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Coesite inclusions in dolomite from eclogite in the southern Dabie Mountains, China: The significance of carbonate minerals in UHPM rocks

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ABSTRACT

Coesite inclusions have been discovered in dolomite from carbonate-bearing eclogite in the Dabie UHP terrane. The eclogite boudins are enclosed in calc-silicate rocks that contain quartz aggregates after coesite in the matrix. The carbonate-bearing eclogite is composed of garnet, coesite or quartz, dolomite, magnesite, omphacite, rutile, ±minor phengite, apatite, and zircon, and was formed at ~760 °C, >28 kbar, and $0.01 < X_{CO_2} < 0.1$. In addition to coesite inclusions in dolomite, inclusions of coesite and quartz pseudomorphs after coesite are abundant in garnet. One inclusion of quartz + calcite aggregates after coesite and aragonite (?) was identified in garnet. Radial fractures developed in garnet around the coesite inclusions but are absent in the dolomite. Dolomite contains about 14 mol% ankerite component, whereas magnesite contains about 2 mol% calcite and 23 mol% siderite. This is the first reported occurrence of coexisting magnesite + dolomite + possible aragonite + coesite in a single eclogitic sample and is consistent with experimentally determined stabilities of these phases at mantle conditions. Systematic mineral parageneses of eclogite, marble, and country-rock gneisses support the previous conclusion that supracrustal rocks were subducted to mantle depths of >100 km.

INTRODUCTION

Recent experimental studies have indicated that magnesite and dolomite should be the principal stable carbonates at mantle conditions and may carry carbon in subducting plates into the lower mantle (Kushiro et al. 1975; Brey et al. 1983; Blundy et al. 1991; Kraft et al. 1991; Gillet 1993; Redfern et al. 1993). Reported occurrences of magnesite in mantle-derived kimberlite and ultrahigh-pressure (UHP) metamorphic ultramafic rocks and eclogite support these experimental results (Lappin and Smith 1978; Okay 1993; Yang et al. 1993; Zhang and Liou 1994; Zhang et al. 1995a). The discovery of coesite inclusions in dolomite from a calc-silicate rock from Wumiao in the Dabie Mountains of central China (Schertl and Okay 1994) provides additional evidence that some continental sediments have been subducted to depths of >100 km and that dolomite is a stable phase at mantle depths. Inclusions of calcite pseudomorphs after aragonite have also been reported in coesite-bearing marbles from the Dabie Mountains (Wang and Liou 1993). This paper reports the second finding of coesite inclusions in dolomite from carbonate-bearing eclogite in the southern Dabie UHP terrane about 25 km south of Wumiao. The significance of the occurrence of three carbonate minerals associated with coesite, the P-T-X_{CO_2} constraints on carbonate-bearing assemblages, and the mineral parageneses of the coesite-bearing eclogites and adjacent calc-silicate rocks are discussed.

GEOLOGICAL BACKGROUND AND PETROGRAPHY

The Triassic Qinling-Dabie collisional belt between the Sino-Korean and Yangtze cratons extends for about 2000 km and has been segmented into several blocks by NE-trending faults subparallel to the Tan-Lu fault. Abundant coesite inclusions and rare microdiamonds occur in a variety of minerals from both eclogites and enclosing country rocks in the Sulu-Dabie UHP terrane (e.g., Xu et al. 1992; Wang et al. 1995; Liou et al. 1995). The newly discovered coesite inclusions in dolomite occur in eclogite near Xinyan village 5 km north of Taihu city in the Dabie UHP terrane; petrological study of eclogites and enclosing marbles from this locality has not been previously reported. Nearby at Shima, the eclogite boudins range from several centimeters to 1 m in size and are enclosed in layers of calc-silicate rock + minor impure marbles, which in turn are enclosed within gneissic rocks that contain coesite inclusions in zircon (Sobolev et al. 1994). The calc-silicate rocks consist of clinopyroxene + dolomite + calcite + rutile ± quartz ± zoisite ± garnet ± apatite in variable proportions. Polygonal dolomite and calcite with sizes of 0.5–1.5 mm constitute 15–50 vol% of the calc-silicate rocks. Clinopyroxene (20–60 vol%) is replaced by symplectitic patches of fine-grained calcic amphibole + plagioclase (Fig. 1A). Quartz pseudomorphs of coesite occur as polycrystalline aggregates both in matrix (Fig. 1A) and as inclusions in garnet (Fig. 1B), and rutile is rimmed by titanite. Garnet (0–5 vol%) is

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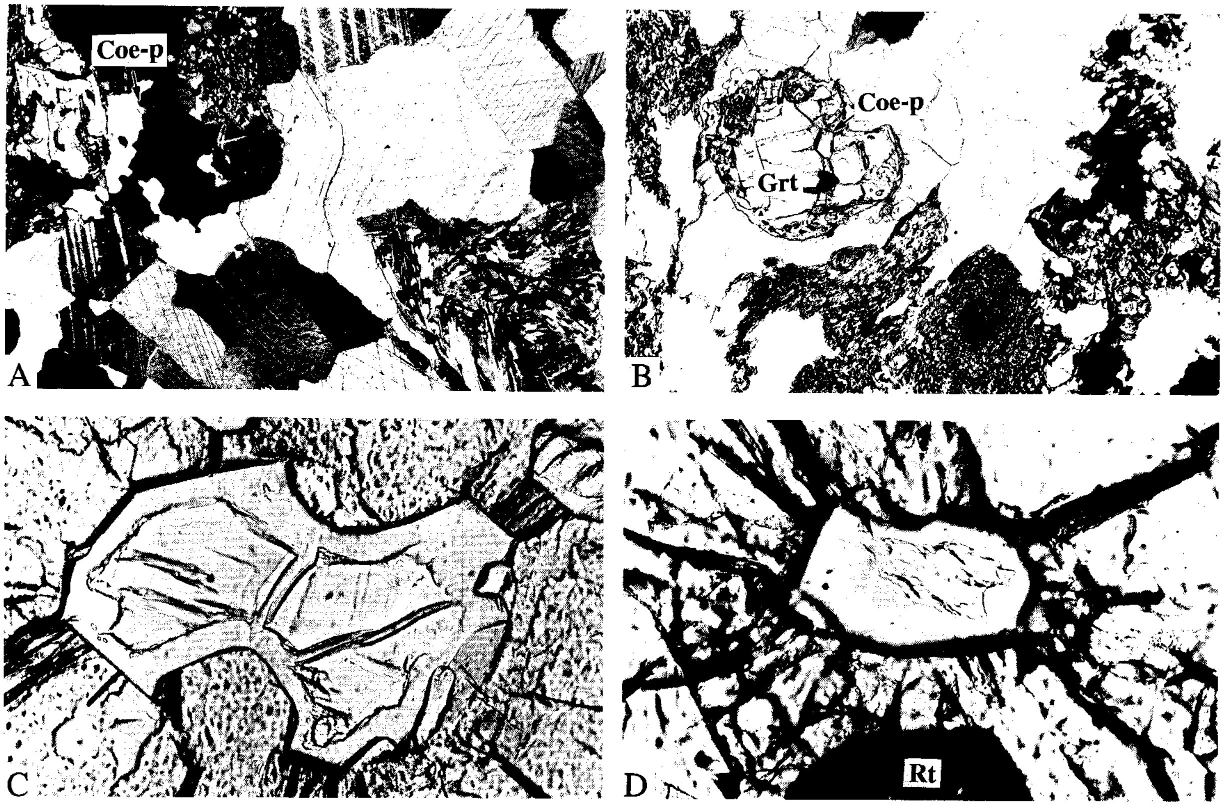

FIGURE 1. Photomicrographs of coesite-bearing marbles and eclogites from Xinyan. All plane light except for A; width of field of view is 0.36 mm. (**A**) Coarse-grained marble (94-17C-1) containing calcite, dolomite, epidote + plagioclase + biotite + calcite (entirely replacing garnet), calcic amphibole + plagioclase (replacing clinopyroxene), and an aggregate of biotite + plagioclase + minor calcite. The oval-shaped quartz aggregates (Coe-p) are believed to be pseudomorphs of a coarse-grained coesite similar to those described by Chopin et al. (1991) from the Dora Maria Massif. (**B**) Relict garnet (Grt) in coarse-grained marble (94-17B) contains a coesite pseudomorph (Coe-p) and is rimmed by fine-grained zoisite. Clinopyroxene crystals were replaced by symplectite of calcic amphibole + plagioclase. Aggregate of epidote + biotite + plagioclase + quartz, possibly a pseudomorph of garnet shown on the right. (**C**) Eclogitic garnet containing a coarse-grained coesite relic rimmed by polycrystalline quartz aggregates that grew radially around the coesite crystal (94-18H). (**D**) Inclusion of coesite relics rimmed by polycrystalline quartz aggregates in garnet of an eclogite sample (94-17C) with well-developed radial fractures. Rt = rutile.

partially overprinted by plagioclase + biotite ± epidote ± amphibole ± calcite or by zoisite-epidote (Figs. 1A and 1B), and phengite is overprinted by biotite aggregates. Eclogites consist of garnet, omphacite, carbonates, coesite or quartz, and minor phengite, rutile, and apatite; the proportions of modal garnet and omphacite vary significantly from layer to layer. Both rock types contain variable amounts of rutile. A characteristic feature of coesite relict inclusions in garnet is that they exhibit well-developed radial fractures, which are thought to result from the 10% increase in volume during the conversion of coesite to quartz (Figs. 1C and 1D).

Carbonate-bearing eclogites contain both magnesite and dolomite and have coesite inclusions in dolomite and garnet. The eclogite (e.g., sample no. 94-17C) is granoblastic, medium grained (0.5–2 mm), and composed of 70% garnet, 10% quartz, 10% carbonates, 5% omphacite, 2–3% rutile, and minor phengite, apatite, and zircon. Omphacite has been replaced largely by calcic amphibole and plagioclase. Dolomite is the major carbonate phase in the matrix; some grains of dolomite are rimmed by calcite (Fig. 2A). Minor magnesite occurs in the matrix or as inclusions in dolomite (Fig. 2A). Phengite is rimmed by fine-grained biotite aggregates. Only two coesite inclusions were identified in dolomite. One oval-shaped coesite inclusion 0.1 mm in diameter has a thin (0.005 mm thick) margin converted to quartz aggregates that grew perpendicular to the boundary between the coesite relic and the dolomite (Fig. 2B). Another coesite inclusion in dolomite is smaller (0.05 mm) and exhibits more than 40% conversion to polycrystalline quartz (Fig. 2C). Both coesite inclusions in dolomite lack radial fractures. The lack of radial fractures around the coesite inclusion is thought to be related to the good cleavage of dolomite (Schertl and Okay 1994). A composite inclusion of calcite + quartz aggregates was also found in garnet, in which radial fractures are well developed and the quartz pseudomorphs show palisade texture (Fig. 2D). The calcite

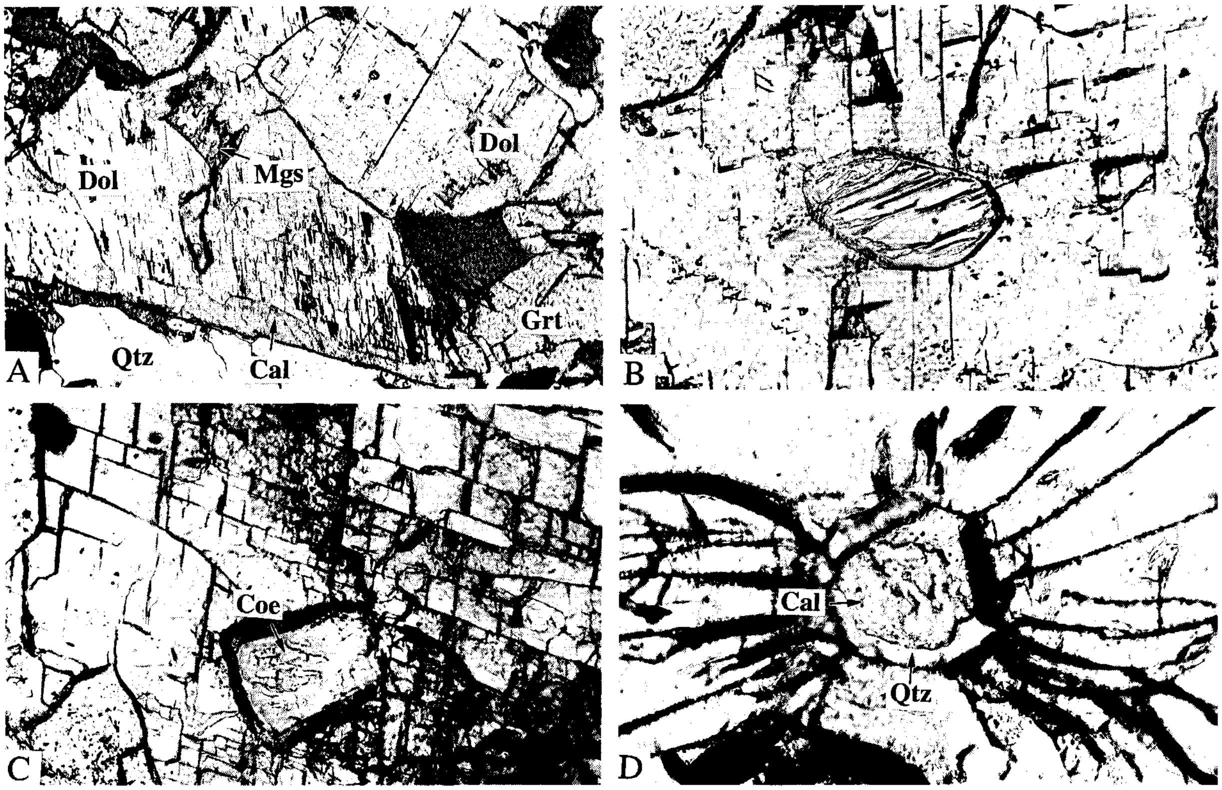

FIGURE 2. Photomicrographs of carbonate and coesite inclusions in dolomite from a single eclogite section (94-17C). All are plane light; width of field of view is 1.44 mm for A and 0.36 mm for the others. (A) Dolomite (Dol) coexisting with garnet (Grt). Some dolomite crystals are rimmed by calcite (Cal) and contain magnesite (Mgs) inclusions. Secondary amphibole developed around garnet. Qtz = quartz. (B) Coesite inclusion (center) in dolomite; only its margin was converted to quartz aggregates. (C) Inclusion of coesite (Coe) relics with quartz pseudomorphs after coesite in dolomite. (D) Inclusion of calcite aggregates (after aragonite) + quartz (after coesite) pseudomorphs in garnet.

aggregates are inferred to be an inversion product after aragonite. Inclusions of calcite pseudomorphs after aragonite in garnet were described in some UHP marbles from the Dabie Mountains by Wang and Liou (1993).

MINERAL COMPOSITION AND *P-T* ESTIMATE

Compositions of minerals from several carbonate-bearing eclogites and calc-silicate rocks were analyzed by a JEOL Superprobe 733 with 15 KV accelerating potential and 12 nA beam current and are given in Table 1. Garnet from the eclogite is a pyrope-almandine-grossular solid solution with negligible MnO (X_{Sps} = 0.01). Most garnet grains in eclogites are homogeneous in composition ($Alm_{42-46}Prp_{15-16}Grs_{38-41}$). A few grains adjacent to omphacite exhibit zoning; almandine and pyrope components increase with decreasing grossular component as the rim is approached (core: $Alm_{43-46}Prp_{15}Grs_{38-42}$; rim: $Alm_{49-51}Prp_{17-18}Grs_{31-33}$). Garnet in impure marble contains higher Gr component (47 mol%). Omphacite is homogenous with X_{Jd} = 0.46–0.53 and $X_{Acm} \leq 0.04$. Magnesite contains 2 mol% calcite and 23 mol% siderite components and has a composition similar to that of magnesite in coesite-bearing eclogite from the Shuanghe area of the Dabie Mountains (Zhang and Liou 1994). Dolomite contains about 14 mol% ankerite component, and the rimming calcite contains 5.5 mol% $MgCO_3$. Phengite has 3.3–3.4 Si pfu.

Both eclogite and country rock experienced at least two stages of metamorphism. Temperature and pressure estimates of the peak metamorphism defined by the assemblage garnet + omphacite + coesite + magnesite (+ dolomite + aragonite) + phengite + rutile are ~765 °C and ≥28 kbar, using the Fe-Mg partitioning between garnet cores and omphacite (Powell 1985). The composition of garnet rims yields a lower temperature of 700 °C, which may have resulted from compositional reequilibration. Garnet and clinopyroxene are replaced by epidote-amphibolite facies assemblages described above. The plagioclase + amphibole thermometer (Blundy and Holland 1990) yields *T* of 560–610 °C for the symplectitic assemblage albite + hornblende. The equilibrium temperature of coexisting dolomite and calcite is about 540–580 °C, determined with the use of the fractionation of Fe + Mg between dolomite and calcite after Powell et al. (1984)

TABLE 1. Mineral compositions of eclogites and impure marble

				94-17C eclogite				94-18H eclogite	
Sample	Mgs	Dol	Cal	Grt-c	Grt-r	Omp	Phn	Grt	Grt
SiO_2	0.00	0.00	0.00	38.91	38.75	56.21	48.59	39.17	39.41
TiO_2	0.00	0.00	0.00	0.09	0.03	0.06	0.38	0.10	0.03
Al_2O_3	0.00	0.00	0.00	21.16	21.14	11.30	28.84	21.41	21.51
FeO	17.88	5.08	1.76	20.23	22.53	4.38	2.39	21.06	23.20
MnO	0.18	0.03	0.20	0.47	0.60	0.02	0.02	0.52	0.52
MgO	32.57	18.27	2.44	4.34	4.51	8.16	2.71	3.96	4.64
CaO	1.02	28.93	53.37	14.85	12.13	12.80	0.06	13.70	11.03
Na_2O	0.01	0.03	0.00	0.03	0.04	7.28	0.74	0.04	0.01
K_2O							9.69	0.00	0.00
Total	51.66	52.34	57.77	100.08	99.73	100.21	93.42	99.96	100.35
O no.				12	12	6	11	12	12
Si	0.00	0.00	0.00	3.01	3.02	1.99	3.30	3.03	3.04
Ti	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.01	0.00
Al	0.00	0.00	0.00	1.93	1.94	0.47	2.31	1.95	1.96
Fe^{3+}									
Fe	0.23	0.07	0.02	1.31	1.47	0.13	0.14	1.36	1.50
Mn	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.03	0.03
Mg	0.75	0.43	0.06	0.50	0.52	0.43	0.28	0.46	0.53
Ca	0.02	0.50	0.92	1.23	1.01	0.49	0.01	1.14	0.91
Na	0.00	0.00	0.00	0.00	0.01	0.50	0.10	0.01	0.00
K							0.84	0.00	0.00
Total	1.00	1.00	1.00	8.02	8.01	4.02	6.99	7.99	7.98

Note: The formulae of magnesite, dolomite, and calcite were calculated on the basis of one cation; c = core, r = rim, sy = symplectite.

and Anovitz and Essene (1987); this may represent the temperature of the epidote-amphibolite facies overprint.

Figure 3 summarizes the *P-T* regimes of various metamorphic facies (Spear 1993), UHP and HP fields, and the experimentally determined stability fields for diamond (Blundy 1980), coesite (Bohlen and Boettcher 1982), jadeite + quartz (Holland 1980), and aragonite (Hacker et al. 1991). Also shown are calculated *P-T* relations for the reactions coesite + dolomite = diopside + CO_2 and coesite + magnesite = enstatite + CO_2 at X_{CO_2} = 0.1 and 0.01 after Ogasawara et al. (1995). These phase equilibria

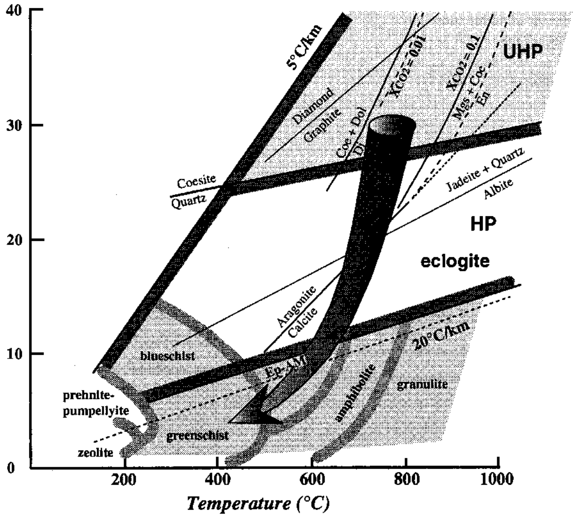

FIGURE 3. *P-T* diagram showing stabilities of diamond, coesite, jadeite + quartz, dolomite + coesite, magnesite + coesite, and aragonite, *P-T* fields of various metamorphic facies, and *P-T* path for Xinyan UHPM rocks (see text for explanation).

and thermobarometers constrain a generalized *P-T* path for the investigated dolomite-bearing eclogites and marbles. Such a *P-T* path shows nearly isothermal decompression from the peak eclogite stage to the epidote-amphibolite stage and cooling during slow decompression afterward; it preserves a clockwise path typical for UHP rocks in the Dabie Mountains and other UHP terranes (e.g., Liou et al. 1994).

DISCUSSION

Experimental studies have shown that aragonite, dolomite, and magnesite are stable at high- and ultrahigh-*P* conditions (e.g., Brey et al. 1983; Kraft et al. 1991; Ross and Reeder 1992; Redfern et al. 1993). In addition, five observations described above and elsewhere have confirmed that these carbonate phases are stable in the coesite and even diamond stability fields: (1) the presence of the magnesite + diopside assemblage in UHP ultramafic rocks (Zhang and Liou 1994); (2) the coexistence of dolomite with magnesite, coesite, garnet, and omphacite; (3) the inclusions of calcite ± quartz pseudomorphs after inferred aragonite ± coesite in garnet (also see Wang and Liou 1993); (4) inclusions of coesite within dolomite (e.g., Schertl and Okay 1994); and (5) coexistence of diamond with dolomite as inclusions in garnet from marble of the Kokchetav Massif (e.g., Zhang et al. 1995b). Magnesite is stable at even higher pressures than dolomite inasmuch as dolomite breaks down in the presence of $MgSiO_3$ to form magnesite at high pressures (e.g., Redfern et al. 1993).

The significance of the occurrence of coesite in dolomite was discussed by Schertl and Okay (1994). Wang and Liou (1993) described some inclusions of calcite pseudomorphs in garnet and omphacite in marbles from

TABLE 1.—*Continued*

	94-18H eclogite						94-17B impure marble		
Sample	Omp	Omp	Phn	Zo	Amp-sy	Ab-Sy	Grt	Pl-sy	Amp-sy
SiO_2	57.16	56.93	51.08	38.85	44.27	68.32	39.12	63.72	48.34
TiO_2	0.07	0.05	0.29	0.10	0.24	0.00	0.13	0.00	0.28
Al_2O_3	11.70	12.50	28.47	27.31	11.97	20.41	21.81	21.98	8.49
FeO	5.21	4.71	2.52	6.49	18.35	0.35	16.48	0.15	13.66
MnO	0.03	0.02	0.00	0.04	0.12	0.00	0.44	0.01	0.08
MgO	7.13	6.87	3.15	0.29	9.58	0.00	4.48	0.01	13.12
CaO	11.94	11.15	0.00	21.51	10.24	0.21	17.28	3.61	11.57
Na_2O	7.74	8.13	0.60	0.04	2.56	11.80	0.05	9.70	1.38
K_2O	0.00	0.00	10.23	0.00	0.52	0.06	0.00	0.10	0.57
Total	100.98	100.36	96.34	95.34	97.85	101.15	99.79	99.28	97.49
O no.	6	6	11	25	23	8	12	8	23
Si	2.01	2.01	3.37	6.49	6.57	2.96	3.00	2.84	7.04
Ti	0.00	0.00	0.01	0.01	0.03	0.00	0.01	0.00	0.03
Al	0.49	0.52	2.21	5.38	2.10	1.04	1.97	1.15	1.46
Fe^{3+}				0.48	0.39				0.18
Fe	0.15	0.14	0.14		1.89	0.01	1.06	0.01	1.48
Mn	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.01
Mg	0.37	0.36	0.31	0.07	2.12	0.00	0.51	0.00	2.85
Ca	0.45	0.42	0.00	3.85	1.63	0.01	1.42	0.17	1.81
Na	0.53	0.56	0.08	0.01	0.74	0.99	0.01	0.84	0.39
K	0.00	0.00	0.86	0.00	0.10	0.00	0.00	0.01	0.11
Total	4.01	4.01	6.98	16.29	15.48	5.02	8.01	5.00	15.25

other localities of the Dabie Mountains and discussed the stability of aragonite at UHP conditions. However, the coexistence of magnesite + dolomite + coesite together with inferred aragonite in a single eclogite section has not been reported. Aragonite is well known to invert readily to calcite during decompression on the basis of observations of natural parageneses in blueschist facies rocks (e.g., Ernst 1988) and kinetic experiments (Carlson and Rosenfeld 1981). The inclusions of the inverted calcite aggregates after aragonite shown in Figure 2D have textures very similar to quartz pseudomorphs after coesite that are present as inclusions in garnet and omphacite in eclogite and have well-developed radiating fractures. On the other hand, secondary calcite rims on dolomite (Fig. 2A) or exsolved calcite lamellae in dolomite tend to be coarser in grain size and have uniform crystallographic orientation.

The assemblage dolomite + coesite occurs in an UHP eclogitic rock (no. 94-17C) with an unusual bulk composition; this rock contains major amounts of garnet, quartz, and dolomite with minor omphacite, phengite, and rutile. The calculated rock composition is characterized by high Al_2O_3 (~16 wt%), by total Fe as FeO (~15 wt%), CaO (~14%), TiO_2 (2.5%), and $CO_2 + H_2O + P_2O_5$ (~5%), and by low SiO_2 (40%) and MgO (7%), with trace Na_2O and K_2O. The protolith is believed to have been a basaltic rock interlayered with carbonate rocks, which may have been metasomatically altered prior to UHP metamorphism at mantle depths.

A petrogenetic grid for UHP metamorphism in the model system MgO-CaO-SiO_2-H_2O-CO_2 was proposed by Ogasawara et al. (1995). The occurrence of dolomite or magnesite is highly dependent on X_{CO_2} as shown in Figure 3. The coexistence of dolomite + coesite is limited in the model system by the reaction dolomite + 2 coesite = diopside + $2CO_2$. At the estimated *P-T* conditions of 760 °C and >28 kbar for the Xinyan eclogite at peak metamorphism, the stable coexistence of coesite + dolomite + omphacite (X_{Di} = 0.5) requires $0.01 < X_{CO_2} < 0.1$. Within the estimated *P-T-*X_{CO_2} conditions, magnesite is stable with coesite (Fig. 3).

On the basis of analyzed compositions of dolomite and omphacite, as well as the unit activity of coesite, *T-*X_{CO_2} relations for the reaction dolomite + 2 coesite = diopside + $2CO_2$ were calculated for the coesite-bearing marble by Wang and Liou (1993; Fig. 13). At 630–760 °C and 30 kbar, they estimated the X_{CO_2} for this reaction at <0.03, consistent with the present calculation shown in Figure 3. Such a low X_{CO_2} in the fluid phase during eclogite facies metamorphism was also suggested by Holland (1979) and Franz and Spear (1983) and is consistent with the lack of CO_2 in fluid inclusions (Cong and Touret 1992, personal communication) and common dehydration during subduction-zone metamorphism (e.g., decomposition of amphibole).

Independent study of calc-silicate rocks, eclogites, and impure marbles from this and adjacent outcrops in the Dabie Mountains yields consistent mineral parageneses and *P-T* estimates (e.g., Wang et al. 1992, Omori et al. 1995). The quartz aggregates in the matrix of the calc-silicate rock (e.g., Fig. 1A) are similar to the retrograde products of coarse-grained matrix coesite from the Dora Maira Massif (Chopin et al. 1991). Field relations and petrological data suggest that eclogites, marbles, and country rocks were subjected to coeval UHP metamorphism. These studies support the previous conclusion that supracrustal rocks of the continental crust were subducted to mantle depths of >100 km and that dolomite and magnesite are stable carbonates under such UHP conditions.

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