American Mineralogist, Volume 88, pages 1153–1156, 2003

Ultrahigh-pressure metamorphism in eclogites from the western Tianshan high-pressure belt (Xinjiang, western China)—Comment

REINER KLEMD*

Mineralogisches Institut, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany

Despite the absence of ultrahigh-pressure (UHP) minerals such as coesite and microdiamond, Zhang et al. (2002a, 2002b) claimed to have found unambiguous evidence for UHP metamorphism in eclogites from the western Tianshan high-pressure (HP-LT) belt. UHP metamorphic rocks with an oceanic protolith provide evidence for the subduction of the oceanic lithosphere to mantle depths. If correct, these conclusions would demand a revision of previous tectonic models of northwestern China (e.g., Gao et al. 1995, 1998).

However evidence for UHP eclogites is contradicted by the recent findings of Gao et al. (1999), Gao and Klemd (2000, 2001, 2003), and Klemd et al. (2002)—none of which was discussed by Zhang et al. (2002a, 2002b)—who estimated peak metamorphic conditions within the high-pressure eclogite-facies field. The equilibrium mineral assemblage of the eclogites and intimately interlayered garnet-omphacite blueschists from 25 different locations (Fig. 1; including the three of Zhang et al. 2002a, 2002b) includes garnet-omphacite-rutile-quartz ± zoisite ± sodic-calcic to alkali amphiboles ± phengite ± paragonite. The eclogites only contain additional carbonates at two localities (Fig. 1; also see Fig. 1 in Zhang et al. 2002a). Using conventional exchange and net-transfer reactions (Gao et al. 1999; Gao and Klemd 2000, 2001, 2003; Klemd et al. 2002), as well as calculated *PT-pseudosections* for a specific bulk composition in the system NCFMASH (Klemd et al. 2002), peak conditions of 480 to 600 °C at 18–21 kbar were derived. Furthermore, Gao and Klemd (2001) suggested an isothermal decompression path as well as the presence of a low-salinity brine during HP-LT metamorphism.

Although Zhang et al. (2002a, 2002b) only described three localities, they favored UHP conditions for all western Tianshan eclogites (see Abstract and Geological Implications in Zhang et al. 2002a) based only on three features: (1) radial cracks around mono- to polycrystalline quartz inclusions in rims of prograde zoned garnets; (2) quartz exsolution lamellae in omphacite; and (3) magnesite inclusions in dolomite and glaucophane.

Regarding the first feature, which was also observed in the southern Tianshan belt of Kirgistan (Tagiri et al. 1995), it should be pointed out that, in the absence of coesite relics and radiating fibers of quartz (palisade quartz) around the core of polycrystalline quartz aggregates (see Fig. 3d in Zhang et al. 2002a), the polycrystalline, mosaic-textured quartz inclusions with radial fractures in garnet do not necessarily indicate UHP-conditions. For example, Wendt et al. (1993) have emphasized that

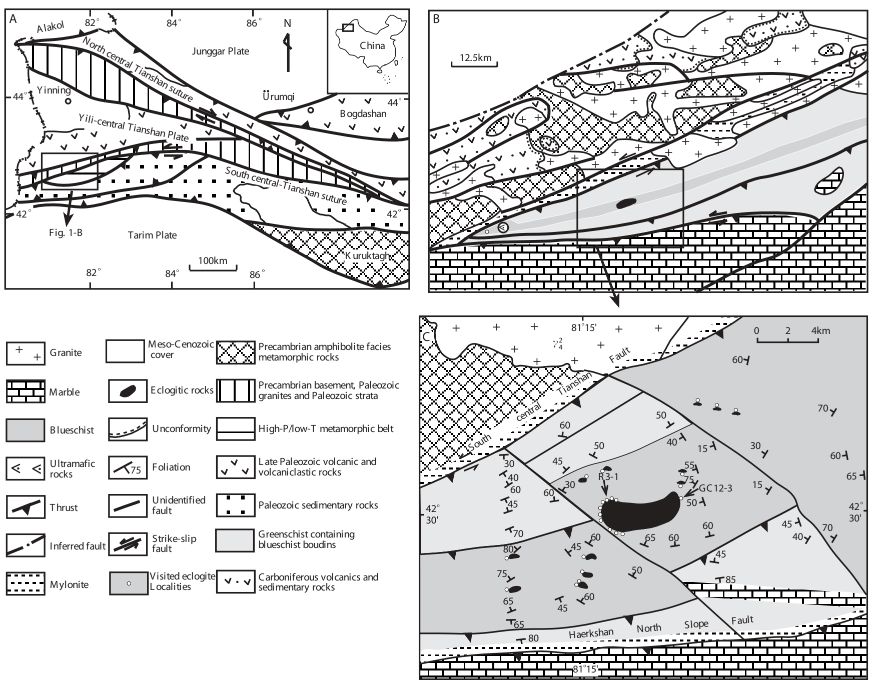

FIGURE 1. Simplified tectonic and geological map of the Chinese Tianshan Orogen (modified after Gao et al. 1999) showing the blueschist and eclogite distribution and sample localities (arrows). None of sample localities shows unambiguous evidence for UHP metamorphism.

* E-mail: reiner.klemd@mail.uni-wuerzburg.de

0003-004X/03/0007–1153$05.00

radial cracks around quartz may result from the dilation of a-quartz without a phase transformation. Furthermore, Whitney et al. (2000) showed that microcracks emanating from quartz inclusions in garnet are primarily a result of inclusion shape and size and do not require UHP-conditions or significant decompression to develop. Radial fractures can form during modest decompression prior to the recrystallization of quartz inclusions in garnet (Whitney at al. 2000; see also discussion in Sisson et al. 1997).

Concerning the second feature, it should be noted that the solubility of the Ca-Eskola component in clinopyroxene potentially could be a useful geobarometer, but the precise *P-T* conditions for this reaction are still disputed and uncertain (cf., Katayama et al. 2000). Therefore, it cannot be used as an unambiguous UHP indicator, as quartz exsolution also occurs in “ordinary” high-pressure granulites (Gayk et al. 1995). A further and more serious implication concerns the estimation of the Ca-Eskola component by Zhang et al. (2002a). We examined more than 50 thin sections of the eclogite from the same locality as Zhang et al. (2002a) and, in so doing, investigated what appeared to be an exsolution texture in omphacite. Although we observed a similar texture to that reported by Zhang et al. (2002a), we in actual fact found the “exsolved quartz rods” to be *c*-axis parallel, tubular to elliptical quartz, rutile, and/or one- or two-phase aqueous fluid inclusions (Fig. 2). Consequently, the estimated Ca-Eskola component of 11–17 mol% is much too high and therefore the estimated pressures (≥25 kbar) are too high as well. There seems to be a further misconception by Zhang et al. (2002a) who, using the formula (Si + Ti) > (Ca + Mg + Fe^{2+} + Mn + Ni – 2Na), regarded those omphacites that contain “exsolved quartz needles” as being supersilicic. According to this formula, almost all omphacites in eclogites worldwide would be supersilicic—including the ”quartz needle-free” omphacites in the eclogites of the western Tianshan (Table 1 in Zhang et al. 2002a and Table 1 in the present paper). However, even according to the correct formula [(Si + Ti – 2Na) > (Ca + Mg + Ni + Fe^{2+} + Mn), Smith and Cheeney (1980)], none of the “exsolved quartz needle-free” omphacites (with the same composition as the “quartz needle”-bearing omphacites) in the same thin section (Table 1) is supersilicic.

The third argument concerns the presence of round to irregular magnesite inclusions in dolomite and glaucophane in a carbonate-bearing eclogite (see Fig. 1a, 1b in Zhang et al. 2002b). The presence of these magnesite inclusions in dolomite, magnesite/dolomite inclusions in glaucophane, as well as the possible former presence of coesite led Zhang et al. (2002b) to define the following equilibrium assemblage: omphacite + garnet + magnesite + coesite, which is replaced by dolomite + glaucophane + clinozoisite, thus neglecting the presence of paragonite inclusions in the dolomite (see Fig. 3a, 3b). Using the internally consistent database of Holland and Powell (1998)—apart from paragonite—all of these phases (as well as H_2O and CO_2) were used to calculate an intersection of mineral end-member reactions at P ~ 38 kbar and T ~ 600 °C at X_{CO_2} = 0.0025. Activity corrected end-member reactions intersected at 27–28 kbar. However, the addition of paragonite and quartz (instead of coesite) to the equilibrium assemblage shifts the invariant point to P ~ 25 kbar at 530 °C and P ~ 20 kbar at 470 °C (X_{CO_2} = 0.0025) for end-member and activity corrected end-member reactions, respectively [we also used the internally consistent dataset of Holland and Powell (1998) and ideal mixing models]. Apart from the fact that the equilibrium conditions among all the phases—in particular of coesite—is questionable, the invariant intersection strongly depends on the

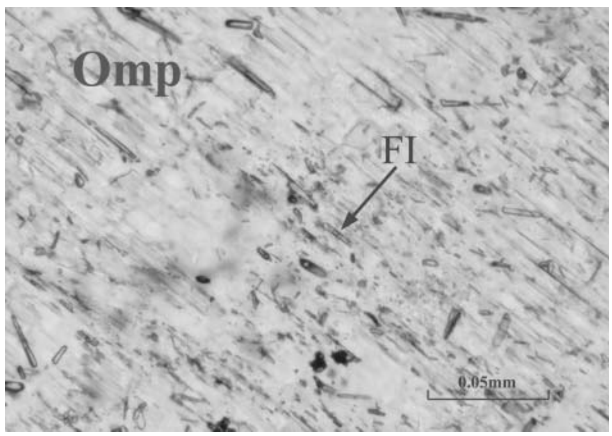

FIGURE 2. Photomicrograph of one- and two-phase (arrow) fluid inclusions parallel to the *c*-axis of omphacite (sample GC 12-3).

TABLE 1A. Selected microprobe analyses of mineral inclusions in dolomite and in the matrix of magnesite-bearing eclogite-facies rocks from the western Tianshan, NW China

	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	FeO*	MgO	MnO	CaO	Na_2O	K_2O	H_2O	Total	Si	Al^{IV}	Al^{VI}	Ti	Cr	Fe^{3+}	Fe^{2+}
Mineral					**Sample R3-1 in dolomite**															
Grt-R	37.59	0.05	21.08	0.00	0.51	30.98	2.86	0.61	7.03	0.00	0.00		100.71	2.98	0.02	1.94	0.00	0.00	0.03	2.05
Omp	55.49	0.00	9.66	0.03		9.03	6.45	0.00	10.93	8.34	0.02		99.95	1.98	0.02	0.39	0.00	0.00	0.21	0.07
Gln	57.02	0.04	9.37	0.03		13.24	10.04	0.00	1.11	7.05	0.02	2.15	100.07	7.87	0.13	1.40	0.00	0.00	0.50	1.03
Czo	38.12	0.08	27.17	0.06	9.08		0.00	0.03	23.48	0.06	0.00	1.92	100.00	2.98	0.02	2.48	0.01	0.00	0.53	0.00
Pg	47.38	0.03	39.66	0.13		0.58	0.08	0.05	0.31	7.30	0.68	4.73	100.93	3.00	1.00	1.96	0.00	0.01	0.00	0.03
Ph	51.76	0.14	24.24	0.05		3.50	4.27	0.01	0.10	0.21	10.73	4.45	99.46	3.49	0.51	1.42	0.01	0.00	0.00	0.20
					Sample R3-1 in matrix															
Grt-R	37.22	0.05	21.07	0.00	0.38	30.90	2.86	0.44	7.27	0.00	0.00		100.19	2.96	0.04	1.93	0.00	0.00	0.02	2.06
Omp	55.00	0.10	9.03	0.07	0.00	10.23	6.02	0.01	10.31	8.24	0.01		99.02	1.99	0.01	0.38	0.00	0.00	0.20	0.11
Gln	57.46	0.01	10.67	0.01		10.79	10.77	0.00	0.55	7.27	0.00	2.17	99.70	7.85	0.15	1.57	0.00	0.00	0.49	0.75
Czo	37.58	0.18	26.49	0.02	9.82		0.00	0.00	23.31	0.01	0.01	1.90	99.32	2.97	0.03	2.43	0.01	0.00	0.58	0.00
Pg	47.28	0.11	39.35	0.07		0.85	0.33	0.04	0.33	7.27	0.94	4.73	101.30	3.00	1.00	1.93	0.01	0.00	0.00	0.05
Ph	50.29	0.16	26.98	0.00		3.18	3.52	0.00	0.00	0.62	10.09	4.46	99.30	3.38	0.62	1.52	0.01	0.00	0.00	0.18

specific mixing models used by Zhang et al. (2002b). Consequently, the *P-T* location of the invariant point is fraught with uncertainties. Furthermore, it also should be mentioned that the glaucophane used by Zhang et al. (2002b) for calculating the UHP-equilibrium conditions shows almost its end-member composition, whereas HP-UHP-glaucophane has a significant substitution of Si by ^{IV}Al and excess Mg on the M4 site (cf., Tropper et al. 2000).

Another even more serious problem involves the textural relations among the minerals in the carbonate-bearing eclogite. Our textural study revealed that, in addition to magnesite, quartz, glaucophane, garnet, omphacite, clinozoisite, phengite, and paragonite also occur as inclusions in dolomite (Figs. 3a, 3b; Table 1) indicating that dolomite grew during and after crystallization of glaucophane, clinozoisite, quartz, and paragonite, and thus cannot have been in equilibrium with the UHP-peak metamorphic minerals (see *P-T* estimate below). Last but not least, it must be pointed out that magnesite itself does not imply UHP conditions (cf., Brey et al. 1983), as it also occurs in the high-pressure Tauern eclogites (P = 19.5 ± 2.5 kbar at T = 620 ± 30 °C, Holland 1979a). Experimental studies of tholeiitic basalts involving mixed H_2O-CO_2 fluids suggest that magnesite forms at $P \geq 18$ kbar (e.g., Poli and Schmidt 2002).

TABLE 1B. Sample R3-1

Mineral	Magnesite	Magnesite	Dolomite	Dolomite
Mg(CO_3)	51.58	49.41	34.85	35.21
Ca(CO_3)	0.87	1.38	52.02	52.45
Mn(CO_3)	0.69	0.45	0.05	0.18
Fe(CO_3)	47.78	48.74	13.41	13.28
Sr(CO_3)	0.00	0.00	0.19	0.17
Ba(CO_3)	0.00	0.00	0.03	0.00
Total	100.92	99.98	100.55	101.29
Mg	0.59	0.57	0.79	0.79
Ca	0.01	0.02	0.99	0.99
Mn	0.01	0.00	0.00	0.00
Fe	0.39	0.41	0.22	0.22
Sr	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00
Cations	1.00	1.00	2.00	2.00

* Electron microprobe analyses were carried out using a CAMECA SX50 microprobe at the Institute of Mineralogy of Universität Würzburg. Operating conditions were 15 kv accelerating potential, 10-15 nA sample current and 10 to 30s counting time. Well-characterized natural minerals (wollastonite: Si, Ca; corundum: Al; rhodonite: Mn; albite: Na; orthoclase: K; rutile: Ti) and synthetic mineral (Fe_2O_3: Fe; MgO: Mg; Cr_2O_3: Cr) were used as standards for silicates. Well-characterized natural minerals (calcite: Ca; dolomite: Mg; siderite: Fe) and synthetic mineral ($MnTiO_3$:Mn; $BaSO_4$:Ba ; $SrCO_3$:Sr) were used as standards for carbonates. The CAMECA PAP-program was used for matrix corrections.The Fe^{2+}/Fe^{3+} ratio of garnet and omphacite were calculated by charge balance.
Formula proportions based on 1 cation for magnesite and 2 cations for dolomite. WEF = Wo + En + Fs

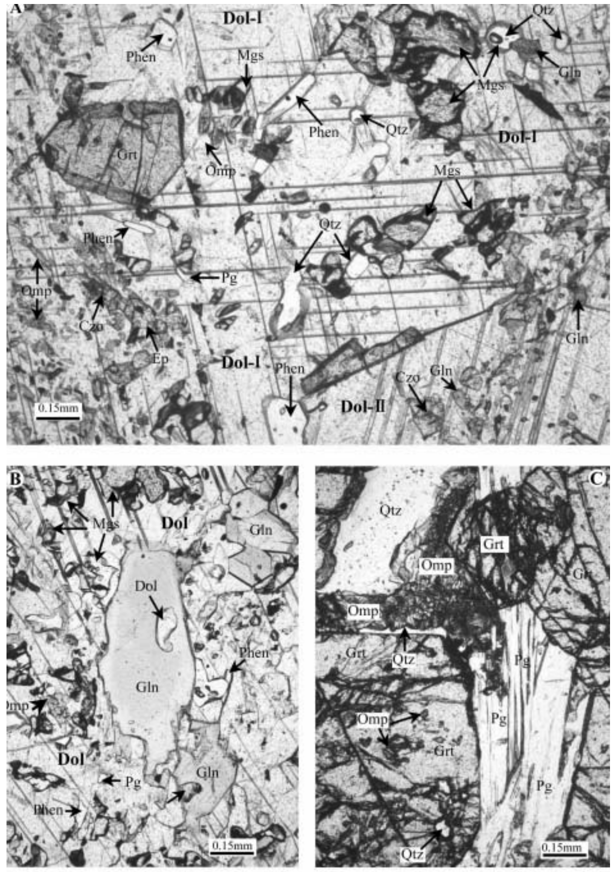

FIGURE 3. (**a**) Dolomite porphyroblasts with inclusions of garnet, omphacite, glaucophane, magnesite, phengite, paragonite, quartz, and clinozoisite/epidote. (**b**) Dolomite porphyroblast with glaucophane, omphacite, phengite, paragonite, and magnesite inclusions. Note the embayed grain boundaries of the glaucophane indicating replacement by the surrounding dolomite. (**c**) Equilibrium texture of garnet, paragonite, omphacite, and quartz. The prograde zoned garnet shows a monocrystalline quartz inclusion with radial fractures in its rim. Abbreviations follow Kretz (1983) except Omp (omphacite) and Phen (phengite).

TABLE 1A. —extended

Mg	Mn	Ca	Na	K	Cations	Alm	And	Grs	Py	Spe	WEF	Jd	Ae
0.34	0.04	0.60	0.00	0.00	8.00	67.79	1.54	18.17	11.16	1.35			
0.34	0.00	0.42	0.58	0.00	4.01						41.70	38.20	21.10
2.07	0.00	0.16	1.89	0.00	15.05								
0.00	0.00	1.97	0.01	0.00	8.00								
0.01	0.00	0.02	0.90	0.06	6.99								
0.43	0.00	0.01	0.03	0.92	7.02								
0.34	0.03	0.62	0.00	0.00	8.00	67.53	1.16	19.20	11.14	0.97			
0.33	0.00	0.40	0.58	0.00	4.00						41.99	38.13	19.89
2.19	0.00	0.08	1.93	0.00	15.01								
0.00	0.00	1.97	0.00	0.00	8.00								
0.03	0.00	0.02	0.89	0.08	7.01								
0.35	0.00	0.00	0.08	0.87	7.01								

Consequently, none of the features described by Zhang et al. (2002a, 2002b) prove UHP metamorphism unambiguously. Furthermore, considering the absence of key indicator UHP-minerals, additional evidence is required from solid-solid reactions and/or devolatilization reactions. Moreover, we note the absence of kyanite (or pseudomorphs after kyanite) in all investigated eclogites and garnet-omphacite blueschists despite their high bulk-chemical Al_2O_3 contents between 16 and 22 wt%. In addition, the presence of paragonite (Fig. 3c; also reported by Zhang et al. 2002b) provides a maximum H_2O-dependent pressure condition of about 21 kbar at 500 °C (Gao et al. 1999; Gao and Klemd 2000, 2002; Klemd et al. 2002), using the experimentally calibrated univariant reaction Pg = Omp_{Jd50} + Ky + H_2O (Holland 1979b). This result is in agreement with pressures of 18 to 22 kbar at 450–580 °C (Klemd et al. 2002), which were derived with the garnet-omphacite-phengite equilibrium after Waters (1996).

These *P-T* conditions have been corroborated by a *PT pseudosection* that was constructed for a specific bulk-rock composition of a garnet-omphacite blueschist in the system NCFMASH + Qtz and H_2O (Klemd et al. 2002). This *PT pseudosection* shows that, for pressures above about 20 kbar, lawsonite should be a stable phase, which is supported by the phase-diagram calculations by Kerrick and Connolly (2001) and Poli and Schmidt (2002). Consequently, the absence of peak-metamorphic lawsonite (or pseudomorphs after lawsonite) in the rim of prograde zoned garnets or the matrix as well as of other UHP phases (such as coesite, microdiamond, talc, K-rich clinopyroxene, and Na-rich garnet) imply that UHP conditions are highly unlikely for the eclogite-facies rocks of the western Tianshan high-pressure belt. A further possibility may be the tectonic introduction of individual UHP bodies and sheets into the Tianshan HP-belt. However, although it cannot be excluded completely, it should be viewed with caution as the intimate interlayering of eclogites and prograde-formed blueschists on a meter to millimeter scale (Gao et al. 1999) indicates that both rock types must have undergone an identical *P-T* evolution.

Thus, it is inappropriate to imply former UHP metamorphism for all the eclogites of the western Tianshan HP-belt without the definite evidence of (former) UHP minerals.

ACKNOWLEDGEMENTS

Financial support of the Deutsche Forschungsgemeinschaft (Kl 692/10-1, 2, 3), the National Science Foundation of China (49972079) and the "Funds for Hundred Outstanding Talents plan" sponsored by the Chinese Academy of Sciences are gratefully acknowledged. I am most grateful to J. Gao for his continuous support and contributions to the manuscript. Furthermore I thank M. Bröcker, T. John, M. Klemd, E. Schmädicke, T.M. Will, and A. Zeh for discussion and comments on the manuscript. A constructive journal review by V.B. Sisson, Rice University, is highly appreciated.

REFERENCES CITED

Brey, G., Brice, W. R., Ellis, D.J., Green, D.H., Harris, K.L., and Ryabchikov, I.D. (1983) Pyroxene-carbonate reactions in the upper mantle. Earth and Planetary Science Letters, 62, 63–74.

Gao, J. and Klemd, R. (2000) Eclogite occurrences in the western Tianshan high-pressure belt, Xinjiang, western China. Gondwana Research, 3, 33–38.

———(2001) Primary fluids entrapped at blueschist to eclogite transition: evidence from the Tianshan meta-subduction complex in northwestern China. Contributions to Mineralogy and Petrology, 142, 1–14.

———(2003) Formation of HP-LT rocks and their tectonic implications in the western Tianshan Orogen, NW China: geochemical and age constraints. Lithos, 66, 1–22.

Gao, J., He, G., Li, M., Xiao, X., Tang, Y., Wang, J., and Zhao, M. (1995) The mineralogy, petrology, metamorphic PTDt trajectory and exhumation mechanism of blueschists, south Tianshan, northwestern China. Tectonophysics, 250, 151–168.

Gao, J., Li, M., Xiao, X., Tang, Y., and He, G. (1998) Paleozoic tectonic evolution of the Tianshan orogen, northwestern China. Tectonophysics, 287, 213–231.

Gao, J., Klemd, R., Zhang, L., Wang, Z., and Xiao, X. (1999) P-T path of high pressure-low temperature rocks and tectonic implications in the western Tianshan Mountains (NW China). Journal of Metamorphic Geology, 17, 621–636.

Gayk, T., Kleinschrodt, R., and Seidel, E. (1995) Quartz exsolution in clinopyroxene of high-pressure granulite from the Münchberg massif. European Journal of Mineralogy, 7, 1217–1220.

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

———(1979b) Experimental determination of the reaction paragonite = jadeite + kyanite + H_2O. Contributions to Mineralogy and Petrology, 68, 293–301.

Holland, T.J.B. and Powell, R. (1998) An internally consistent thermodynamic dataset for phases of petrological interest. Journal of Metamorphic Geology, 16, 309–343.

Katayama, I., Parkinson, C.D., Okamoto, K., Nakajima, Y., and Marayuma, S. (2000) Supersilicic clinopyroxene and silica exsolution in UHPM eclogite and pelitic gneiss from the Kokchetav massif, Kazakhstan. American Mineralogist, 85, 1368–1374.

Klemd, R., Schröter, F.C., Will, T.M., and Gao, J. (2002) PT-evolution of glaucophane-omphacite bearing HP-LT rocks in the western Tianshan orogen, NW China: new evidence for 'Alpine-type' tectonics. Journal of Metamorphic Geology, 20, 239–254.

Kerrick, D.M. and Conolly, J.A.D. (2001) Metamorphic devolitilisation of subducted oceanic metabasalts: implications for seismicity, arc magmatism and volatile recycling. Earth and Planetary Science Letters, 189, 19–29.

Kretz, R. (1983) Symbols for rock-forming minerals. American Mineralogist, 68, 277–279.

Poli, S. and Schmidt, M. (2002) Petrology of subducted slabs. Annual Reviews of Earth Planetary Science Letters, 30, 207–235.

Sisson, V.B., Ertan, I.E., and AveLallemant, H.G. (1997) High-pressure (~2000 MPa) kyanite- and glaucophane-bearing pelitic schist and eclogite from Cordillera de la Costa Belt, Venezuela. Journal of Petrology, 38, 65–83.

Smith, D.C. and Cheeney, R.F. (1980) Oriented needles of quartz in clinopyroxene: evidence for exsolution of SiO_2 from a non-stoichiometric supersilicic "clinopyroxene". 26th International Geological Congress, Paris, France, 145 p.

Tagiri, M., Yano, Y., Bakirov, A., Nakajima, T., and Uchiumi, S. (1995) Mineral parageneses and metamorphic P-T paths of ultrahigh-pressure eclogites from Kyrghyztan Tien Shan. The Island Arc, 4, 280–292.

Tropper, P., Manning, C. E., Essene, E.J., and Kao, L.-S. (2000) The compositional variation of synthetic sodic amphiboles at high and ultra-high pressures. Contributions to Mineralogy and Petrology, 139, 146–162.

Wendt, A.S., D'Arco, P., Goffe, B., and Oberhänsli, R. (1993) Radial cracks aroung alpha-quartz inclusions in almandine: constraints on the metamorphic history of the Oman mountains. Earth and Planetary Science Letters, 114, 449–461.

Waters, D.J. (1996) The garnet-cpx-phengite barometer—recommended calibration and calculation method. http://www.earth.ox.ac.uk/%7Edavewa/research/ecbarcal.html.

Whitney, D.L., Cooke, M.L., and Du Frane, S.A. (2000) Modeling of radial microcracks at corners of inclusions in garnet using fracture mechanics. Journal of Geophysical Research, 105, B2, 2843–2853.

Zhang, L., Ellis, D.J., and Jiang, W. (2002a) Ultrahigh-pressure metamorphism in western Tianshan, China: Part I. Evidence from inclusions of coesite pseudomorphs in garnet and from quartz exsolution lamellae in omphacite in eclogite. American Mineralogist, 87, 853–860.

Zhang, L., Ellis, D.J., Williams, S., and Jiang, W. (2002b) Ultrahigh-pressure metamorphism in western Tianshan, China: Part II. Evidence from magnesite in eclogite. American Mineralogist, 87, 856–866.

MANUSCRIPT RECEIVED DECEMBER 11, 2002
MANUSCRIPT ACCEPTED MARCH 9, 2003
MANUSCRIPT HANDLED BY ROBERT DYMEK