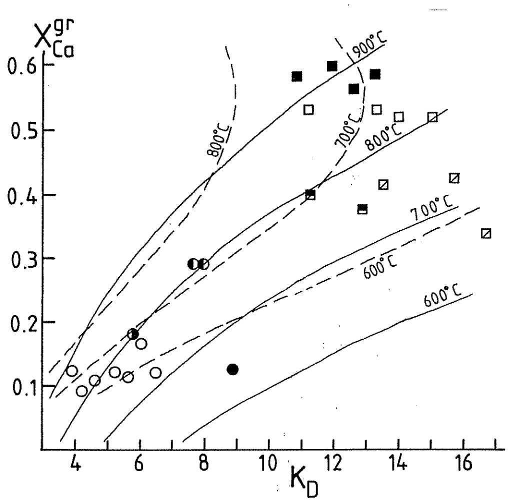

Fig. 7. The K_D values $((Fe^{2+}/Mg)_{gt}/(Fe^{2+}/Mg)_{px})$ of eclogitic rocks plotted against the grossular content (Ca/(Ca+Fe+Mg+Mn)) of garnet; symbols as in Fig. 4. Also shown are the 30-kbar isotherms of Ellis & Green (1979) (continuous lines) and Krogh (1988) (broken lines).

The primary mineral assemblage in the marble was diopside + dolomite + aragonite, which is stable to very high pressures. The tremolite has formed by the following reaction:

dolomite + 4 diopside + H_2O + CO_2 =
3 calcite + tremolite (3).

This reaction has a very steep P/T slope for a wide range of X_{CO_2} values and for pressures of over 4 kbar (*cf.* Fig. 12). As both calcite and dolomite compositions are homogeneous in the rock, the calcite-dolomite geothermometry probably indicates the temperature of the reaction (3).

The dark grey calc-silicate band (sample 575G) has a similar mineral assemblage to the eclogite (garnet + omphacite + phengite + quartz + calcite) but is characterised by the much greater abundance of quartz and phengite (Table 1). Garnet ($alm_{37}gr_{43}py_{19}sp_1$) forms a-few-millimetre-large subhedral grains, that show no zoning (Fig. 4). The primary clinopyroxene is now all replaced by a dark, very fine-grained intergrowth of sodic diopside and oligoclase (an_{15}). The up to 3 mm large phengite flakes, with wide

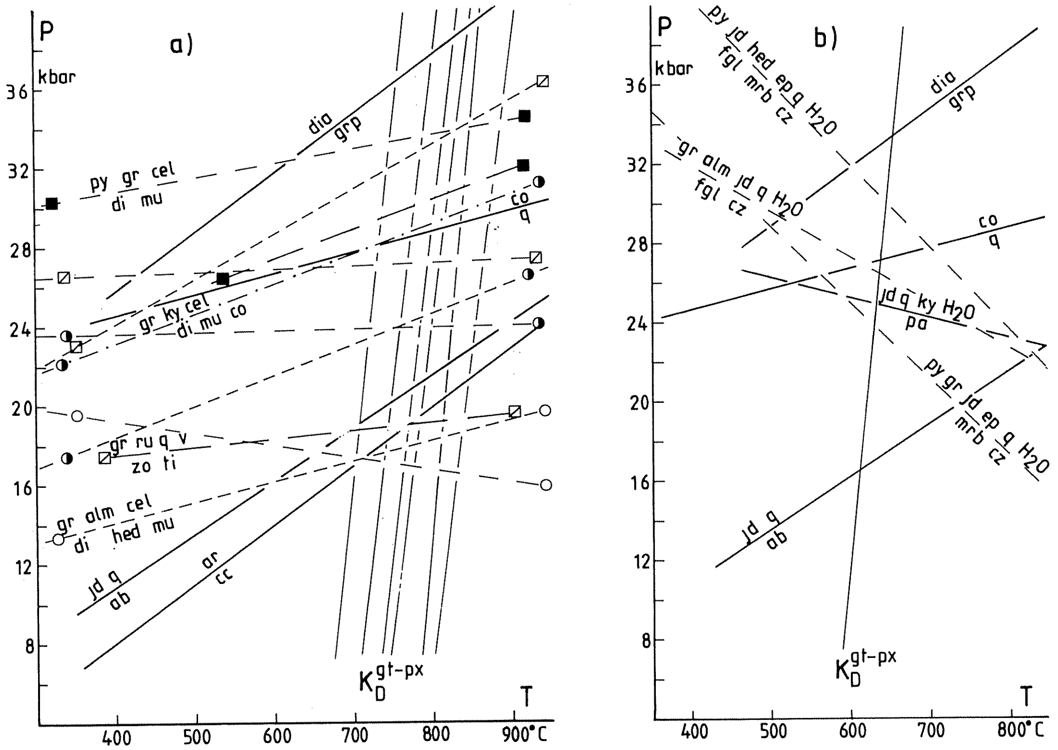

Fig. 8. Relevant P-T equilibria for the eclogite-zone assemblages. Garnet-clinopyroxene equilibria are after Ellis & Green (1979), all other reaction lines with uncertainties of ±3 kbar are calculated using THERMOCALC software (Holland & Powell, 1990).
a) Reactions for the hot eclogite terrain. The dashed lines represent reactions using garnet, clinopyroxene and phengite components in the analysed samples (circles, 250H; half-filled circles, 250G; square with the diagonal, 575C; filled square, 230D). For mineral compositions used in these reaction see Tables 2 to 4. The solid lines are end-member reactions. Also shown are representative garnet-clinopyroxene equilibria from the above assemblages using garnets with grossular contents less than 50 mol%.
b) Reactions for the cold eclogite terrain sample 272A. The dashed lines represent reactions using garnet, clinopyroxene, sodic amphibole and epidote components (*cf.* Table 2). The solid lines are end-member reactions. ab, high albite; alm, almandine; ar, aragonite; cc, calcite; co, coesite; cz, clinozoisite; di, diopside; dia, diamond; ep, epidote; fgl, ferroglaucophane; gl, glaucophane; gr, grossular; grp, graphite; hed, hedenbergite; jd, jadeite; ky, kyanite; mrb, magnesioriebeckite; mu, muscovite; px, clinopyroxene; py, pyrope; q, quartz; ru, rutile; ti, titanite; v, H_2O; zo, zoisite.

reaction rims of biotite + orthoclase + oligoclase, show a consistent rimward decrease in silicon from around 3.53 to 3.46 p.f.u. (Fig. 6).

The mineral assemblage in the eclogite pod (sample 230D) in the calc-silicate band is garnet + sodic augite + zoisite + phengite + dolomite + rutile + diamond. Garnet forms up to 1.5 cm large anhedral grains overgrowing and enclosing smaller omphacite, zoisite, phengite, rutile and dolomite crystals. Garnet ($alm_{19}gr_{58}py_{23}$) and clinopyroxene ($jd_{24}au_{75}aeg_{1}$) are not zoned (Fig. 4). Two 30 μm large crystals of diamond of cubic shape with stepped-layered faces, recognised from their characteristic cubic crystal forms and optical properties (*cf.* Xu *et al.*, 1992), occur as inclusions in the garnet porphyroblasts. Sm-Nd garnet-whole rock and Rb-Sr phengite-whole rock ages from this sample are 246±6 and 240±2.4 Ma respectively (M. Satır, pers. comm., 1992). Diamond is also identified from the eclogite blocks in marble (Fig. 3) where coesite was first described in the Dabie Shan Complex (Sample 233, Okay *et al.*, 1989). In this sample diamond occurs as aggregates of twelve 2 to

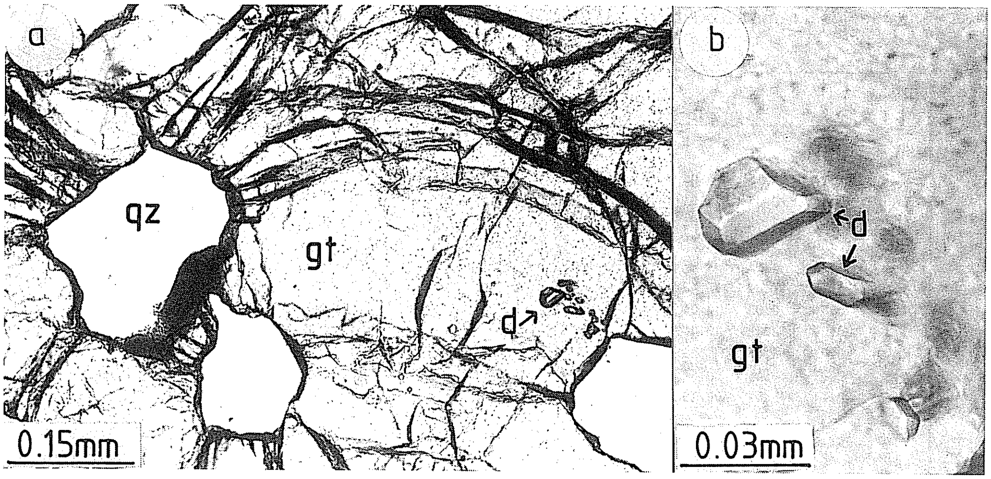

Fig. 9. a) Inclusion of diamonds (d) and quartz pseudomorphs after coesite (qz) in garnet (gt) from an eclogite block in marble (locality 233, see Fig. 3).
b) Enlarged view of the diamond inclusions with cubo-octahedral faces. The dark areas to the right of the inclusions are smaller cubic and octahedral diamonds that are out of focus. Micrograph with plane polarised light.

30 μm large cubic, cubo-octahedral and octahedral crystal inclusions in garnet (Fig. 9). The cube faces have a convex curvature which is characteristic for natural diamonds as opposed to the flat faces in synthetic diamonds (*cf.* Shatsky *et al.*, 1989). The other studied eclogite block from this outcrop (575C) is texturally and mineralogically similar to 230D (Table 1) but is characterised by less Ca-rich garnet ($alm_{38}gr_{41}py_{20}sp_1$) and omphacite ($jd_{35}au_{63}aeg_2$); diamond is absent in this rock while a single rounded crystal of coesite 0.3 mm across with narrow rims of quartz occurs as inclusion in omphacite which is itself semi-enclosed by garnet (Fig. 10). Coesite is recognised from its optical properties, from the radial fractures around it, and its presence was confirmed by the electron microprobe analysis.

Another sampled calc-silicate locality is a 4-m-

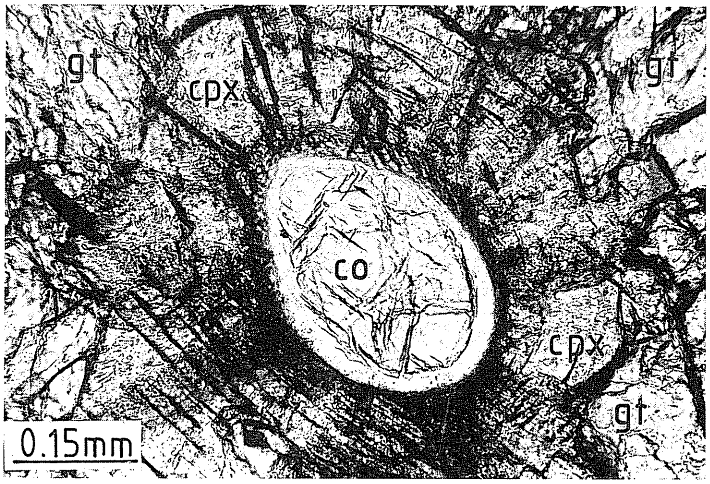

Fig. 10. Rounded coesite (co) inclusion in omphacite (cpx) in eclogite from the marble (sample 575C). Notice the radial strain patterns and fractures around the coesite. The omphacite is itself enclosed by garnet (gt). Micrograph with plane polarised light.

Table 4. Microprobe analyses of minerals from eclogites in marble and from the gneiss.

	223B				251A		215D				251C	
	eclogites in marble						common gneiss				jadeite-gneiss	
	gt	am	px	K-fs	gt	px	gt	ph inc	mu rim	bi	gt	px
SiO_2	39.17	51.15	55.04	64.97	38.80	56.29	37.19	52.17	45.11	35.60	38.88	58.34
TiO_2	0.13	0.07	0.03	0.01	0.07	0.04	0.10	0.34	0.51	1.80	0.03	0.03
Al_2O_3	21.97	5.92	5.84	18.75	21.67	12.48	21.41	22.71	31.80	16.80	22.00	19.92
Cr_2O_3	0.00	0.03	0.00	0.02	0.02	0.03	0.01	0.04	0.04	0.05	0.01	0.06
FeO	14.31	6.86	3.27	0.02	21.83	3.99	26.07	2.63	2.54	20.50	26.21	3.55
MgO	3.95	17.89	12.42	0.00	3.37	7.05	2.23	4.71	1.66	8.91	6.51	2.29
MnO	0.53	0.08	0.01	0.00	0.44	0.00	0.64	0.05	0.05	0.23	0.61	0.01
CaO	20.29	10.62	19.14	0.21	14.63	11.82	12.39	0.00	0.03	0.02	6.27	3.81
Na_2O	0.03	2.46	3.39	0.21	0.01	7.65	0.07	0.10	0.65	0.20	0.04	11.81
K_2O	0.03	0.45	0.00	15.22	0.01	0.01	0.00	11.09	10.78	9.86	0.00	0.00
Total	100.41	95.53	99.15	99.22	100.85	99.35	100.11	93.84	93.17	93.97	100.56	99.42
	12 Ox	23 Ox	6 Ox	8 Ox	12 Ox		12 Ox	11 Ox	11 Ox	11 Ox	12 Ox	6 Ox
Si	2.982	7.330	1.996	3.003	2.994	2.002	2.945	3.555	3.113	2.781	2.998	2.021
Al^4	0.018	0.670	0.004	0.000	0.006	0.000	0.055	0.445	0.887	1.219	0.002	0.000
Al^6	1.954	0.332	0.246	1.021	1.965	0.523	1.947	1.378	1.700	0.328	1.997	0.797
Ti	0.008	0.008	0.001	0.000	0.004	0.001	0.006	0.017	0.025	0.106	0.002	0.001
Cr	0.003	0.000	0.000	0.000	0.001	0.001	0.000	0.002	0.002	0.007	0.000	0.002
Fe^{3+}	0.049	0.269	0.000	0.001	0.030	0.002	0.047			0.041	0.000	
Fe^{2+}	0.860	0.553	0.099		1.376	0.117	1.681	0.150	0.147	1.340	1.690	0.103
Mg	0.448	3.823	0.671	0.000	0.388	0.374	0.264	0.479	0.170	1.038	0.749	0.118
Mn	0.034	0.012	0.000	0.000	0.029	0.000	0.042	0.002	0.002	0.015	0.040	0.000
Ca	1.655	1.639	0.743	0.001	1.210	0.451	1.052	0.000	0.002	0.002	0.518	0.141
Na	0.005	0.689	0.238	0.019	0.001	0.527	0.010	0.013	0.086	0.031	0.007	0.793
K	0.003	0.081	0.000	0.897	0.001	0.000	0.000	0.964	0.950	0.983	0.000	0.000
Total	8.005	15.406	3.998	4.942	8.005	3.998	8.049	7.005	7.084	7.850	8.004	3.976
alm	28.7		jd 23.8	or 97.8	alm 45.8	jd 52.3	alm 55.3				alm 56.4	jd 79.3
py	15.0		ac 0.0	ab 2.1	py 12.9	ac 0.2	py 8.7				py 25.0	ac 0.0
sp	1.1		au 76.2	an 0.1	sp 1.0	au 47.5	sp 1.4				sp 1.3	au 20.7
gr+and	55.2				gr+and 40.3		gr+and 34.6				gr+and 17.3	

thick marble horizon between a jadeite-gneiss band and common acidic gneiss. It includes distinct eclogite blocks of 5 cm to 1 m in size. The sample 251A is a fresh bimineralic eclogite with a well annealed, slightly foliated, granoblastic metamorphic texture defined by millimetre-size garnet and omphacite with inclusions of several quartz pseudomorphs after coesite.

A third marble outcrop north of Changpu (Fig. 2) consists of impure marble bands intercalated on a metre-scale with gneiss and eclogite bands. One fresh calcium-rich eclogite block (223B) in marble consists of 1 to 3-millimetre-large interlocking omphacite and garnet grains, which contain several rounded inclusions of titanite, quartz pseudomorphs after coesite, possible calcite pseudomorphs after aragonite (*cf.* Wang & Liou, 1991). Other rounded inclusions with radial cracks in omphacite are 0.15 mm large polycrystalline K-feldspar (Table 4, Fig. 11). K-feldspar is known to be stable at least up to 40 kbar (Lindsey, 1966) and has been previously reported

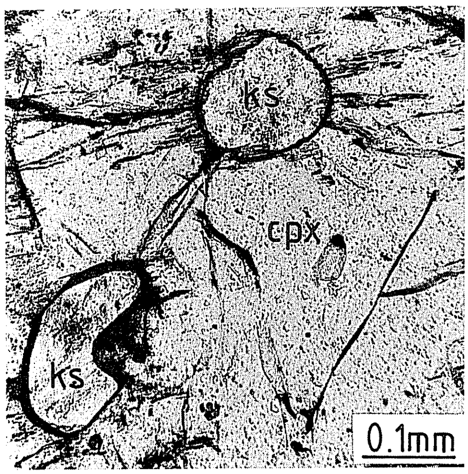

Fig. 11. K-feldspar (ks) inclusions with radial cracks in omphacite (cpx) in the eclogite block from marble (sample 223B). Micrograph with plane polarised light.

along with coesite, in the matrix (Smyth & Hatton, 1977) and as inclusions in clinopyroxene (Schulze & Helmstaedt, 1988) of kimberlitic eclogites. The radial cracks around the K-feldspar inclusions in clinopyroxene are probably due to the isothermal uplift of the eclogites. The isothermal compressibility coefficient for K-feldspar is four times that of pyroxene, while the thermal expansion coefficients of the two are similar (*cf.* Holland & Powell, 1990).

Garnet-clinopyroxene geothermometry, based on the compositions of adjoining grains, indicates for the samples 575C, 230D, 251A and 223B temperatures of 768±40°C, 927±40°C, 771±30°C and 863±50°C respectively for 40 kbar pressure. The significant difference in the calculated temperatures, even between samples collected 1 m apart, is most likely due to the reversed effect of Ca on the Fe-Mg partitioning between garnet and clinopyroxene at $X_{gr} > 0.5$; samples that give temperatures above 850°C have $X_{gr} > 0.5$. The 927°C temperature estimate from the sample 230D is reduced to 780°C using the calibration of Krogh (1988), which takes account of this effect. Thus, the best estimate for metamorphic temperatures for the eclogite in marble is 800±80°C, which is similar to those from the eclogite in gneiss. The presence of coesite and diamond at these temperatures gives minimum pressure estimates of 29 and 38 kbar respectively. Pressures calculated using reactions (1) and (2) for the samples 575C and 230D are 30±4 and 34.0±2 kbar respectively for 800°C. Considering the absence of titanite and assuming the presence of a hydrous fluid, minimum pressures of 20 and 30 kbar can also be estimated for 575C and 230D from the reaction (Fig. 8, *cf.* Chopin *et al.*, 1991):

3 grossular + 5 rutile + 2 quartz + H_2O =
5 titanite + 2 zoisite (4).

The calcium-rich mineral compositions of the eclogites in the marble, the diffuse boundaries between the eclogitic calc-silicate bands and the marble, and the mineral assemblage in the marble itself indicate that the marble matrix has been metamorphosed together with the eclogites. This is confirmed by the recent discovery of coesite inclusions in dolomite in the road side quarry south of Wumiao (Schertl and Okay, in prep.).

Acidic gneiss

The mineral assemblage in the common acidic gneiss, based on the petrographic study of 58 samples from 40 localities, is quartz + oligoclase + phengite + epidote + garnet ± microcline ± biotite ± opaque ± titanite. Hornblende and late chlorite also occur in some samples. Quartz and feldspar grains, 0.5 to 1 mm large, make up the bulk of the rock and form a granoblastic mosaic with phengite, biotite, relict garnet and epidote crystals. Reaction textures are rare and include narrow biotite + feldspar rims around phengite in some specimens.

In the analysed gneiss sample (215D, Table 1) rounded and cracked garnets with phengite, rutile and quartz inclusions and poikilitic epidotes with biotite and quartz inclusions are associated with smaller biotite, phengite, quartz, oligoclase (an_{12-17}), calcite and ilmenite grains that define a planar fabric. Titanite has replaced virtually all the rutile in the matrix, while chlorite has formed along the cracks and margins of the garnet. Garnet ($alm_{57}py_{10}gr_{31}sp_2$) does not show zoning while phengite exhibits a very wide silica range (Fig. 6). Phengite inclusions in garnet have the highest Si content of 3.49 to 3.56 p.f.u. The large phengite cores in the matrix have around 3.45 Si p.f.u., while the rims and small mica flakes in the matrix have around 3.10 Si p.f.u. (Fig. 6). The Fe/Mg ratio increases from 0.31 in the most phengitic micas in garnets to 0.86 in the small muscovite flakes in the matrix (Table 4). The very siliceous phengites in the garnet cores indicate a minimum pressure of 17 kbar for a temperature of 700°C according to the calibration of Massonne & Schreyer (1987). The high metamorphic temperatures of 700-780°C given by garnet-biotite geothermometry are spurious as garnet and biotite were never in equilibrium with each other.

The zoisite-gneiss 250G was collected from a 3-cm-thick gneissic layer between two eclogite bands from the same outcrop as sample 250H. Although the mineral assemblage in this sample is similar to that of the common eclogite (Table 1), it is texturally and modally quite distinct. The rock consists dominantly of up to one-centimetre-long, roughly parallel aligned, poikilitic zoisite, quartz and phengite. Zoisite porphyroblasts contain 0.4-0.8 mm large inclusions of garnet, omphacite, kyanite and quartz. The mineral compositions from this sample are similar to those from the eclogites in the gneiss (Table 2, Fig. 4 and 6). The garnet-clinopyroxene geothermometry using average garnet and clinopyroxene compositions, as these minerals are not in contact, indicates a temperature of 806±50°C for 30 kbar pressure, similar to that estimated from adjoining eclogites. A pressure sensitive reaction involving garnet, omphacite, kyanite and phengite is (Fig. 8):

3 diopside + 3 muscovite + 2 coesite =
grossular + 3 celadonite + 2 kyanite (5).

This reaction together with reactions (1) and (2) indicate a pressure of 27±4 kbar at 800°C for 250G. The reaction:

zoisite = 4 grossular + 5 kyanite + quartz +
3 H_2O (6)

indicates much lower pressures and temperatures (11 kbar at 600°C with a negative slope) suggesting that zoisite has formed after the peak P-T conditions.

The high-pressure paragenesis in acidic gneisses is best preserved in some jadeite-gneisses north of Huangpu (Fig. 2). The studied jadeite-gneiss (sample 251C) forms a 2-m-thick and at least 100-m-long massive band adjacent to the marble band with eclogite nodules described earlier. The primary assemblage in the jadeite-gneiss (251C) is quartz + jadeite + garnet + rutile. Jadeite ($jd_{79}au_{21}$) forms 2 to 3-mm-large grains, which are largely transformed to a fine-grained symplectite of albite (ab_{99}) and amphibole (*cf.* Fig. 4a of Xu *et al.*, 1992). Garnet crystals ($alm_{57}py_{24}gr_{18}sp_1$) have thick kelyphitic reaction rims of bluish-green hornblende. A thin rim of green aegerine ($jd_1au_{19}aeg_{80}$) marks the contact between quartz and altered garnet and jadeite. These textures are similar to those described from Syros in Greece (Okrusch *et al.*, 1978) and from Dora Maira (Chopin *et al.*, 1991). Acicular blue magnesioriebeckite (Fig. 4), ilmenite and titanite occur as late generation minerals. The presence of jadeite in the gneiss gives a minimum pressure estimate of 22 kbar at 800°C.

There is no conclusive evidence that all the common gneiss that makes up over 90% of the eclogite zone reached temperatures of 800°C and pressures above 29 kbar as recorded in the eclogites. However, the description of quartz pseudomorphs after coesite in garnet from some gneisses (Wang & Liou, 1991) and the presence of gneisses with a high-pressure paragenesis suggest an *in situ* ultra-high-pressure metamorphism.

Petrography, mineral chemistry and P-T conditions in the "cold" eclogite terrain

The southern cold eclogite terrain is lithologically similar to the hot eclogite terrain except for the absence of the marble-eclogite association and the presence of sodic amphibole-bearing eclogites, which correspond to the "type-IV eclogites from Huangzhen" of Wang *et al.* (1992). Twentytwo metabasite samples from 10 localities in the cold eclogite terrain were petrographically examined. The mineral assemblage in the analysed sample (272A), from a 6-m-large, rounded boudin in the acidic gneiss, is garnet + chloromelanite + crossite + kyanite + epidote + quartz + rutile (Table 1). Pale blue Mg-crossite with appreciable tetrahedral aluminium (0.3-0.4 p.f.u., Fig. 4), and epidote with 25 mol% pistacite component (Table 2) form up to 1 cm large strongly poikilitic porphyroblasts enclosing and overgrowing 0.2 to 0.4-mm-large, equant garnet, chloromelanite, kyanite and quartz. Garnets, although small, show consistent prograde zoning profiles involving a decrease in grossular and almandine component at the expense of pyrope (*cf.* Wang *et al.*, 1992), while the chloromelanite is unzoned. Peak metamorphic temperature calculated using average omphacite and garnet rim compositions is 635±40°C for 25 kbar pressure, considerably lower than the temperatures from the sodic amphibole-free eclogites in the north. A lower temperature is also suggested by the preservation of zoning in the garnet. Wang *et al.* (1992) record paragonite inclusions in garnet from the cold eclogite terrain, which are not present in the hot eclogite terrain. The amphibole and epidote textures in the rock suggest that garnet and clinopyroxene are reacting to hydrous minerals:

garnet + clinopyroxene + quartz + H_2O =
sodic amphibole + epidote (7).

For this eclogite to blueschist reaction several subreactions using end-member compositions of the phases can be written (Fig. 8); these subreactions indicate a pressure of 26±3 kbar for 635°C and for unit activity of water. The presence of chloromelanite, kyanite and quartz indicates a minimum pressure of 18 kbar at 635°C by the reaction:

$jadeite_{0.39}$ + kyanite + H_2O = paragonite (8).

The apparent absence of coesite in the cold eclogite terrain gives a maximum pressure of 26 kbar at 635°C (*cf.* Wang *et al.*, 1992). The P-T conditions of the cold eclogite terrain, 635±70°C and 24±3 kbar are similar to that deduced by Wang *et al.* (1992) for the same region. The prograde zoning in the garnet shows that the lower temperatures recorded by the mineral assemblage is not due to reequilibration of the hot eclogite terrain assemblages. A tectonic boundary between the hot and cold eclogite terrain is here preferred rather than a gradual metamorphic transition (*cf.* Wang & Liou, 1991). This is based on the lack of unequivocal evidence showing gradual southward decrease in metamorphic temperature and pressure, and on the absence of the characteristic marble-eclogite association in the south. The garnet-clinopyroxene Fe^{2+}-Mg partition coefficients (K_D) are strongly dependent on the grossular content of the garnet (*cf.* Fig. 7), so that variation of K_D across the area (*cf.* Fig. 12 of Wang *et al.*, 1992) would not be meaningful unless K_D values of garnets with similar grossular contents are compared. Furthermore, if the eclogite zone is restored to a horizontal position, the sodic amphibole-bearing eclogite sample (272D) would lie structurally 14 km above the diamond-bearing eclogite (230D), which is far less than that required to create the 15 kbar pressure gap between these two samples. This indicates that large parts of the section between the cold and hot eclogite terrains were tectonically removed. However, no structural boundary can be established in the field between these two terrains, and the country-rock gneisses from both terrains are texturally and mineralogically similar. The boundary in Fig. 2 is located where the marble bands disappear and the sodic amphibole-bearing eclogites appear.

Discussion and conclusions

The eclogite zone in Dabie Shan probably contains two units with different ultra-high-pressure metamorphic conditions: the hot eclogite terrain (800±50°C, > 38 kbar) and the cold eclogite terrain (635±40°C, 18-26 kbar). Some assemblages of the hot eclogite terrain indicate lower pressures than this maximum possibly due to reequilibration of the mineral assemblage during the uplift, and thus may give clues on the uplift path followed by the rock. This uplift path of the hot eclogite terrain can be tentatively constructed using the P-T conditions deduced from the presence of diamond, from mineral reactions and from the minimum temperatures provided by calcite-dolomite geothermometry on the aragonite/calcite reaction curve (Fig. 12). The resulting P-T path shows an initial near isothermal uplift, that is also qualitatively indicated by the radial fractures around the K-feldspar inclusions in omphacite. Based on the uplift path of the hot eclogite terrain, the juxtaposition of the two rock units must have occurred at pressures below 10 kbar (Fig. 12). The presence of lower-temperature and lower-pressure rocks on top of higher-temperature and higher-pressure rocks indicates a normal shear zone contact between the hot and cold eclogite terrain and the Susong Group. The dominant structural imprint, characterised by the strong foliation, was probably contemporaneous with this tectonic event. Juxtaposition of terrains with different P-T histories are increasingly recognised in regions with high-pressure metamorphism (*e.g.* Holland, 1979; Okay, 1989; Chopin *et al.*, 1991). In most cases the late strong structural imprint leaves the metamorphic petrology as the only tool in the recognition of such terrains.

The lack of partial melting in the hot eclogite terrain, where the conditions are within the liquidus of the hydrous melting of alkali granite

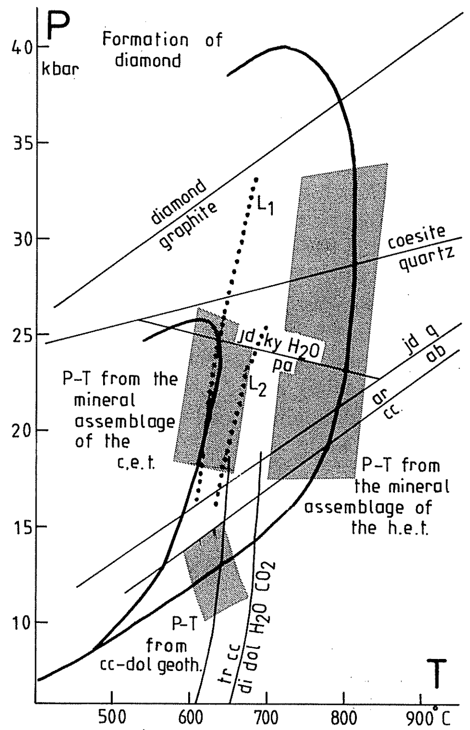

Fig. 12. Tentative P-T paths for the cold (c.e.t.) and for the hot eclogite terrain (h.e.t). The hydrous solidus of alkali granite (L_1, Huang & Wyllie, 1975) and that of eclogite (L_2, Hill & Boettcher, 1970) are shown; the tremolite reaction is plotted for X_{CO_2} values of 0.1 and 0.88. dol, dolomite; tr, tremolite; for other abbreviations see Fig. 8.

(Fig. 12) indicates that P_{H_2O} was in general less than P_{total}. Preliminary isotopic data as well as tectonic relations suggest that the protoliths for the ultra-high-pressure metamorphic rocks were Precambrian, amphibolite- to granulite-facies basement gneisses and amphibolites. No pervasive inter-granular fluid would be expected in the regional metamorphism of such rocks. An H_2O-rich fluid phase would have been produced locally during the dehydration of the amphibolite to eclogite while no such fluid phase would be expected in the gneisses where the high-pressure metamorphism would lead to hydration reactions involving the formation of phengite, zoisite and jadeitic pyroxene from feldspar (*cf.* Heinrich, 1982). This explains the existence of coarse kyanite + zoisite nests in the eclogites, which imply the presence of a local fluid phase. On the other hand, most of the gneisses being initially dry probably never had an equilibrium high-pressure assemblage and only those near the fluid-emitting eclogites could develop high-pressure assemblages. This is analogous to the eclogitisation of lower crustal granulites by fluid migration in the Norwegian Caledonides (Austrheim, 1987).

The pressures recorded by the hot eclogite terrain correspond to the base of the lithosphere (≈ 130 km) where the temperatures are 1100-1200°C. The lower temperature (800±50°C) recorded in the hot eclogite terrain and the very steep uplift P-T path indicates rapid exhumation, which is thought to have been achieved largely by thrusting and erosion. Evidence for this type of exhumation lies in the abrupt termination of the sinistral Tanlu Fault immediately south of the Dabie Shan Complex (Fig. 1), whereby the 530 km of off-set along the Tanlu Fault is transferred to southward thrusting during the Mesozoic leading to the exhumation of the ultra-high-pressure rocks (Okay & Şengör, 1992).

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References

Austrheim, H. (1987): Eclogitisation of lower crustal granulites by fluid migration through shear zones. *Earth Planet. Sci. Lett.*, **81**, 221-232.

Chopin, C. (1984): Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first record and some consequences. *Contrib. Mineral. Petrol.*, **86**, 107-118.

Chopin, C., Henry, C., Michard, A. (1991): Geology and petrology of the coesite-bearing terrain, Dora Maira massif, Western Alps. *Eur. J. Mineral.*, **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. *Contrib. Mineral. Petrol.*, **71**, 13-22.

Franz, G. & Spear, F.S. (1983): High pressure metamorphism of siliceous dolomites from the central Tauern Window, Austria. *Amer. Jour. Science*, **283-A**, 396-413.

Goldsmith, J.R. & Newton, R.C. (1969): P-T-X relations in the system $CaCO_3$-$MgCO_3$. *J. Geol.*, **267-A**, 160-190.

Heinrich, C.A. (1982): Kyanite-eclogite to amphibolite facies evolution of hydrous mafic and pelitic rocks, Adula Nappe, Central Alps. *Contrib. Mineral. Petrol.*, **81**, 30-38.

Holland, T. (1979): High water activities in the generation of high pressure kyanite eclogites of the Tauern Window, Austria. *J. Geol.*, **87**, 1-27.

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. *J. metam. Geol.*, **8**, 89-124.

Huang, W.L. & Wyllie, P.J. (1975): Melting reactions in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 to 35 kilobars, dry and with excess water. *J. Geol.*, **83**, 737-748.

Hill, R.E.T. & Boettcher, A.L. (1970): Water in earth's mantle: melting curves of basalt-water and basalt-water-carbon dioxide. *Science*, **167**, 980-982.

Koziol, A.M. & Newton, R.C. (1989): Grossular activity-composition relationships in ternary garnets determined by reversed displaced-equilibrium experiments. *Contrib. Mineral. Petrol.*, **103**, 423-433.

Krogh, E.J. (1988): The garnet-clinopyroxene Fe-Mg geothermometer - a reinterpretation of existing experimental data. *Contrib. Mineral. Petrol.*, **99**, 44-48.

Li, S.G., Hart, S.R., Zheng, S.G., Liu, D.L., Zhang, G.W., Guo, A.L. (1989): Timing of collision between the North and South China blocks - the Sm-Nd isotopic age evidence. *Science in China (Ser. B)*, **32**, 1393-1400.

Lindsey, D.H. (1966): Melting relations of $KAlSi_3O_8$: effect of pressure up to 40 kilobars. *Am. Mineral.*, **51**, 1793-1799.

Lovering, J.F. & White, A.J.R. (1969): Granulitic and eclogitic inclusions from basic pipes at Delegate, Australia. *Contrib. Mineral. Petrol.*, **21**, 9-52.

Massonne, H.J. & Schreyer, W. (1987): Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite and quartz. *Contrib. Mineral. Petrol.*, **96**, 212-224.

Mattauer, M., Matte, P., Malavieille, J., Tapponnier, P., Maluski, H., Xu, Z.Q., Lu, Y.L., Tang, Y.Q. (1985): Tectonics of the Qinling Belt: build-up and evolution of eastern Asia. *Nature*, **317**, 496-500.

Newton, R.C. & Haselton, H.T. (1981): Thermodynamics of the garnet-plagioclase-Al_2SiO_5-quartz geobarometer. *in* "Thermodynamics of Minerals and Melts", R.C. Newton, A. Navrotsky, B.J. Wood eds. Springer, Berlin, 131-147.

Okay, A.I. (1989): An exotic eclogite/blueschist slice in a Barrovian-style metamorphic terrain, Alanya Nappes, southern Turkey. *J. Petrol.*, **30**, 107-132.

Okay, A.I. & Şengör, A.M.C. (1992): Evidence for intra-continental thrust related exhumation of the ultra-high pressure rocks in China. *Geology*, **20**, 411-414.

Okay, A.I., Xu S.T., Şengör, A.M.C. (1989): Coesite from the Dabie Shan eclogites, central China. *Eur. J. Mineral.*, **1**, 595-598.

Okrusch, M., Seidel, E., Davis, E.N. (1978): The assemblage jadeite + quartz in the glaucophane rocks of Sifnos (Cycladic Archipelago, Greece). *N. Jb. Mineral. Abh.*, **132**, 284-308.

Schulze, D.J. & Helmstaedt, H. (1988): Coesite-sanidine eclogites from kimberlite: products of mantle fractionation or subduction ? *J. Geol.*, **96**, 435-443.

Shatsky, V.S., Sobolev, N.V., Yefimova, E.S. (1989): Morphological features of accessory microdiamonds from metamorphic rocks of the earth's crust. 28th Int. Geol. Congress, Abstracts, 94-95.

Smyth, D.R. & Hatton, C.J. (1977): A coesite-sanidine grospydite from the Roberts Victor kimberlite. *Earth Planet. Sci. Lett.*, **34**, 284-290.

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

Xu, S.T., Okay, A.I., Ji, S.Y., Şengör, 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.

Wang, X. & Liou, J.G. (1991): Regional ultrahigh-pressure coesite-bearing eclogitic terrane in central China: Evidence from country rocks, gneiss, marble and metapelite. *Geology*, **19**, 933-936.

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. *J. Geol.*, **100**, 231-250.

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