Significance of ultrahigh-P talc-bearing eclogitic assemblages

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Abstract

Talc was identified as an equilibrium associate of omphacite, kyanite, zoisite, and garnet in some coesite-bearing eclogites and as a retrograde phase in associated garnet peridotite from the Bixiling mafic-ultramafic complex in the Dabie ultrahigh-P metamorphic terrane, central China. Observed talc- and tremolite-bearing assemblages within the coexisting mafic and ultramafic rocks together with established phase relations for the simple system $CaO-MgO-Al_2O_3-SiO_2-H_2O$ constrain the P-T path for retrograde metamorphism. This, together with reported talc occurrences from the Dora Maira massif, leads to the conclusion that UHP talc assemblages are confined to mafic and pelitic rocks of unusual chemistry, and are not stable at ultrahigh pressures in ultramafic rocks. Thus, talc cannot be an important H_2O-bearing phase in deep mantle ultramafic rocks.

KEYWORDS: talc, eclogite, phase equilibria, China.

Introduction

TALC occurs mainly in metamorphosed ultramafic rocks but also in siliceous dolomites as a replacement of enstatite, tremolite and olivine under shallow crustal conditions. Talc has also been reported in high-P (HP) pelites (Chopin, 1981; Zhang et al., 1989), and Mg—Al metabasalts (Mottana et al., 1990). Talc-bearing assemblages in manganiferous quartzite from the Zermatt-Saas zone, Western Alps (Reinecke, 1991), and in Mg-rich quartzite from the Dora Maira (Chopin, 1991; Schertl et al., 1991) have been identified recently in some ultrahigh-P metamorphic (UHPM) terranes and their stabilities have been experimentally delineated (e.g. Schreyer, 1988a; Chopin et al., 1991). The classic whiteschist assemblage talc + kyanite has a very large stability field under H_2O-saturated conditions from 6 kbar to probably 40 kbar at 550—800°C (Schreyer, 1988a). Talc + kyanite + coesite + pyrope from Mg-rich quartzites of the Dora Maira ultrahigh-P massif formed at P of 30 kbar and T of 700—750°C (Chopin, 1984).

The aforementioned UHP talc-bearing assemblages are restricted to non-mafic supracrustal lithologies. Talc in coesite-bearing eclogites has recently been discovered in a number of localities in the UHPM terrane of central eastern China (e.g. Zhang and Liou, 1994a). Our analyses of parageneses and phase relations of minerals in talc-bearing mafic-ultramafic rocks from the Bixiling complex indicate that talc is an important H_2O-bearing phase of deeply subducted mafic and continental supracrustal rocks. Our analysis also shows that talc in ultramafic rocks is restricted only to retrograde stage phase and is not stable at mantle conditions. Talc- and tremolite-bearing assemblages in coexisting mafic and ultramafic rocks can be used to constrain the retrograde P-T path.

Occurrence and mineral assemblages

The ultrahigh-P metamorphic belt of the Triassic collision zone between the Sino- Korean and Yangtze cratons extends from the Su-Lu region westward through the Dabie Mountains to the Hongan block for more than 700 km. Coesite and quartz aggregate pseudomorphs after coesite occur as minute ellipsoidal inclusions in garnet, omphacite, epidote, kyanite and zoisite; they are best preserved in eclogite enclosed within gneiss, ultramafic rocks, and marble. Some coesite pseudomorphs have also
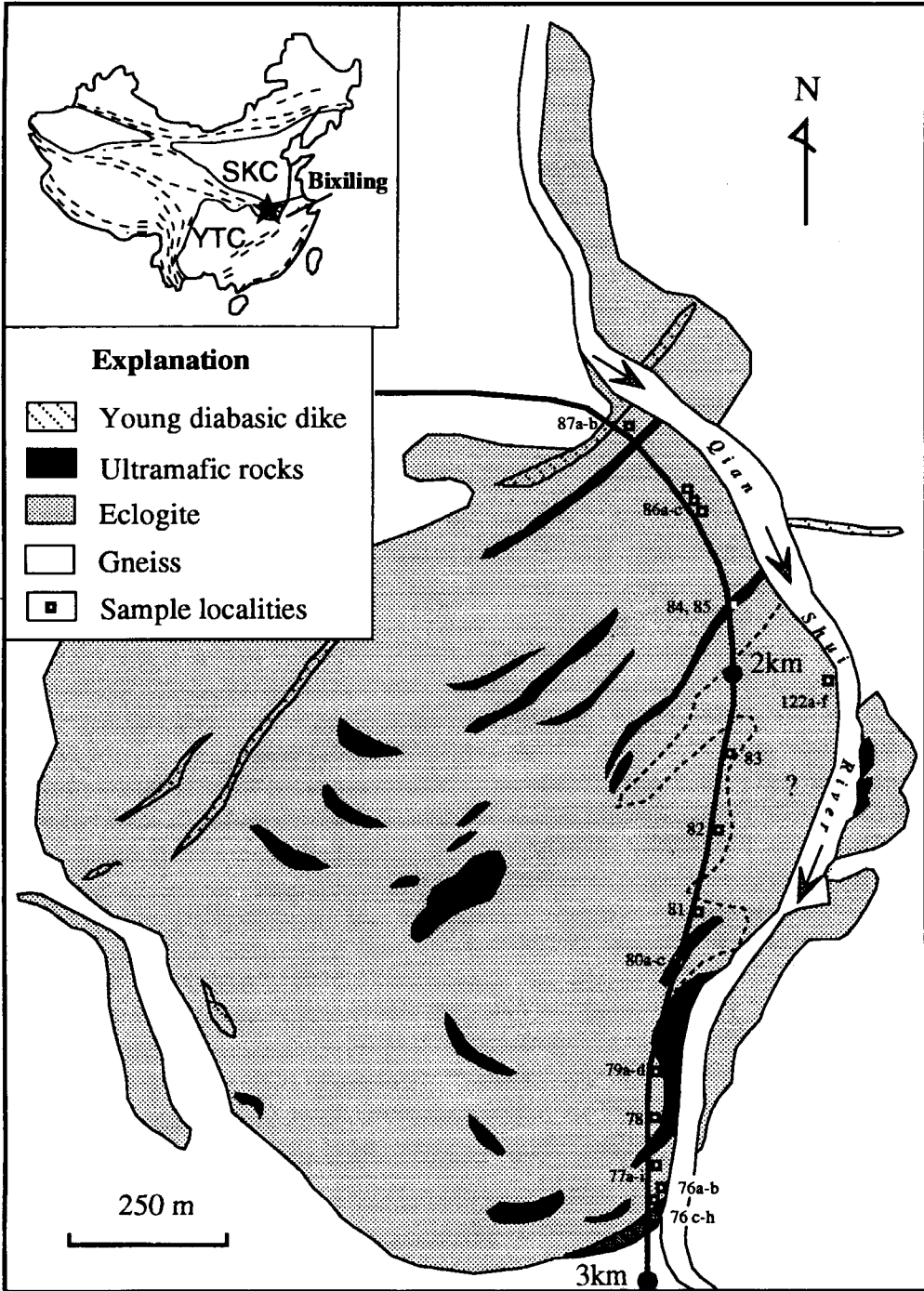
FIG. 1. Location and schematic geological setting of the Bixiling mafic-ultramafic complex in the ultrahigh-*P* belt in the Dabie block, central China.
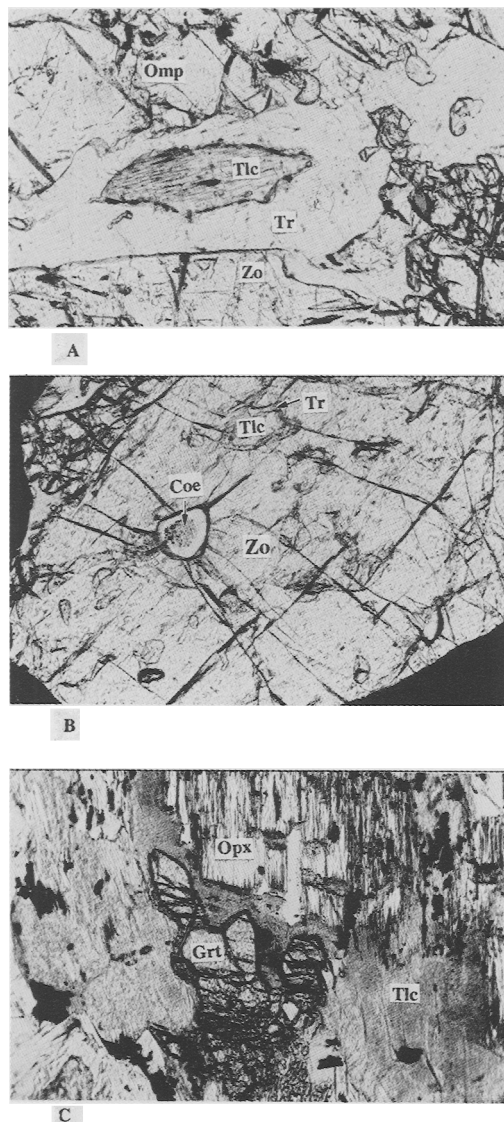
FIG. 2. Photomicrographs of talc-bearing assemblages in both eclogite and garnet peridotite from the Bixiling Complex. Compositions of analysed phases are listed in Table 1 (plane polar; long dimension is 1.44 mm). (A) Relict talc (Tlc) surround by tremolite (Tr) in zoisite (Zo)-bearing eclogite (sample # 77I) which contains abundant omphacite (Omp) and garnet. (B) Coesite (Coe) and talc (Tlc) inclusions within coarse-grained zoisite (Zo) in eclogite (sample # 83). Coesite relic is surrounded by thin rim of fine-grained quartz aggregates and radial fractures around the inclusion is well developed. Talc is rimmed by thin tremolite at the contact with zoisite. (C) Retrograde talc (Tlc) after orthopyroxene (Opx) in garnet (Grt) peridotite (sample #

been described in the country rocks that include the eclogite, hence the concept of a regional *UHP* terrane has been suggested (Wang and Liou, 1991; Okay, 1993). Diamond has also been recently reported in the Dabie Mountains (Xu *et al.*, 1992; Okay, 1993).

The Bixiling mafic-ultramafic body, 1.5 km^2 in outcrop area, is the largest coesite-bearing mafic/ultramafic massif in the Dabie Mountains (Fig. 1); it is enclosed within gneissic rocks, and the contact itself has been folded. Along the margins of the body, smaller eclogitic blocks are encased in gneiss. Younger diabasic dykes cut across both the mafic-ultramafic body and its gneissic country rocks. As shown in Fig. 1, the Bixiling complex consists dominantly of layered eclogites of various compositions; it contains several elongated lenses of garnet-bearing ultramafic rocks which are partially serpentinized and are in gradational contact with the layered eclogitic rocks. Ultramafic rocks could be more abundant than shown in the map inasmuch as these garnet-bearing rocks are easily misidentified as eclogite in the field. The layered eclogitic-ultramafic rocks provide an excellent opportunity to examine parageneses of minerals of various mafic-ultramafic compositions. A detailed petrological description is presented elsewhere (Zhang *et al.*, in press).

Talc was identified as inclusions in zoisite, omphacite or garnet, and as discrete grains in a matrix of several eclogitic rocks. These rocks contain garnet + omphacite + zoisite + talc + rutile + coesite ± kyanite ± phengite. Some coarse-grained talcs in the matrix are in sharp contact with garnet, omphacite and zoisite, suggesting textural equilibrium with garnet + zoisite ± kyanite. Figure 2A shows inclusions of talc and coesite rimmed by quartz pseudomorphs after coesite in a coarse-grained zoisite crystal. Talc inclusions are rimmed by a narrow band of tremolite at the contact with zoisite. Figure 2B shows a coarse-grained talc relic surrounded by tremolite that is in direct contact with omphacite. Such textural relations suggest that talc reacted with Ca-bearing phases such as omphacitic pyroxene or zoisite to form tremolite following a simple reaction such as talc + diopside = tremolite. Compositions of tremolite, talc and diopsidic pyroxene of Fig. 2A and B are listed in Table 1.

Depending on bulk composition, most ultramafic rocks contain garnet + olivine + enstatite + diopside as primary phases. Some ultramafic rocks contain titanoclinohumite and magnesite (Zhang and Liou, 1994b). Mineral assemblages of successive retrograde stages were recognized; parageneses of

79-B). Note the relict cleavages of Opx in talc aggregates are well preserved.

minerals and retrograde *P-T* path are described elsewhere (Zhang *et al.*, in press). Tremolite occurs as a replacement of diopside; talc is ubiquitous as a retrograde phase after enstatite, as shown in Fig. 2C where massive talc aggregates replace orthopyroxene. Analysed talc from websterite (79B) is slightly higher in FeO and lower in MgO than talcs from eclogites (see Table 1). The distinct differences between the talc parageneses in the coexisting mafic and ultramafic rocks help to constrain the retrograde *P-T* path described below.

Phase relations

Phase relations involving diopside (Di), tremolite (Tr), talc (Tlc), zoisite (Zo), dolomite (Dol) and calcite (Cc) in the $CaO–MgO–SiO_2–Al_2O_3–H_2O–CO_2$ system have been described by Franz and Spear (1983) for *HP* siliceous dolomites from central Tauern Window, Austria. Assemblage Di + Tr +

Dol + Cc + Qtz $\pm$ Zo + secondary Tlc and Tr is stable up to about 14 kbar/630°C in the presence of fluids with intermediate X_{CO_2}. The inset of Fig. 3 is a ternary plot for end-member compositions of common minerals in meta-ultramafic and marble assemblages; these phases include Tr, Di, Tlc, forsterite (Fo), enstatite (En), quartz (Qtz), coesite (Coe) and water (F) in the system $CaO–MgO–SiO_2–H_2O$. Bulk compositions for mafic (10 wt.% CaO, 10 wt.% MgO and 50 wt.% SiO_2) and ultramafic (30 wt.% MgO, 5 wt.% CaO and 45 wt.% SiO_2) rocks are also shown. Calculated phase relations for this system, together with the stable assemblages for mafic eclogitic and ultramafic rocks, are shown in Fig. 3. This diagram was calculated using the GEOCALC program of Berman (1988); several significant features are described below.

(A) The stability of tremolite is limited by a dehydration reaction: Tr = Di + En + Qtz + H_2O at high *T* and by a solid–solid reaction Tr = Di + Tlc at

TABLE 1. Compositions of clinopyroxene, talc and tremolite in selected coesite-bearing eclogites (77I and 83) and garnet-peridotite (79B)

| Sample no. Min. | Eclogite (77I) | | | Eclogite (83) | | | 79B |
	Cpx	Tlc	Tr	Cpx	Tlc	Tr	Tlc
SiO_2	55.27	61.04	55.61	56.63	61.90	55.80	60.56
TiO_2	0.02	0.00	0.05	0.70	0.01	0.01	0.04
Cr_2O_3	0.08	0.00	0.11	0.12	0.00	0.04	0.16
Al_2O_3	6.71	0.39	4.29	11.41	0.48	5.65	0.14
Fe_2O_3			1.94			1.72	
FeO	1.64	2.15	1.75	1.52	2.10	1.55	3.15
MnO	0.04	0.05	0.06	0.05	0.01	0.00	0.03
MgO	13.13	29.20	21.17	9.49	29.47	21.48	28.64
CaO	18.85	0.03	10.77	13.91	0.03	10.46	0.02
Na_2O	3.79	0.03	1.43	7.03	0.02	1.79	0.05
K_2O	0.00	0.01	0.10	0.00	0.00	0.01	0.01
Total	99.52	92.91	97.27	100.24	94.02	98.51	92.75
# of O p.f.u.	6	11	23	6	11	23	11
Si	1.98	3.99	7.65	1.98	4.00	7.56	3.99
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Al	0.28	0.03	0.70	0.47	0.04	0.90	0.01
Fe^{3+}			0.20			0.18	
Fe	0.09	0.12	0.20	0.05	0.11	0.18	0.17
Mn	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Mg	0.70	2.85	4.34	0.50	2.84	4.34	2.81
Ca	0.72	0.00	1.59	0.52	0.00	1.52	0.00
Na	0.26	0.00	0.38	0.48	0.00	0.47	0.01
K	0.00	0.00	0.02	0.00	0.00	0.00	0.00
Total cations	4.01	7.00	15.09	4.01	6.99	15.14	7.01
Di mol.%	73			52			
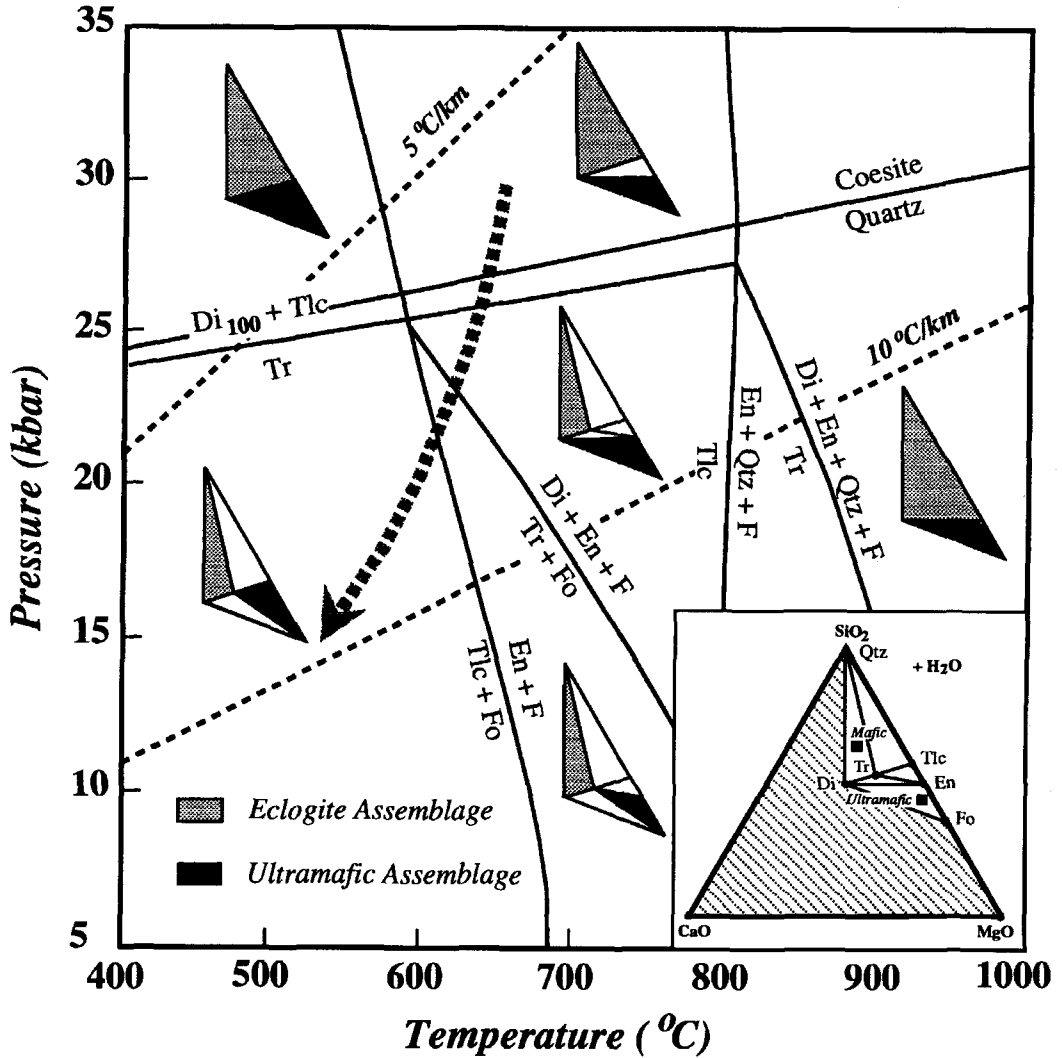
FIG. 3. $P-T$ diagram showing phase relations of talc (Tlc), tremolite (Tr), diopside (Di), forsterite (Fo), enstatite (En) and SiO_2 polymorphs calculated in the simple system $CaO-MgO-SiO_2-H_2O$ using GEO-CALC program of Berman (1988). Mineral parageneses for representative eclogite and ultramafic compositions together with geothermal gradients of 5°C km^{-1} and 10°C km^{-1} and estimated retrograded $P-T$ path for Bixiling complex are also shown.

high P; both reactions have been experimentally determined (e.g. Jenkins, 1987; Jenkins and Clare, 1991) and thermodynamically calculated (e.g. Welch and Pawley, 1991). The calculated end-member reaction, $Tr = Tlc + Di$, is located about 1 kbar lower than and parallel to the coesite–quartz transition (Bohlen and Boettcher, 1982). This together with another reaction, $Tlc = En + Coe + H_2O$, restricts the stability of talc + coesite to upper-

mantle pressures, whereas tremolite is limited to the quartz stability field.

(B) The $P-T$ positions of two invariant points in this system for Fo-absent and Qtz-absent equilibria were located. Several well determined reactions involving tremolite and talc ($\pm$ Fo) radiate from these invariant points; hence the stability relations of the considered phases in this simple system are well constrained.

(C) Assemblages for ultramafic and mafic compositions of Fig. 3 show systematic contrast at similar $P-T$ conditions. For example, for the basaltic protolith, the assemblage Coe + Di + Tlc is stable within the coesite field; in contrast, coexisting ultramafic rocks contain Fo + En + Di. During retrograde recrystallization along a clockwise $P-T$ path, the mafic assemblage is replaced by Tr + Di + Qtz, whereas the ultramafic assemblage successively changes to (1) Tr + Fo + En, and then (2) Tlc +Tr +

Fo. These paragenetic sequences for mafic–ultramafic assemblages were preserved in the Bixiling mafic-ultramafic complex as described above (Fig. 2).

(D) With introduction of other components such as jadeite for clinopyroxene, and tschermakite, glaucophane and F substitution for tremolite, these simplified phase relations will be significantly modified. For example, the solid–solid reaction Tr = Di + Tlc will be displaced toward lower P with the introduction of the Jd component to Di to form
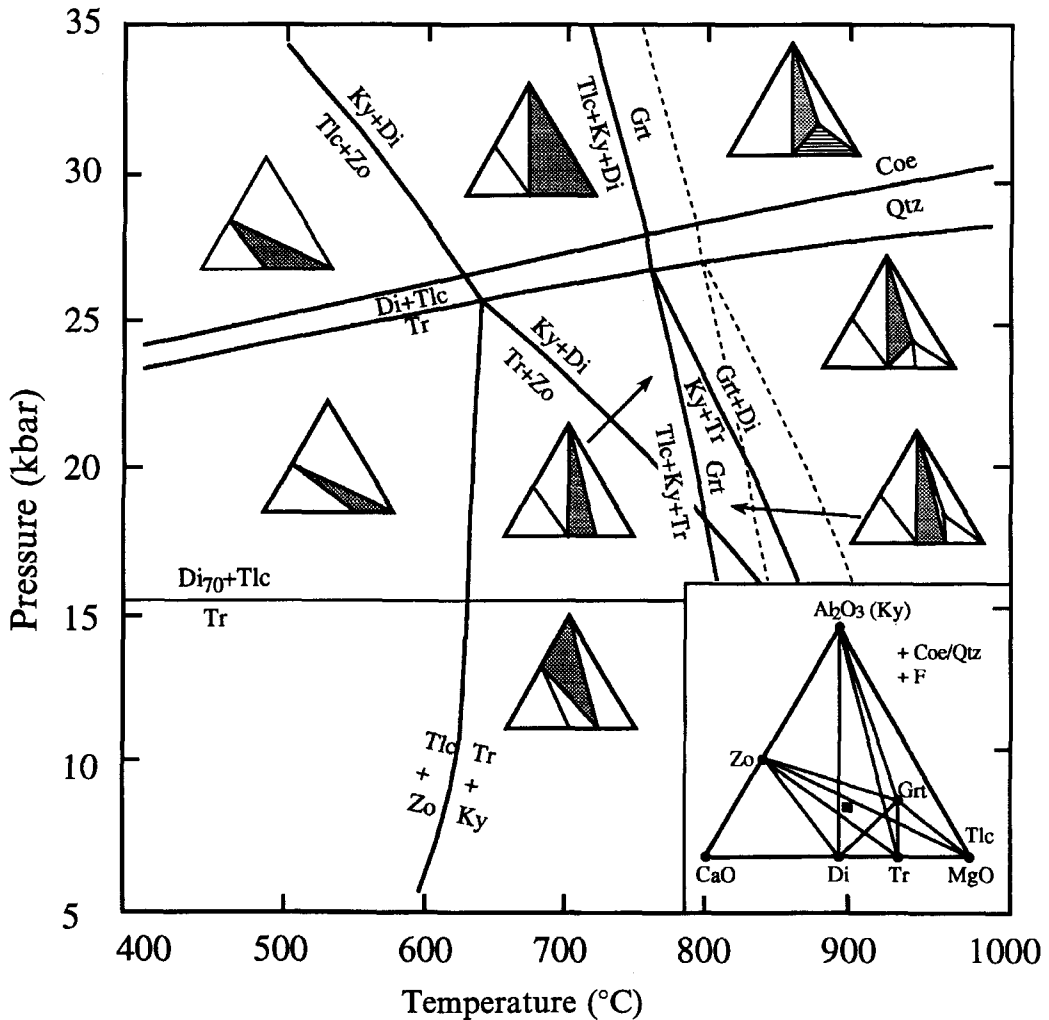

FIG. 4. $P-T$ diagram showing phase relations of talc (Tlc), tremolite (Tr), diopside (Di), zoisite (Zo), kyanite (Ky), garnet (Grt) and SiO_2 polymorphs calculated in the simple system $CaO–MgO–Al_2O_3–SiO_2–H_2O$ using the GEO-CALC program of Berman (1988) in the presence of excess SiO_2 phase. Garnet contains 25 mol.% grossular and 75% pyrope. Univariant lines involving pyrope end-member garnet are shown as dashed lines. The mineral assemblage Tlc + Di + Grt occurs only for Mg-rich composition as highlighted in a horizontally lined region. Mineral parageneses for calculated eclogitic bulk composition are also shown.

omphacite + talc. This assemblage is observed in some Bixiling eclogites. Using the analysed compositions of tremolite, omphacite (Di_{70}) and talc of Fig. 2A listed in Table 1 and assuming ideal mixing models for amphibole and clinopyroxene, the $P-T$ position of this equilibrium was calculated at a P of about 15 kbar (Fig. 3).

(E) Occurrence of talc in eclogite containing Grt + Omp + Coe + Tlc $\pm$ Ky assemblage requires additional major Al_2O_3 and FeO components to be considered. Figure 4. shows calculated $P-T$ relations of phases in the system $CaO-Al_2O_3-MgO-SiO_2-H_2O$ assuming a garnet composition of $Pyr_{75}Gr_{25}$ and using the GEO-CALC program of Berman (1988) in the presence of excess SiO_2. Also shown are mineral assemblages for the Bixiling Tlc-bearing eclogite composition (17 wt.% Al_2O_3, 9 wt.% MgO and 10 wt.% CaO) in various $P-T$ fields. For this simple system, assemblages Grt + Di + Tlc and Grt + Di + Ky are stable at $P-T$ conditions higher than that of the garnet-appearance univariant line. At lower temperatures, kyanite + talc coexist with diopside + coesite and the assemblage Ky + Tlc + Di occurs for the assumed composition. The garnet appearance

reaction Tlc + Ky + Di = Grt, is located at about 30°C lower than that for the end-member pyrope composition (dashed line in Fig. 4). Apparently, the stability field of the assemblage talc + garnet + diopside is bounded by the garnet-appearance reaction and the upper-P limit of tremolite and is restricted only to Mg-rich bulk composition (horizontally lined region of Fig. 4). As shown in this figure, the introduction of the Jd component to clinopyroxene significantly displaces the upper-P limit of tremolite toward lower P. Thus, talc may appear in eclogite assemblage at much lower P than that shown in Fig. 4 so long as the bulk rock composition is appropriate. Moreover, if the FeO component is considered, the phase relationship of Fig. 4 will be significantly modified; the appearance of a typical eclogitic garnet will occur at lower T and the reaction assemblage Tlc + Ky + Omp + Grt + Coe observed from the Bixiling eclogite will be stable in a diavariant $P-T$ field.

Figure 5 shows the experimentally determined upper-P stabilities of tremolite, hence the minimum pressure for the appearance of talc in eclogitic assemblage. Stoichiometric tremolite has not been
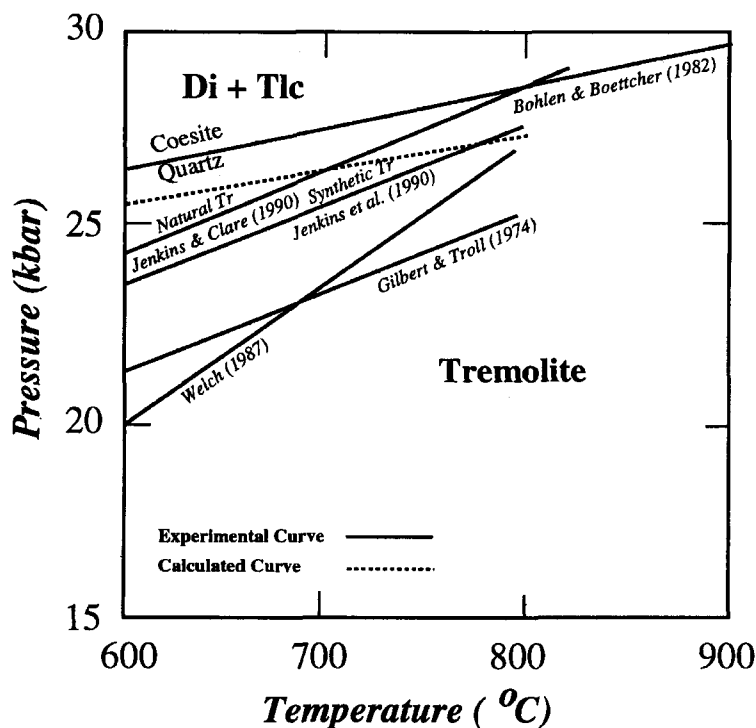

FIG. 5. $P-T$ diagram comparing experimentally determined and thermodynamically calculated upper-P stability limits of tremolite = talc + diopside. Also shown is the quartz–coesite transition of Bohlen and Boettcher (1982).

synthesized (Jenkins, 1987; Jenkins and Clare, 1990) and this might be one of the reasons for the differences in the upper-P stability limit for tremolite shown in several experimental studies. The difference in the stability of natural *vs* synthetic tremolite shown in Fig. 5 may in part be due to compositional effects. For example, about 0.5 wt.% F in natural tremolite may raise the upper-T limit as much as 30–40°C at 4 kbar, and F-tremolite would break down to a different high-P assemblage inasmuch as F-talc is not stable at high P. Differences in grain-size, hence surface energies, may also be responsible in part for the difference in behaviour of natural coarse-grained starting material compared with rather uniform fine-grained synthetic tremolite. However, Jenkins and Clare (1990) pointed out the maximum difference of 0.28 kJ mol^{-1} attributed to the surface free energy is insufficient to account for the observed differences of 0.4–2.9 kJ mol^{-1} for the reaction.

The reaction Tr = Tlc + Di involves transformation from a double-chain to single-chain + sheet (multiple chain) silicates. Intracrystalline defects including chain multiplicity of these chain silicates may contribute in part to the difficulty in synthesizing pure tremolite, and in part to the difference in $P-T$ position between natural *vs* synthetic tremolite. Quantitative effects of chain multiplicity on mineral stability have not been well documented.

Finally, uncertainties in thermodynamic properties, including composition-activity mixing properties of these silicates, contribute to differences in $P-T$ determinations. Such uncertainties in thermodynamic data may result in as much as $\pm$ 1.5 kbar uncertainty for the upper-pressure limit of Tr = Di + Tlc (Welch and Pawley, 1991). Nevertheless, the calculated $P-T$ position for this reaction using the GEO-CALC program of Berman (1988) resulted in remarkable agreement with the stability experimentally determined by Jenkins and his associates. These experimental and calculated results indicate that tremolite of stoichiometric composition is restricted to the quartz stability field. On the other hand, talc is stable with omphacitic pyroxene + coesite in the Bixiling eclogites.

Two reference geothermal gradients of 5°C km^{-1} and 10°C km^{-1} are shown in Fig. 3. The assemblage Tlc + Di + Coe in mafic rocks is stable with Di + En + Fo in uftramafic rocks at ultrahigh-P conditions bounded by geothermal gradients of 5°C km^{-1} to 10°C km^{-1}. The talc-bearing ultramafic assemblage (Tlc + Fo + Di) cannot occur at upper-mantle pressures because it is restricted to unrealistically low geothermal gradients less than 5°C km^{-1}. On the other hand, talc is a typical retrograde phase in ultramafic rocks, and is stable with forsterite + tremolite at crustal depths. Hence, the occurrence of

talc at mantle depths can only be achieved in deeply subducted non-ultramafic rocks subjected to *UHP* conditions.

Discussion and conclusions

Talc-bearing assemblages in supracrustal rocks recrystallized at mantle depths have been recognized in whiteschist, pyrope coesitite, jadeitite and Mg-rich pelites from the Dora Maira massif (e.g. Chopin, 1984; Chopin *et al.*, 1991; Schertl *et al.*, 1991). These assemblages include talc + kyanite + pyrope + coesite, talc + phengite (Si > 3.5) + kyanite + coesite, and talc + jadeite. Talc together with coesite occurs as inclusions in pyrope and kyanite, and as a matrix mineral; several generations of talc formation in these rocks have been documented and their $P-T$ paths have been determined. Stability relations of talc-bearing assemblages in the K_2O–MgO–Al_2O_3–SiO_2–H_2O system at mantle pressures have been established by Schreyer and his associates (see reviews by Schreyer, 1988*a*; Massonne and Schreyer, 1989). Both field and laboratory studies conclude that talc + kyanite, talc + jadeite, talc + phengite are stable with coesite in ultrahigh-P metamorphism of crustal rocks subjected to geothermal gradients between 5°C km^{-1} and 15°C km^{-1}.

However, such talc-bearing assemblages have not been described in eclogitic metabasites from the Dora Maira massif. The observed parageneses of minerals in the coexisting mafic and ultramafic rocks of the Bixiling complex together with established phase relations for the system CaO–MgO–Al_2O_3–SiO_2–H_2O indicate that talc is stable at *UHP* conditions only for certain compositionally differentiated layers of the mafic-ultramafic complex. Most *HP* and *UHP* eclogitic rocks do not contain talc and kyanite; minor talc appears in equilibrium with garnet + omphacite only in Mg-rich metabasites (Montana *et al.*, 1990). The associated ultramafic rocks carry a common assemblage of garnet + olivine + enstatite + diopside; talc is only a late-stage retrograde mineral after primary enstatite. This together with the reported occurrence of talc in the Dora Maira massif leads us to conclude that *UHP* talc assemblages are confined to pelitic and Mg–Al-rich basaltic compositions. Therefore, talc cannot be an important H_2O-bearing phase in mantle ultramafic rocks as Bose and Ganguly (1993) recently suggested.

Figure 3 shows that talc + diopside + olivine and talc + diopside + coesite assemblages respectively are stable in ultramafic and mafic compositions at pressures > 25 kbar and temperatures < 600°C. Compilation of the maximum $P-T$ conditions for several well-investigated blueschist and eclogite terranes indicates subduction-zone metamorphism

occurred at more-or-less similar thermal regimes characterized by low geotherms of $7-10$ km^{-1} (e.g. Schreyer, 1988b). Thermal regimes with geothermal gradient $< 5°C$ km^{-1} have not been verified on Earth. Therefore, these assemblages apparently do not occur in supracrustal rocks metamorphosed at mantle pressures.

References

Berman, R. G. (1988) Internally-consistent thermodynamic data for minerals in the system Na$_2$O–K$_2$O–CaO–MgO–FeO–Fe$_2$O$_3$–Al$_2$O$_3$–SiO$_2$–H$_2$O–CO$_2$. *J. Petrol.*, **29**, 445–522.

Bohlen, S. R. and Boettcher, A. L. (1982) The quartz-coesite transformation: a pressure determination and the effects of other components. *J. Geophys. Res.*, **87**, 7073–8.

Bose, K. and Ganguly, J. (1993) Stability of talc at high pressures: Experimental determination, retrieval of thermodynamic properties, and applications to subduction processes. *Geol. Soc. Amer. Abstract with Program*, **25**, A213–4.

Chopin, C. (1981) Talc-phengite: a widespread assemblage in high-grade pelitic blueschists of the Western Alps. *J. Petrol.*, **22**, 628–50.

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**, 107–18.

Chopin, C., Henry, C. and Michard, A. (1991) Geology and petrology of the coesite-bearing terrain, Dora Maira massif, Western Alps. *Eur. J. Mineral.*, **3**, 263–91.

Franz, G. and Spear, F.S. (1983) High pressure metamorphism in siliceous dolomites from the central Tauern Window, Austria. *Amer. J. Sci.*, **283A**, 396–413.

Gilbert, M.C and Troll. G. (1974) A comparison of the stabilities of OH- and F-tremolite. *Internat. Mineral. Assoc., 9th General Meeting*, Berlin and Regensburg, Collected Abstracts.

Jenkins, D.M. (1987) Synthesis and characterization of tremolite in the system H$_2$O–CaO–MgO–SiO$_2$. *Amer. Mineral.*, **72**, 707–15.

Jenkins, D. M. and Clare, A. K. (1990) Comparison of the high-temperature and high-pressure stability limits of synthetic and natural tremolite. *Amer. Mineral.*, **75**, 358–66.

Massonne, H. J. and Schreyer, W. (1987) Phengite geobarometry based on the limiting assemblage with K-feldspar, phlogopite, and quartz. *Contrib. Mineral. Petrol.*, **96**, 212–24.

Mottana, A., Carswell, D. A., Chopin, C. and Oberhänsli, R. (1990) Eclogite facies mineral parageneses. In *Eclogite Facies Rocks*, D. A. Carswell (ed.), Blackie, 14–52.

Okay, A. I. (1993) Petrology of a diamond and coesite-bearing metamorphic terrain: Dabie Shan, China. *Eur. J. Mineral.*, **5**, 659–73.

Schertl, H., Schreyer, W. and Chopin, C. (1991) The pyrope-coesite rocks and their country rocks at Parigi, Dora Maira massif, western Alps: detailed petrography, mineral chemistry and *PT*-path. *Contrib. Mineral. Petrol.*, **108**, 1–21.

Reinecke, T. (1991) Very-high-pressure metamorphism and uplift of coesite-bearing metasediments from the Zermatt-Saas zone, Western Alps. *Eur. J. Mineral.*, **3**, 7–17.

Schreyer, W. (1988a) Experimental studies on metamorphism of crustal rocks under mantle pressures. *Mineral. Mag.*, **51**, 1–26.

Schreyer, W. (1988b) Subduction of continental crust to mantle depths: Petrological evidence. *Episodes*, **11**, 97–104.

Wang, X. and Liou, J. G. (1991) Regional ultrahigh-pressure coesite-bearing eclogitic terrane in central China: evidence from country rocks, gneiss, marble, and metapelite. *Ceology*, **19**, 933–6.

Welch, M. D. (1987) *Experimental studies of selected amphiboles in the system Na$_2$O–CaO–MgO–Al$_2$O$_3$–SiO$_2$–H$_2$O–F$_2$ and its subsystems*. Unpubl. Ph.D. thesis, Edinburgh University, 200 pp.

Welch, M. D. and Pawley, A. R. (1991) Tremolite: New enthalpy and entropy data from a phase equilibrium study of the reaction tremolite = 2 diopside + 1.5 orthoenstatite + β-quartz + H$_2$O. *Amer. Mineral.*, **76**, 1931–9.

Xu, S., Okay, A. I., Ji, S., Sengor, A. M. C., Su, W., Liu, Y. and Jiang, L. (1992) Diamond from the Dabie Shan metamorphic rocks and its implication for tectonic setting. *Science*, **256**, 80–2.

Zhang, R. Y. and Liou, J. G. (1994a) Coesite-bearing eclogite in Henan Province, Central China: detailed petrography, glaucophane stability and *PT*-path. *Eur. J. Mineral.* **6**, 217–33.

Zhang, R. Y. and Liou, J. G. (1994b) Significance of magnesite paragenesis in ultrahigh-pressure metamorphic rocks. *Amer. Mineral.*, **79**, 397–400.

Zhang, R. Y., Liou, J. G. and Cong, B. L. (in press) Ultrahigh-Pressure Talc-, Magnesite- and Ti-clino-humite-bearing Mafic and Ultramafic Complex in The Dabie Mountains, China. *J. Petrol.*,

Zhang, R. Y. and Han, X. L. (1989) Amphiboles of blueschist in the Dianxi region, China. *Ofioliti*, **14**, 293–306.