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Quartz pseudomorphs after coesite in eclogites from Shandong province, east China

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ABSTRACT

Quartz pseudomorphs after coesite occur as inclusions in garnet in four eclogite samples from the Rongchen, Zhucheng, and Lunan areas in Shandong province, east China. The subrounded quartz inclusions are composed of randomly oriented polycrystalline quartz aggregates at the core with radiating quartz fibers on the rim; some inclusions also contain fine-grained K-feldspar. Quartz can occur also as polygonal crystals in the matrix. The primary assemblage in the eclogite samples consists mainly of garnet (pyrope = 23–40 mol% and grossular = 15–30 mol%), omphacite (jadeite = 38–57 mol% and acmite = 0–4 mol%), amphibole, muscovite, apatite, and rutile. The primary amphibole shows wide chemical variations from pargasitic hornblende to magnesian taramite. The Rongchen and Lunan samples also contain primary kyanite. Secondary minerals formed under amphibolite-facies regional metamorphic conditions are pargasitic hornblende (or subsilicic pargasite), epidote, and symplectitic intergrowth of sodic augite and sodic plagioclase.

The *P-T* conditions of the coesite-eclogite stage are estimated at >28 kbar and 800–840 °C. The eclogites occur sporadically as individual blocks near the suture zone between the Sino-Korean and Yangtze cratons. High-pressure eclogites containing coesite or its pseudomorph may be widely distributed in the Precambrian terranes in east and central China.

INTRODUCTION

Coesite is a high-pressure polymorph of SiO_2 and is stable at pressures of >29 kbar at 800 °C (Mirwald and Massonne, 1980). Nonimpact-generated coesite on the Earth has been described from high-pressure metasedimentary rocks in the Alps (Chopin, 1984), "crustal" eclogites in the Norwegian Caledonides (Smith, 1984, 1988), and some eclogites in kimberlite (e.g., Smyth and Hatton, 1977; Schulze and Helmstaedt, 1988). Quartz pseudomorphs after coesite were reported from eclogites in the southern Urals and Münchberg, Germany (Chesnokov and Popov, 1965). The coesite-bearing eclogites are considered to be metamorphic in origin; their occurrences are significant to the interpretation of tectonic environments as they relate to the petrogenesis of subducted lithospheres at depths >90 km and their subsequent uplift to the surface.

In the course of our petrologic study on Precambrian metamorphic rocks of east China (Enami et al., 1986; Enami and Zang, 1988), we found quartz pseudomorphs after coesite in several eclogite samples from Shandong province. Positive identification of coesite in some eclogites from Dabie Mountain, Anhui province, has been recently established (Wang et al., 1989). The samples from Shandong province and the Dabie Mountain area are considered to be part of the same eclogite belt, which is currently offset by the Tanlu fault zone (Fig. 1). Thus, unusually high-pressure metamorphic rocks may be widespread in the Precambrian terrane of east and central China.

GEOLOGICAL SETTING AND PETROGRAPHY

Quartz pseudomorphs after coesite are found in four eclogite samples from the Rongchen, Zhucheng, and Lunan areas in Shandong province, east China. Figure 1 shows a tectonic sketch map of east China and the sample localities. The Precambrian basement of this area is divided into two units by the Tanlu fault zone: an eastern unit of the Jiaoliao massif with a metamorphic age 1300–2400 Ma, and a western unit of the Jilu massif with a metamorphic age >2400 Ma (Tectonic map compiling group, Academia Sinica, 1974). The eclogite samples from the Rongchen, Zhucheng, and Lunan areas are distributed along a major northeast-trending fault zone in the Shandong Peninsula. These areas lie within the Jiaoliao massif and are situated at the southeastern border of the Sino-Korean craton.

Eclogite and garnet amphibolite occur as blocks or lenticular bodies of less than 20 m in size within pelitic and basic gneisses in the Shandong province and in the neighboring area. The garnet amphibolite is considered to be an eclogite that was strongly retrograded to the amphibolite facies during regional metamorphism. Blocks of garnet-corundum rock, garnet clinopyroxenite and eclogite within serpentinized garnet lherzolite in the same area have also been described (Enami et al., 1986; Enami and Zang, 1988).

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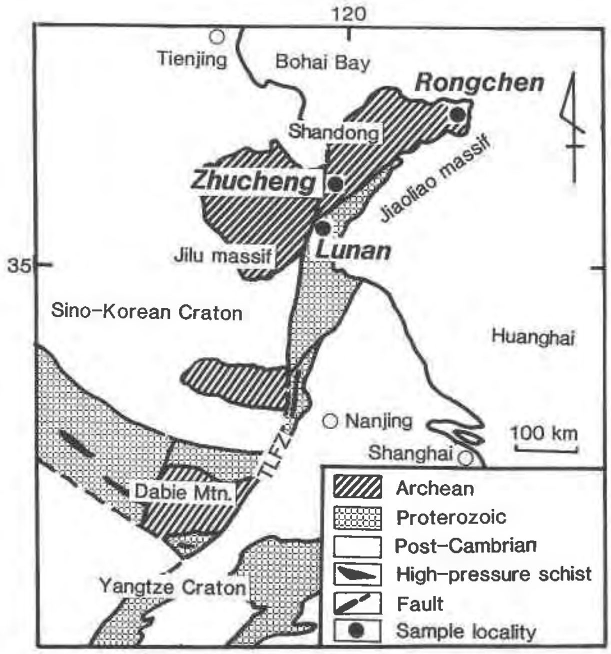

Fig. 1. Schematic tectonic map of east China showing localities of the eclogites studied (simplified from Dong et al., 1986). TLFZ, Tanlu fault zone; Huanghai, Yellow Sea.

The Rongchen (R1-7) and Zhucheng (SD0401) eclogite samples occur as subrounded blocks of 20–60 cm in diameter in pelitic gneiss. The Lunan samples (SD0301 and SD0304) occur as thin layers or as lenticular bodies 1–2 m wide within pelitic gneiss. These samples show banded structures that consist of brown garnet-rich and green omphacite-rich layers.

Table 1 lists mineral assemblages of the eclogite samples investigated. The primary mineral assemblage in the eclogites consists mainly of garnet, omphacite, amphibole, muscovite, apatite, rutile, and zircon. Some garnets include polycrystalline quartz aggregates that are pseudomorphs after coesite, as will be discussed later. Quartz occurs also as polygonal crystals in the matrix. K-feldspar occurs as fine-grained subhedral crystals (diameter, 1–20 μm) within some polycrystalline quartz aggregates. Samples R1-7 and SD0304 also contain primary kyanite; and SD0301 contains calcic amphibole, paragonite, epidote, and calcite inclusions in garnet and omphacite. Zoisite and calcic amphibole occur as both inclusions in garnet and as matrix minerals in SD0304 and SD0401, respectively.

Eclogites from these areas were recrystallized to amphibolite facies by regional metamorphism. The resultant retrograde minerals include symplectitic sodic augite and sodic plagioclase, calcic amphibole, and epidote. The symplectites formed from a retrograde reaction between omphacite and quartz (Fig. 2d) and are observed in all of the samples studied except SD0301, which contains little quartz. The secondary calcic amphibole and epidote replace garnet and omphacite around rims and along cracks. In R1-7 and SD0304, sodic plagioclase rims kyanite crystals.

Quartz pseudomorphs after coesite

The omphacite + kyanite assemblage observed in R1-7 and SD0304 is stable at pressures greater than about 20 kbar at 600 °C (Holland, 1979). Enami and Zang (1988) reported magnesian staurolite [X_{Mg} = Mg/(Mg + Fe^{2+}) = 0.68–0.74] in garnet-corundum rocks and in an eclogite (garnet clinopyroxenite) from the Donghai area, about 100 km south of Shandong province. Magnesian staurolite is a typical high-pressure mineral (Schreyer, 1967; Schreyer and Seifert, 1969) and has been reported as an inclusion in pyrope from a coesite-bearing terrane in the western Alps (Chopin, 1987). Therefore, coesite or its pseudomorph should be expected to occur in eclogites from Shandong province.

Figures 2a, 2b and 2c show textural characteristics of quartz pseudomorphs after coesite. Randomly oriented polycrystalline quartz inclusions (diameter, 50–300 μm) occur in garnet. Some radiating quartz fibers rim the cores of polycrystalline quartz (Fig. 2b, 2c); this feature resembles the characteristic radiating texture of inverted quartz aggregates around coesite described by Smyth (1977), Chopin (1984), and Smith (1984). Fractures in the host garnet radiate out from the inclusion toward the garnet grain boundaries (Fig. 2a). Concentric fractures are also visible in Figures 2a and 2b. These fractures are consistent with a large volume increase that accompanies the transition from coesite to quartz (Chesnokov and Popov, 1965; Chopin, 1984; Smith, 1984). These mineralogical and textural features suggest that the polycrystalline quartz inclusions are pseudomorphs after coesite, although no relict coesite was detected. Similar quartz pseudomorphs have been described in eclogites from the Urals and from Münchberg (Chesnokov and Popov, 1965).

Table 1. Mineral assemblages of eclogites containing quartz pseudomorphs after coesite from Shandong province

	Grt	Cpx	Amp	Ky	Ep	Zo	Ms	Pg	Cal	Pl	Kfs	Qtz	Apt	Rt	Ilm	Zrn
R1-7	+	b	s	+	s		+			s	i	+	+	+	+	+
SD0401	+	b	b				+			s	i	+	+	+		+
SD0301	+	+	+		b		+	i	i		i	+	+	+		+
SD0304	+	b	s	+	s	+				s		+	+	+		

Note: Abbreviations are +, primary phase; b, both primary and secondary phases; s, secondary phase only; i, inclusion in garnet and/or omphacite only; Grt, garnet; Cpx, clinopyroxene; Amp, amphibole; Ky, kyanite; Ep, epidote; Zo, zoisite; Ms, muscovite; Pg, paragonite; Cal, calcite; Pl, plagioclase; Kfs, K-feldspar; Qtz, SiO_2 mineral; Apt, apatite; Rt, rutile; Ilm, ilmenite; Zrn, zircon.

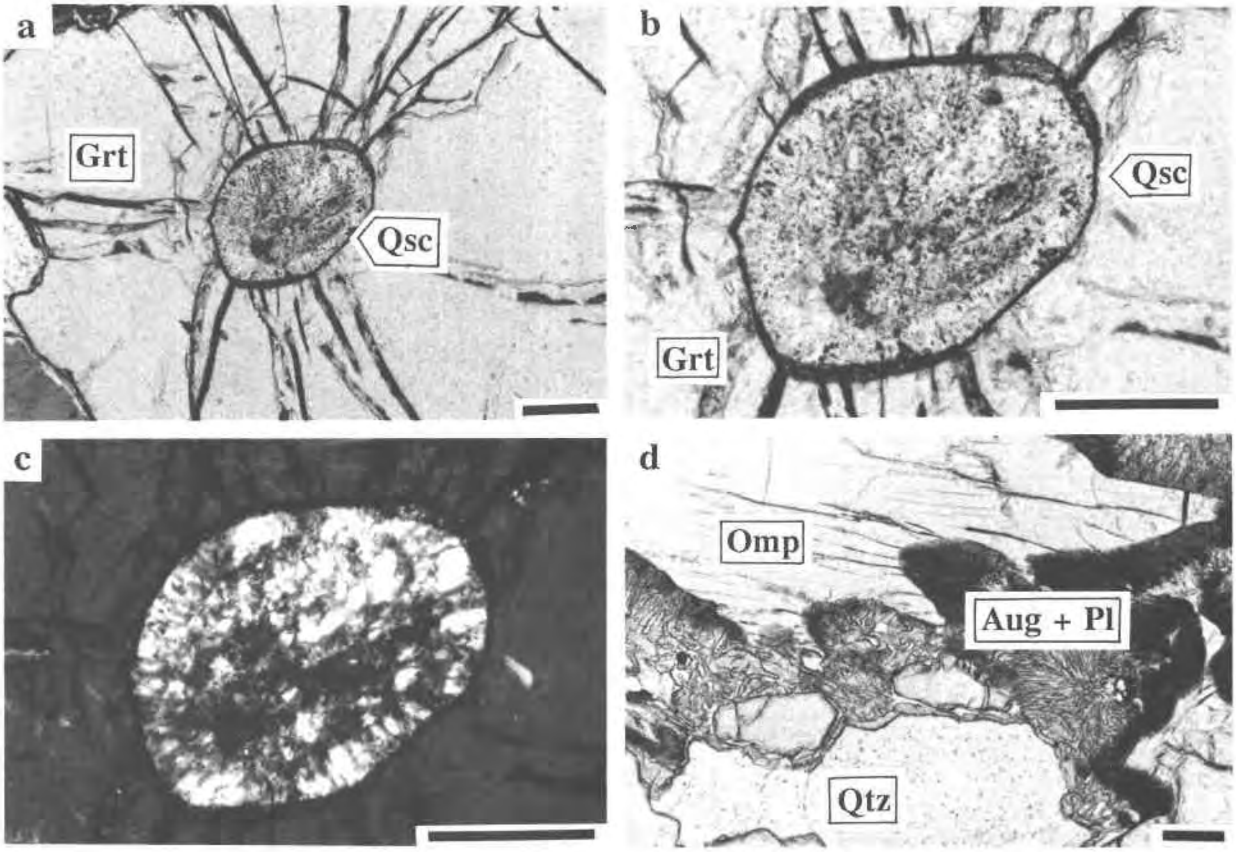

Fig. 2. Microphotographs of quartz pseudomorphs after coesite [(a), (b), and (c)] and symplectitic intergrowth of sodic augite and sodic plagioclase (d) in sample R1-7 from the Rongchen area. (a), (b) and (d) Plane-polarized light. (c) Polarizers slightly uncrossed. Scale bars indicate 100 μm. (**a**) Fractures in the host garnet crystal radiate out from the quartz inclusion (pseudomorph after coesite) towards the grain boundaries. Concentric fractures are also visible around quartz inclusion. (**b**) and (c) Close-up views of a part of (a), showing radiating fibers of quartz around core of polycrystalline quartz aggregate. (**d**) Symplectitic sodic augite and sodic plagioclase were retrogressively formed from a reaction between primary omphacite and quartz. Abbreviation for minerals are Omp, omphacite; Aug + Pl, symplectitic intergrowth of sodic augite and sodic plagioclase; Qsc, quartz pseudomorph after coesite. Others are defined in Table 1.

MINERAL CHEMISTRY

Chemical analyses were performed on samples R1-7, SD0401, and SD0301 with a JEOL electron-probe microanalyzer (EMPA) JCXA-733 at Nagoya University. Accelerating voltage, sample current, and beam diameter were 15 kV, 12 nÅ, and 3 μm, respectively. Synthetic quartz (for Si), rutile (Ti), corundum (Al), Cr_2O_3 (Cr), MnO (Mn), periclase (Mg), NiO (Ni), and wollastonite (Ca), as well as natural hematite (Fe), albite (Na), and adularia (K) were used as standards. The Bence and Albee (1968) method was employed for matrix corrections. Chemical compositions of major constituent minerals are in Table 2. Cr_2O_3 and NiO contents of analyzed minerals are below the limits of detection, i.e., less than 0.03 wt% and 0.02 wt% for Cr_2O_3 and NiO, respectively.

The ferric iron contents in clinopyroxene and amphibole were calculated using the computer program by Papike et al. (1974). The end-member proportions of garnet and clinopyroxene were calculated as follows: Prp = Mg, Alm = total Fe as Fe^{2+}, Grs = Ca and Sps = Mn for garnet, and Jd = Na-Fe^{3+}, Acm = Fe^{3+}, and Aug = 1 − Na for clinopyroxene (abbreviations for end-members after Kretz, 1983). Chemical characteristics of amphiboles are discussed with reference to the medium value between the possible maximum and minimum Fe^{3+} contents.

Garnet, clinopyroxene and amphibole

The garnets present belong to a grossular-rich pyrope-almandine series with less than 0.5 wt% MnO. Most garnet grains in R1-7 and SD0401 are homogeneous, and their average compositions in terms of garnet end-members are $Prp_{22.6}Alm_{48.4}Grs_{28.2}Sps_{0.9}$ and $Prp_{39.9}Alm_{43.9}$-$Grs_{15.1}Sps_{1.2}$, respectively. Garnet in SD0301 shows prograde zoning (e.g., Ghent, 1988) with increasing X_{Mg} and

TABLE 2. Representative chemical analyses (wt%) of major constituent minerals

	R1-7 (Rongchen)							SD0401 (Zhucheng)			
		Cpx			Amp				Cpx		
	Grt	Mx(c)	Mx(r)	Sym	Pgt	Pcp	Ky	Grt	Mx(c)	Mx(r)	Sym
SiO_2	38.8	56.7	57.0	53.6	38.2	43.1	37.3	39.5	55.2	55.4	51.9
TiO_2	0.05	0.10	0.09	0.12	0.10	0.56	0.04	0.00	0.10	0.12	0.19
Al_2O_3	21.8	14.3	15.1	5.14	20.8	11.9	62.1	22.7	10.3	10.8	7.12
FeO*	22.9	4.37	3.62	8.99	13.3	12.7	0.36	20.6	4.03	3.73	5.24
MnO	0.40	0.06	0.00	0.00	0.13	0.07	0.05	0.54	0.11	0.11	0.09
MgO	5.98	6.48	6.00	10.1	10.9	14.0	0.00	10.5	9.44	9.10	11.5
CaO	10.4	10.8	9.83	17.6	10.7	10.4	0.00	5.53	14.6	14.0	18.9
Na_2O	0.03	7.96	8.35	3.89	3.66	3.28	0.03	0.00	5.44	6.08	3.44
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.4	100.8	100.0	99.4	97.8	96.0	99.9	99.4	99.2	99.3	98.4
Formulae											
	O = 12	O = 6	O = 6	O = 6	O = 23	O = 23	O = 5	O = 12	O = 6	O = 6	O = 6
Si	2.989	1.984	1.995	1.972	5.566	6.363	1.009	2.993	1.981	1.982	1.905
Al	1.979	0.590	0.623	0.223	3.573	2.071	1.980	2.027	0.436	0.455	0.308
Ti	0.003	0.003	0.002	0.003	0.011	0.062	0.001	0.000	0.003	0.003	0.005
Fe^{3+}		0.000	0.000	0.104	0.593	0.543			0.000	0.000	0.115
Fe^{2+}	1.475	0.128	0.106	0.173	1.028	1.026	0.008	1.305	0.121	0.112	0.045
Mn	0.026	0.002	0.000	0.000	0.016	0.009	0.001	0.035	0.003	0.003	0.003
Mg	0.687	0.338	0.313	0.554	2.367	3.080	0.000	1.186	0.505	0.485	0.629
Ca	0.858	0.405	0.369	0.694	1.671	1.645	0.000	0.449	0.561	0.537	0.743
Na	0.004	0.540	0.567	0.277	1.034	0.939	0.002	0.000	0.378	0.442	0.245
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: Abbreviations are Mx, primary phase in matrix; (c), core; (r), rim; Sym, secondary phase in symplectite; Pgt, pseudomorph after garnet; Pcp, pseudomorph after omphacite; In, inclusion in garnet. Others are defined in Table 1.

* Total Fe as FeO.

decreasing Mn and Ca contents from core ($Prp_{22.9}Alm_{45.9}$-$Grs_{30.3}Sps_{0.9}$) to rim ($Prp_{28.6}Alm_{46.7}Grs_{24.3}Sps_{0.5}$).

The Jd component of primary omphacite is 49–57 mol%, 38–45 mol%, and 43–53 mol% in R1-7, SD0401, and SD0301, respectively. Omphacites in R1-7 and SD0401 show weak prograde zoning as the Jd component increases from core to rim (see Table 2). The Acm component is less than 4 mol% in primary omphacite. Symplectitic sodic augite has an average composition of Jd = 17 mol% and Acm = 10 mol% for R1-7, and Jd = 13 mol% and Acm = 12 mol% for SD0401.

Primary calcic amphibole in SD0401 is pargasitic hornblende with Al_2O_3 = 14.5–16.4 wt%, using the nomenclature of Leake (1978). In SD0301, amphibole inclusions in garnet are ferroan pargasite with Al_2O_3 = 16.8–19.6 wt%, and some amphiboles in the matrix have magnesian katophorite or magnesian taramite compositions (Si = 6.5–6.6, Ca = 1.35–1.37, and Na + K = 1.16–1.21 for O = 23). Secondary amphibole varies in composition from crystal to crystal. In R1-7, the amphibole replacing garnet is subsilicic pargasite with maximum Al_2O_3 = 20.8 wt% (Rock and Leake, 1984), whereas amphibole replacing omphacite is pargasitic hornblende with maximum Al_2O_3 = 11.9 wt%. The SiO_2, Al_2O_3, and CaO contents of the subsilicic pargasite (SiO_2 = 38.2 wt%, Al_2O_3 = 20.8 wt%, and CaO = 10.7 wt%) replacing garnet are quite similar to those of the host garnet (SiO_2 = 38.8 wt%, Al_2O_3 = 21.8 wt%, and CaO = 10.4 wt%), indicating that these components may not have been modified during the retrograde stage.

Other minerals

Muscovite is phengitic (FeO + MgO = 3.8–5.6 wt%), and the Na_2O content is 0.5–1.3 wt%. Paragonite contains 0.5–0.7 wt% CaO and 0.5–0.8 wt% K_2O. Some epidotes show compositional zoning and consist of a REE-rich core and a REE-free rim. Fe_2O_3 content of the REE-free rim is 6–14 wt%. Average chemical compositions of sodic plagioclase and K-feldspar are $Ab_{90}An_{10}Or_0$ and $Ab_1An_0Or_{99}$, respectively. Kyanite shows no pleochroism, and its Fe_2O_3 content is 0.40–0.52 wt%. Calcite has a nearly pure end-member composition, and FeO (less than 0.4 wt%) and MgO (less than 0.1 wt%) are present in only minor amounts.

Formation of coesite pseudomorphs

Pressure-temperature conditions

Both garnet and omphacite in the eclogites from Shandong province show prograde zoning. They contain some hydrous mineral inclusions of calcic amphibole, muscovite, paragonite, and epidote group minerals. These data suggest that the eclogites are prograde metamorphic products and thus represent previously subducted crustal rocks (e.g., Chopin, 1984; Smith, 1984; Schulze and Helmstaedt, 1988).

Figure 3 shows *P-T* estimates for the coesite pseudomorph-bearing eclogites. Combining the available data for the Mg-Fe partitioning between garnet and omphacite (Powell, 1985) and for the coesite stability field (Mirwald and Massonne, 1980), we estimate the most likely *P-T*

TABLE 2.—*Continued*

SD0401 (Zhucheng)		SD0301 (Lunan)							
Amp		Grt		Cpx				Amp	
Mx	Pgt	(c)	(r)	Mx(c)	Mx(r)	In(c)	In(r)	Mx	In
45.6	37.6	39.7	40.3	56.9	55.0	56.8	56.8	45.6	40.2
0.37	0.12	0.14	0.10	0.07	0.24	0.04	0.08	0.35	0.63
16.4	20.6	22.4	22.4	12.7	11.7	11.7	11.8	15.5	19.6
7.13	15.4	21.7	22.1	3.50	4.30	3.39	3.21	9.94	13.2
0.04	0.32	0.41	0.22	0.00	0.00	0.00	0.00	0.00	0.00
14.1	8.75	6.08	7.59	7.74	8.33	8.62	8.31	12.1	10.0
9.35	9.92	11.2	8.97	11.8	13.7	12.6	12.7	8.71	10.3
3.64	3.43	0.03	0.02	7.65	6.47	7.33	7.30	3.95	3.86
0.44	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.00
97.1	96.7	101.7	101.7	100.4	99.7	100.5	100.2	96.4	97.8
O = 23	O = 23	O = 12	O = 12	O = 6	O = 6	O = 6	O = 6	O = 23	O = 23
6.459	5.610	3.000	3.023	1.998	1.961	1.993	2.000	6.577	5.862
2.739	3.624	1.995	1.980	0.525	0.492	0.484	0.490	2.636	3.369
0.039	0.014	0.008	0.006	0.002	0.006	0.001	0.002	0.038	0.069
0.222	0.548			0.000	0.021	0.027	0.004	0.181	0.293
0.623	1.374	1.371	1.386	0.103	0.107	0.072	0.090	1.018	1.317
0.005	0.040	0.026	0.014	0.000	0.000	0.000	0.000	0.000	0.000
2.976	1.946	0.685	0.849	0.405	0.443	0.451	0.436	2.601	2.173
1.419	1.586	0.907	0.721	0.444	0.523	0.474	0.479	1.346	1.609
1.000	0.992	0.004	0.003	0.521	0.447	0.499	0.498	1.105	1.091
0.080	0.107	0.000	0.000	0.000	0.000	0.000	0.000	0.053	0.000

brackets to be >28 kbar and 800–840 °C for equilibration of the primary eclogite stage. The *P-T* estimate is similar to that of a high-pressure eclogite from the Donghai area, Jiangsu province (>19 kbar and 820–850 °C; Enami et al., 1986). Retrograde *P-T* conditions are estimated to be 9–14 kbar and 670–750 °C mainly on the basis of the following observations: (1) Symplectitic intergrowths of sodic augite (Jd = 13–17 mol%) and sodic plagioclase coexist with quartz in R1-7 and SD0401. A suggested reaction for the symplectite formation is as follows:

$$\underset{\text{omphacite}}{8(Na_{0.5}Ca_{0.5})(Al_{0.45}Fe^{3+}_{0.05})(Mg,Fe^{2+})_{0.5}Si_2O_6} + \underset{\text{quartz}}{3SiO_2}$$

$$\rightarrow \underset{\text{sodic augite}}{5(Na_{0.2}Ca_{0.8})(Al_{0.12}Fe^{3+}_{0.08})(Mg,Fe^{2+})_{0.8}Si_2O_6}$$

$$+ \underset{\text{albite}}{3NaAlSi_3O_8}$$

(2) Kyanite in R1-7 and SD0304 is replaced after secondary sodic plagioclase, suggesting that paragonite + quartz was unstable during the retrograde stage (cf. Reaction 3 in Fig. 3). The retrograde conditions imply that coesite-bearing eclogites might have been subjected to amphibolite facies metamorphism with the surrounding gneisses and that coesite inverted completely to polycrystalline quartz aggregates with rapid decrease of pressure under relatively high-temperature conditions.

Geological implication

Coesite-bearing eclogites in the Precambrian gneiss terrane were found in the Dabie Mountain area, Anhui province, about 600–700 km south-southwest of

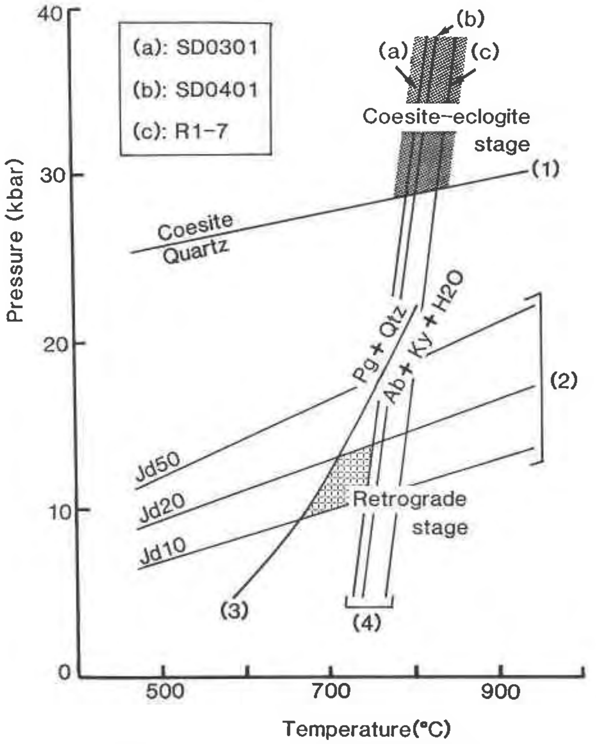

Fig. 3. *P-T* estimates of eclogites from Shandong province. (1) Quartz ↔ coesite transition (Mirwald and Massonne, 1980). (2) Lower pressure limits of sodic pyroxene (Jd = 10, 20, and 50) + quartz assemblages (Banno, 1986). (3) Paragonite + quartz stability (Chatterjee, 1972). (4) *P-T* relations of eclogites estimated using the garnet clinopyroxene geothermometer (Powell, 1985).

Shandong province (Wang et al., 1989). The eclogites in both Shandong province and the Dabie Mountain area occur within or near a similar suture zone between the Sino-Korean and Yangtze cratons. They are considered to have been offset for about 600–700 km by the left-lateral Tanlu fault zone (Zhang et al., 1984). Careful petrographic examinations may reveal more occurrences of coesite-bearing high-pressure eclogites in east China. Although age determinations are not conclusive, the eclogites from Shandong and Anhui provinces have been considered to be Precambrian (Dong et al., 1986). The occurrences of the high-pressure eclogites in China suggest that active subduction existed in Precambrian time during growth of the Sino-Korean craton.

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