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A Brief Review of UHP Meta-ophiolitic Rocks, Southwestern Tianshan, Western China

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Abstract

We here summarize recent studies of the occurrence, petrology, geochemistry, and geochronology of a new UHP metamorphic belt in the southwestern Tianshan. Eclogites here are grouped into three types: (1) lenticular eclogite bodies surrounded by blueschists; (2) eclogites with relict pillow structures; and (3) banded eclogite layers within marbles. They contain inclusions of coesite pseudomorphs in garnet, coesite exsolution rods in omphacite, and the possible stable association of aragonite + magnesite after dolomite. Rocks record three discrete stages of recrystallization: a peak UHP eclogite stage at 560–600°C and 4.9–5.0 GPa, a main UHP eclogite stage at 598–496°C and 2.6–2.7 GPa and retrograde overprinting under epidote blueschist-facies conditions. Protoliths possess geochemical characteristics of ocean-island basalts that originated from an enriched mantle with $\epsilon\text{Nd} = -1.4$ to -0.4 , NMORB from depleted mantle with $\epsilon\text{Nd} = +6.7$ to $+7.4$, and EMORB from enriched mantle with $\epsilon\text{Nd} = -2.5$ to $+3.2$. SHRIMP dating of zircon separates shows that the oceanic basaltic protoliths formed in a pre-Carboniferous (>310 Ma) seamount environment, began northward subduction beneath the Yili-central Tianshan craton at the end of the Permian (280–290 Ma), and were subjected to HP-UHP metamorphism in the Triassic (220–230 Ma). Based on the occurrence of this Triassic HP-UHP belt together with discovery of coeval low-P granulite-facies rocks to the north, a paired metamorphic belt tectonic model is proposed for the southwestern Tianshan, western China.

Introduction

THE RECOGNITION of ultrahigh-pressure (UHP) metamorphism is among the most outstanding achievements made in the field of solid Earth science in recent years. UHP metamorphic rocks have been documented in more than 20 orogenic belts in the world so far; most of them occur in Eurasian continental collision belts and possess similar supercrustal protoliths, whereas UHP ophiolitic rocks are extremely rare (Coleman and Wang, 1995; Schreyer 1995; Liou et al., 1998, 2004; Ernst, 2001; Carswell and Compagnoni, 2003). Although the studies of deep-focus earthquakes suggest that oceanic rocks have been subducted

600 km or more into the mantle (Widiyantoro and Hirt, 1996; Zhao, 2001), the subducted oceanic crust would be delaminated and sunk into deeper mantle after breaking off from its continental counterparts because of its greater density (Davies and von Blanckenburg, 1995; Liou et al., 1998; Ernst, 2001). Hence, only two examples of UHP ophiolitic rocks have been reported so far: i.e., the Zermatt-Saas zone in the western Alps (Reinecke, 1991, 1998; Bucher et al., 2005) and the southern Tianshan orogenic belt extending from the Athashy-Makbal eclogite-blueschist belt in Kyrgyzstan (Tagiri et al., 1995, 2001) eastward to the southwestern Tianshan eclogite-blueschist belt in western China (Zhang et al., 2002a, 2002b). Since inclusions of coesite pseudomorphs in garnet, quartz exsolution in omphacite, and relict metamorphic

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magnesite in Tianshan eclogites were reported (Zhang et al., 2002a, 2002b), the existence of UHP metamorphism in the southwestern Tianshan was hotly debated (see the comment and reply by Klemd, 2003 and Zhang et al., 2003a). Recently, new UHP minerals such as the coexistence of magnesite and aragonite after dolomite in metapelites, and relict coesite exsolution in porphyroblastic omphacite in eclogites have been found in the southwestern Tianshan of western China (Zhang et al., 2003a, 2005b). In this paper, a brief summary of research progress on the UHP metamorphism and a tectonic model based on the paired metamorphic belt in the southwestern Tianshan is presented.

Geological Background and Petrological Features

The eclogites of the southwestern Tianshan and blueschists are exposed in a 200 km long orogenic belt between the Yili-central Tianshan and Tarim plates in Xinjiang, China. This HP-UHP metamorphic belt extends westward to the Atbashe eclogite-blueschist belt, where inclusions of coesite pseudomorphs in eclogitic garnet have been reported in Kazakstan and Kyrgyzstan (Dobretsov et al., 1987; Tagiri et al., 1995) (Fig. 1A). It consists mainly of eclogite, blueschist, garnet phengite schist, and greenschist. Eclogite and blueschist lenses and blocks are enclosed within country-rock garnet phengite schists (Fig. 1). This HP-UHP belt is fault bounded to the north by a low-P, high-T metamorphic belt comprised of cordierite-bearing garnet sillimanite gneisses and two-pyroxene granulites (Li and Zhang, 2004), and by intercalating marbles and chlorite muscovite schists to the south (Fig. 1B). This HP-UHP belt is considered to have formed by the northward subduction of the Tarim plate beneath the Yili-central Tianshan plate during closure of the southern Tianshan ocean (Gao et al., 1999; Zhang et al., 2000).

The southwestern Tianshan eclogites are classified into three types by their field occurrences and petrological features (Zhang et al., 2000, 2002a). Type I eclogites occur as lenses (15–25 cm), pods (20 × 50 cm), thin (2–50 cm thick) to thick (>50 cm) beds and huge blocks (nearly 2 km²) within mafic blueschists, and contain a mineral assemblage of garnet (15–20%), omphacite (25–30%), zoisite (15–20%), glaucophane (10–15%), paragonite (5–10%), quartz, and minor titanite + rutile. Porphyroblastic

garnet in eclogite is 0.1–4 mm in diameter and exhibits pronounced zoning; many inclusions such as omphacite, zoisite, paragonite, and blue amphiboles occur in the core, and only coesite pseudomorph inclusions are present in the rim. Mineral analyses of porphyroblastic garnet show prograde compositional zonation: from core to rim, Prp and Grs contents increase, whereas Alm and Sps contents decrease ($\text{Alm}_{59-70}\text{Prp}_{6-13}\text{Grs}_{17-24}\text{Sps}_{1-4}$; abbreviations after Kretz, 1983).

Type II eclogites have similar parageneses as type I eclogites; most metabasalts preserve 80 cm long, 40 cm wide pillow structure (Zhang et al., 2002a). They are composed of garnet (10–15%), omphacite (20%), glaucophane (20–30%), zoisite (20%), calcite (10–15%), paragonite (5–10%), and a small amount of rutile + titanite. Two kinds of omphacite occur in type II eclogites: (1) porphyroblastic omphacite with strongly oriented needles of quartz inclusions; and (2) matrix omphacite without any inclusions. Some porphyroblastic omphacites have retrograded to blue amphiboles. Unlike type I eclogites, garnet of type II eclogites occurs in the matrix, is free from mineral inclusions, and has a composition of $\text{Alm}_{60-66}\text{Prp}_{5-9}\text{Grs}_{20-25}\text{Sps}_{1-9}$ (Zhang et al., 2002a, 2003b).

Type III eclogites occur as lenses in marbles and exhibit banded structures with variable amounts of carbonates (>30%, mainly calcite and dolomite), garnet (15%), omphacite (20%), glaucophane (20%), zoisite (10%), paragonite (5%), and minor titanite and rutile. Compositional banding is pronounced by alternating calcite/dolomite layers and garnet + omphacite layers. Inclusions of coesite pseudomorphs also occur in these eclogites (Zhang et al., 2002b). The country rocks include blueschists, garnet-bearing phengite schists, and rare magnesite-bearing chloritoid glaucophane schists whose typical minerals are chloritoid (5%), glaucophane (3%), garnet (5%), phengite (30%), dolomite/magnesite (10%), quartz (45%), and rutile (2%). Porphyroblastic dolomite is in equilibrium with chloritoid + glaucophane, and exhibits a metamorphic reaction showing relict magnesite and calcite pseudomorphs after aragonite being transformed into dolomite (Zhang et al., 2003a).

Most rocks have apparently been subjected to ductile deformation; eclogite, blueschist, and garnet phengite schist are well foliated. Isoclinal and recumbent folds prevail, and the folded rocks are cut by thrust faults (Fig. 2).

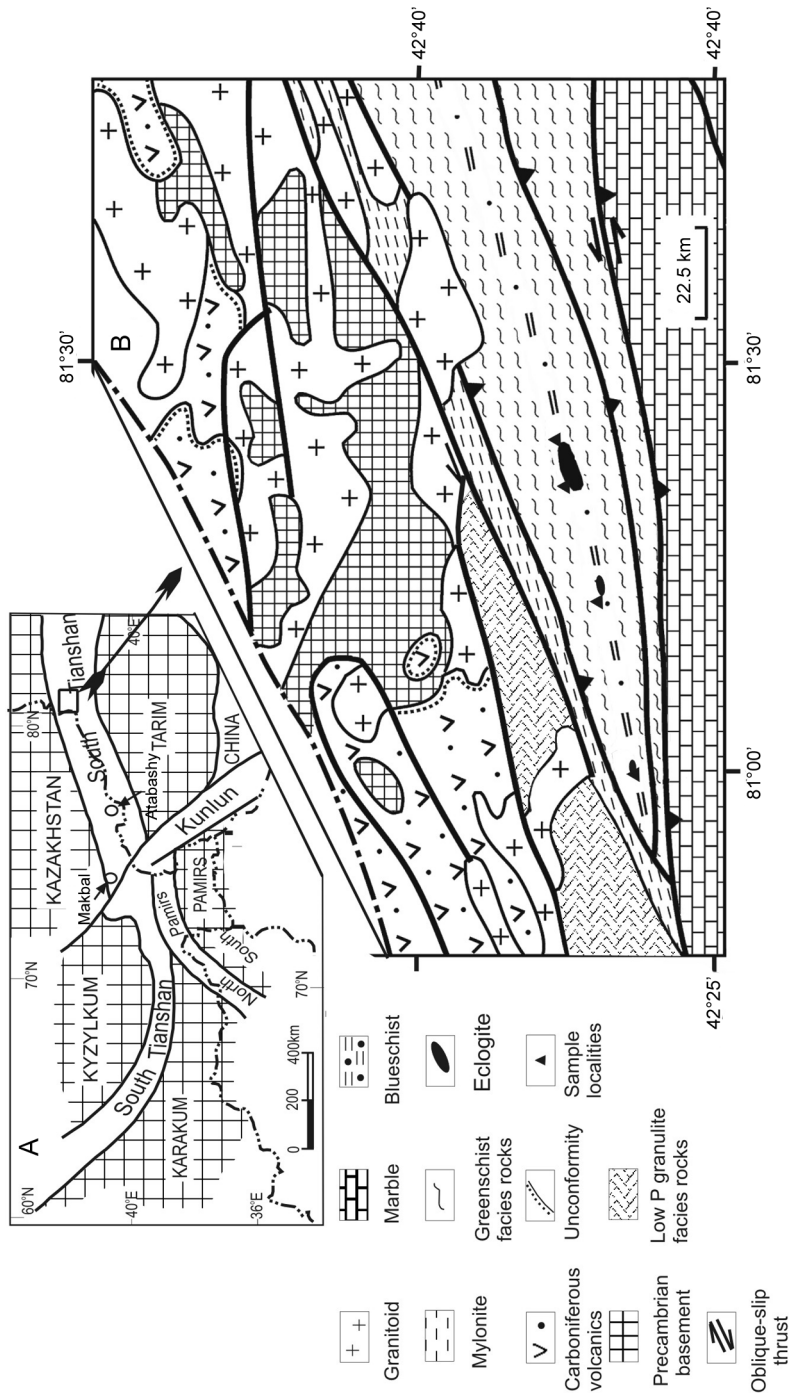


FIG. 1. Schematic geological map of the southwestern Tianshan UHP belt in western China (modified after Zhang et al., 2002a). The inset map shows the distribution of various lithotectonic units including the South Tianshan orogenic belt in east-central Asia.

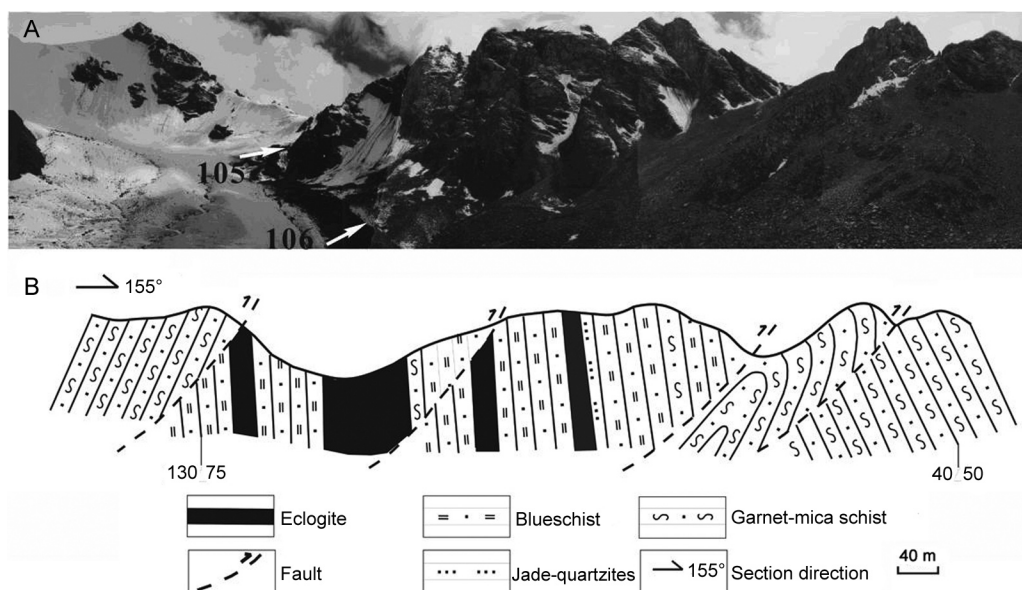


FIG. 2. A. Field view of the study area. B. Cross-section shows the contact relations of UHP eclogites, blueschists, and phengite schists (Zhang et al., 2005a).

The UHP metamorphic belt is bounded by the Changawuzi fault in the north with a low P/T metamorphic belt. Low P/T metamorphic rocks consist mainly of amphibolites, hornblende plagioclase gneisses, and sillimanite gneisses, and belong to high amphibolite-facies metamorphosed Precambrian crystalline basement (Wang et al., 1994; Wang, 1996). Li and Zhang (2004) described some additional cordierite garnet sillimanite gneisses and hornblende two-pyroxene granulites in this low P/T metamorphic belt. Two-pyroxene granulites occur as lenticular bodies within cordierite garnet sillimanite gneisses and have SHRIMP zircon U-Pb ages of 290 Ma (Li and Zhang, 2004). Petrological study shows that both cordierite garnet sillimanite gneisses and hornblende-bearing two-pyroxene granulites have been subjected to granulite-facies metamorphism at $T = 681\text{--}705^\circ\text{C}$, $P = 0.4\text{--}0.5$ GPa, and amphibolite-facies retrograde metamorphism at $T = 571\text{--}637^\circ\text{C}$, $P = 0.4\text{--}0.5$ GPa. The metamorphic P-T path is characterized by (counterclockwise) isobaric cooling (IBC), which suggests that the granulite-facies metamorphism took place in an extensional setting originated from island-arc magmatism formed landward during the northward subduction of the Tarim plate beneath the Yili-central Tianshan plate (Li and Zhang, 2004; Zhu et al., 2005).

UHP Metamorphic Minerals

So far, the characteristic UHP metamorphic minerals reported in this belt include coesite pseudomorphs, coesite/quartz exsolution lamellae in omphacites, and relict metamorphic magnesites (Zhang et al., 2002a, 2002b, 2003a, 2003b, 2005a). The P-T conditions of peak UHP metamorphic stage were calculated based on the reaction: magnesite + aragonite = dolomite (Zhang et al., 2003a) and the coesite exsolution lamellae in porphyroblastic omphacite (Zhang et al., 2005b).

Coesite pseudomorphs

Inclusions of coesite pseudomorphs are ubiquitous in porphyroblastic garnets of type I and III eclogites, most of which have been recrystallized to single quartz crystals. Very few inclusions of polycrystalline aggregates are preserved in the rims of garnet hosts with typical radiating cracks, which is consistent with the prograde compositional zonation of the garnets (Zhang et al., 2002a, 2003b). The inclusions are elongate ellipses in shape, 50–400 μm in diameter, and are pure SiO_2 . Some inclusions show extremely fine-grained polycrystalline aggregates of quartz with a “palisade” texture (Zhang et al., 2002a, 2003b).

Coesite/quartz exsolution lamellae in omphacites

In our early studies, quartz exsolution lamellae in omphacites were only found in type II eclogites. They are strongly oriented needle-shaped quartz crystals occurring within the cores of porphyroblastic omphacite, 30 μm long and 2–3 μm wide, with consistent optic orientations parallel to the crystal axes of the host omphacites, and have pure SiO_2 composition (Zhang et al., 2002a). The omphacites with quartz exsolution lamellae are supersilicic, and contain higher Si and Na than the omphacites without such quartz needles. The calculated Ca-Eskola ($\text{Ca}_{0.5}\text{AlSi}_2\text{O}_6$) component of omphacites from the southwestern Tianshan eclogites varies from 11 to ~17 mol% based on the content of exsolved quartz. According to experimental results in the Na_2O - CaO - Al_2O_3 - SiO_2 system by Gasparik (1985), clinopyroxenes with such high Ca-Eskola contents must be stable at $P > 2.5$ GPa. Our recent study revealed that SiO_2 exsolution rods also are present in omphacites of type I eclogites, and some of such exsolved quartz lamellae were derived from the earlier coesite via retrograde reaction, as their Raman spectra preserve typical coesite peaks at 521 cm^{-1} , 375 cm^{-1} , 270 cm^{-1} , 181 cm^{-1} , 151 cm^{-1} , 118 cm^{-1} , and the inverse relationship between the content of quartz and coesite has also been reported (Zhang et al., 2005b).

Magnesite of metamorphic origin found in eclogites

Magnesite and dolomite were identified in type III eclogites in which the reaction: $\text{Omp} + \text{Mgs} + \text{Coesite} = \text{Dol} + \text{Gl} + \text{Zo}$ is preserved (Zhang et al., 2002b). Based on the ThermoCalc program using an internally consistent thermodynamic mineral data set, and according to analyzed compositions of minerals from Tianshan eclogites, P-T conditions of the above reaction are calculated at 525–607°C, 2.7–2.8 GPa, with X_{CO_2} less than 0.006 (Zhang et al., 2002b).

Dolomite decomposition reaction in metapelitic schists

A metamorphic reaction of magnesite + aragonite = dolomite was identified based on the observed textural relations among minerals in garnet chloritoid-glaucophane schists (Zhang et al., 2003a). Most magnesite grains occur as semi-euhedral, rounded, or rhombic inclusions within dolomite porphyroblasts; an oxidized rust rim appears around most magnesite grains. Most aragonites are replaced by

polycrystalline aggregates of calcite. Porphyroblastic dolomite is in equilibrium with chloritoid, glaucophane, and garnet. Petrographic observations show that there are two generations of metamorphic mineral assemblage—i.e., an earlier assemblage of magnesite + aragonite + garnet + coesite and a later assemblage of glaucophane + chloritoid + dolomite + garnet + quartz. Metamorphic temperatures calculated by the geothermometer based on the equilibration of Mg^{2+} between calcite and magnetite in CaCO_3 - MgCO_3 - FeCO_3 system: $T =$

$$-2360.0 X_{\text{CC}}^{\text{MgCO}_3} - 0.01345/(X_{\text{CC}}^{\text{MgCO}_3})^2 + 2620.0(X_{\text{CC}}^{\text{MgCO}_3})^2 + 2608.0(X_{\text{CC}}^{\text{MgCO}_3})^{0.5} + 334.0 \text{ (T,K)}$$

(Anovitz and Essene, 1987) are 560–600°C. The calculated metamorphic pressures at these temperatures for the reaction $\text{Mgs} (\text{MgCO}_3) + \text{Cc} (\text{Ar}) (\text{CaCO}_3) = \text{Dol} (\text{CaMg}(\text{CO}_3)_2)$ are ~5 GPa (Zhang et al., 2003a) based on analyzed compositions of minerals in the metapelites using the activity model by Holland and Powell (1998), which is consistent with the experimental study on the same reaction by Luth (2001) and Sato and Katsura (2001).

Metamorphic Evolution of UHP Eclogites

Petrographic studies indicate that three generations of metamorphic mineral assemblages are present in the UHP metamorphic eclogites: peak UHP eclogite-facies stage, main UHP eclogite-facies stage, and retrograded epidote blueschist-facies stage (Fig. 3). The peak UHP eclogite-facies stage is characterized by magnesite + aragonite and coesite exsolution within the core of omphacite porphyroblasts (Figs. 3A and 3B). Combined with P-T estimates of the reaction $\text{Dol} = \text{Mgs} + \text{Arag}$, the peak UHP stage for coesite exsolution may have occurred at about 5.0 GPa. The mineral assemblage of the main UHP eclogite-facies stage comprises the clear rim of porphyroblastic omphacite, matrix omphacite, garnet, phengite, coesite, and rutile (Fig. 3C). P-T estimates based on the Omp-Crt-Phe geothermobarometer (Waters and Martin, 1993) are $T = 598\text{--}496^\circ\text{C}$, and $P = 2.6\text{--}2.7 \pm 0.1$ GPa (Zhang et al., 2002a, 2003b); the coesite lamellae in omphacite being transformed to quartz observed in Raman spectra also took place at this stage. Mineral assemblage of the epidote blueschist-facies stage consists of glaucophane + epidote + paragonite $\pm$ chlorite $\pm$

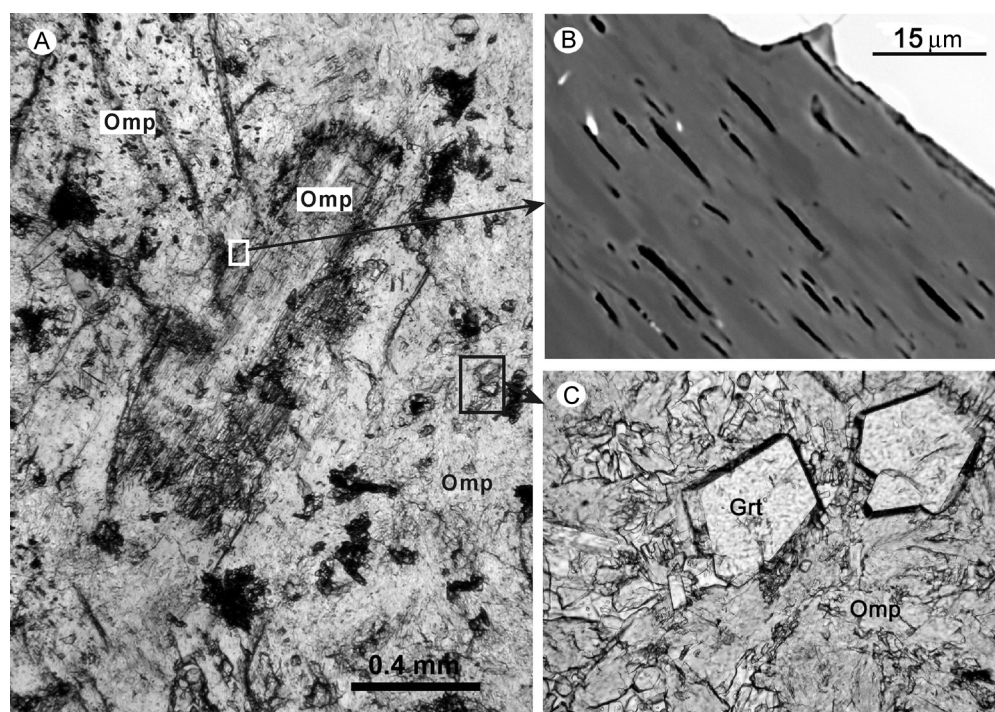


FIG. 3. Photomicrographs show two generations of UHP eclogite mineral assemblage from the southwestern Tianshan, China. A. Porphyroblastic omphacite shows two-stage growth—a core with, and a rim without, coesite/quartz exsolution associated with matrix idioblastic omphacite (plane-polarized light). B. Relict coesite exsolution rods in the core of omphacite (BSE image after Zhang et al., 2005b). C. Matrix idioblastic omphacites associated with fine-grained garnet (plane-polarized light) (Zhang et al., 2005a).

quartz and has P-T estimates of 500–530°C and 1.0–1.2 GPa (Zhang et al., 2002a).

As shown in Figure 4, a three-stage metamorphic evolution of the southwestern Tianshan eclogites has been proposed, i. e., peak UHP eclogite-facies stage, main UHP eclogite-facies stage, and retrograded epidote blueschist-facies stage. The geothermal gradient referred from the peak stage P-T conditions of the southwestern Tianshan UHP eclogites is near 4°C/km, entering the P-T “Forbidden Zone” field (Zhang et al., 2003b).

On the other hand, Klemd et al. (2002), Klemd (2003), and Klemd et al. (2005) yield peak metamorphic P-T conditions at 480–600°C and 1.8–2.1 GPa for the southwestern Tianshan eclogites. They did not recognize kyanite or the UHP minerals mentioned above. Their P-T estimates are mainly based on the garnet-clinopyroxene geothermometer, the upper pressure limit for the reaction of $\text{Pg} = \text{Omp} + \text{Ky} + \text{H}_2\text{O}$, and their pseudosections for the south-

western Tianshan eclogites in the system NCF-MASH. In contrast, we interpret that the lack of kyanite in eclogites is mainly a consequence of the lower T near 600°C rather than the pressure. Carswell (1990) suggested that the appearance of kyanite as an index mineral is characteristic for medium-temperature eclogites (900–550°C); this suggestion was also supported by a new petrogenetic grid for kyanite eclogite, showing it to be stable at temperatures greater than 590°C (Wei et al., 2003). Whether paragonite is a stable phase in the UHP eclogite facies remains to be answered; the similar UHP paragonite-bearing eclogites from the Zermatt-Saas zone of the western Alps has been reported (van der Klaww et al., 1997). So far, there is no clear conclusion about the stability of paragonite during UHP metamorphism of metabasites. Schertl et al. (1991) first described the coexistence of paragonite and coesite from UHP eclogites at Dora Maira. Similar paragonite eclogite with coesite inclusions in

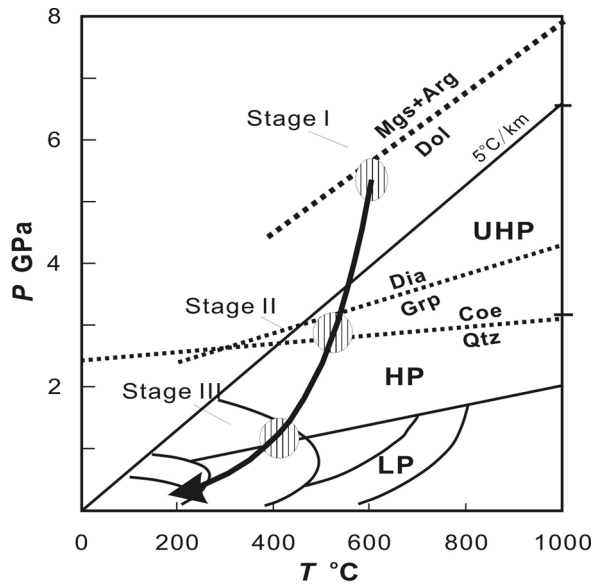


FIG. 4. P-T path of UHP eclogite from the southwestern Tianshan, China. Stage I. Peak P-T conditions were calculated by the reaction of magnesite and aragonite = dolomite in metapelite associated with coesite-bearing eclogite (Zhang et al., 2003a, 2005b). Stage II. P-T conditions of the main UHP stage suggested by the coesite pseudomorph in garnet rim, exsolution lamellae of coesite transformation to quartz in the core of porphyroblastic omphacite, and the calculation based on the omphacite-garnet-phengite geothermobarometer of Waters and Martin (1993) (Zhang et al., 2002a, 2003b). Stage III. P-T conditions of retrograde epidote-blueschist facies. Metamorphic reactions $\text{Coe} = \text{Qtz}$ (Mirwald and Massonne, 1980); $\text{Grp} = \text{Dia}$ (Kennedy and Kennedy, 1976); $\text{Mgs} + \text{Arg} = \text{Dol}$ (Sato and Katsura, 2001).

garnet from the Dabie Shan had been reported by Okay (1995), in which the minimum pressure was estimated as 2.7 GPa at 700°C. Van der Klaw et al. (1997) showed that paragonite may be in domain equilibrium with UHP minerals along certain microstructures; for example, paragonite may be in equilibrium with adjacent omphacite matrix grains with inclusions of coesite in the Zermatt-Saas eclogite. In addition, P-T pseudosections in the NCFMASH system calculated by Klemd et al. (2002) do not include carbonate in parageneses and are not suitable for the southwestern Tianshan eclogites, inasmuch as they contain numerous carbonate minerals such as magnesite and dolomite.

Geochemistry and Geochronology

According to recent geochemical studies, the southwestern Tianshan UHP eclogites and associated blueschists comprise three geochemical groups of protoliths (Fig. 5, Ai et al., 2005). Group I protolith assemblages (EC_1) are represented by type I

eclogite and blueschist, and vary in SiO_2 content from 47.3 to 49.9 wt%. They have high REE contents, $\Sigma\text{REE} = 166.4\text{--}205.6$ (normalized to primitive mantle). LREE are highly enriched and fractionated, $\Sigma\text{Ce}/\Sigma\text{Y} = 1.72\text{--}3.44$, $(\text{La}/\text{Yb})_n = 5.09\text{--}10.65$, $(\text{La}/\text{Sm})_n = 2.12\text{--}2.78$, and La contents are 105–134 times that of chondrite (Fig. 5A). HREE patterns are relatively flat: average $(\text{Gd}/\text{Yb})_n = 2$. No evident Eu anomalies are observed, $\text{Eu}/\text{Eu}^* = 0.92\text{--}0.97$. $\text{Zr}/\text{Hf} = 43.53\text{--}46.12$, $\text{Nb}/\text{La} = 1.09\text{--}1.55$ (except T1053 = 0.89), and Nb = 25.21–40.32 (> 8 ppm), are all close to average OIB (Sun and McDonough, 1989). Relative depletion of Sr and enrichment of Pb in some samples probably can be attributed to subduction dehydration and/or mixing of minor sediments. $\epsilon\text{Nd}(t) = 1.4$ to -0.4 indicates that they could have been derived from an enriched mantle source.

Group II protolith assemblage (EC_2) comprises mainly type II eclogites and widespread massive blueschists, whose SiO_2 contents vary between 47.0 and 54.1 wt%. They are also LREE enriched, $\Sigma\text{Ce}/$

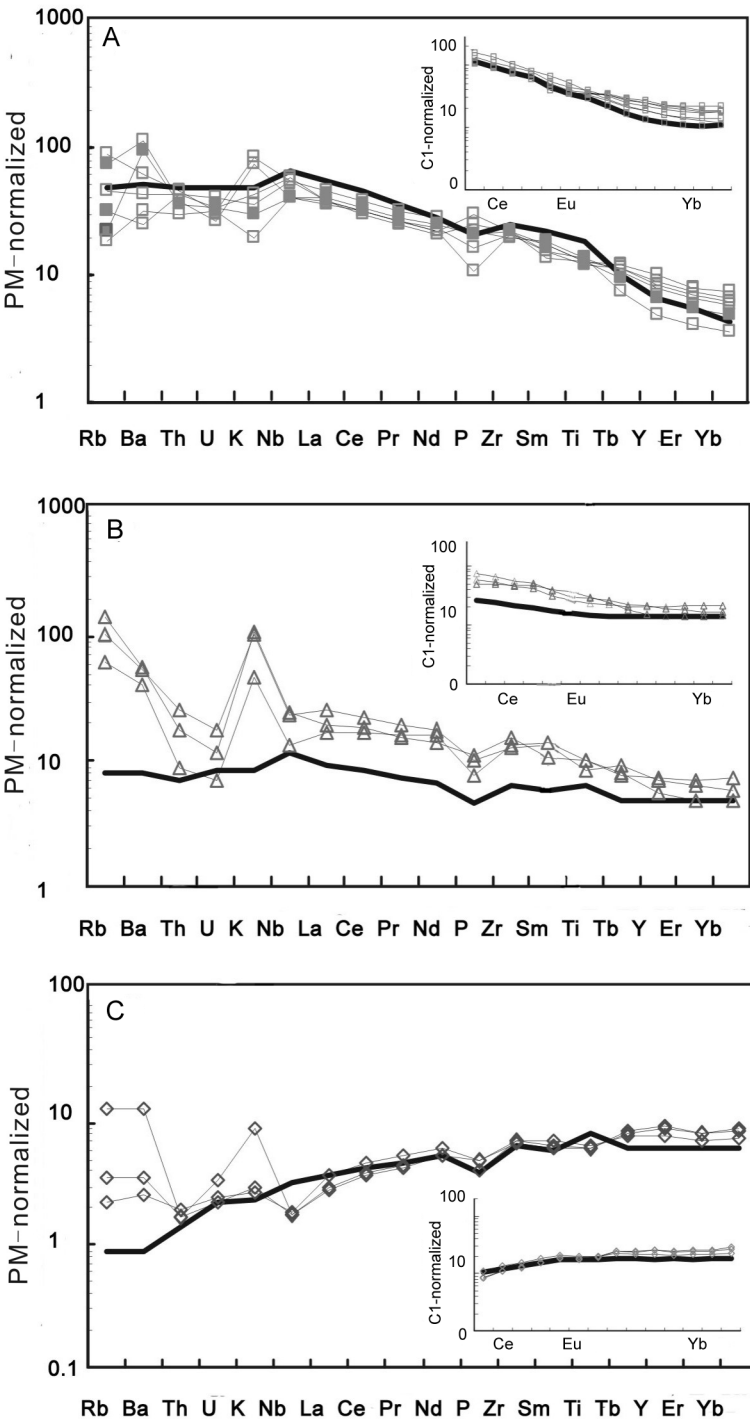


FIG. 5. Spider diagram of three types of southwestern Tianshan eclogites (after Ai et al., 2005). Data are normalized to primitive mantle from Sun and McDonough (1989); solid line represents the standard OIB (A), EMOR (B), and NMORB (C).

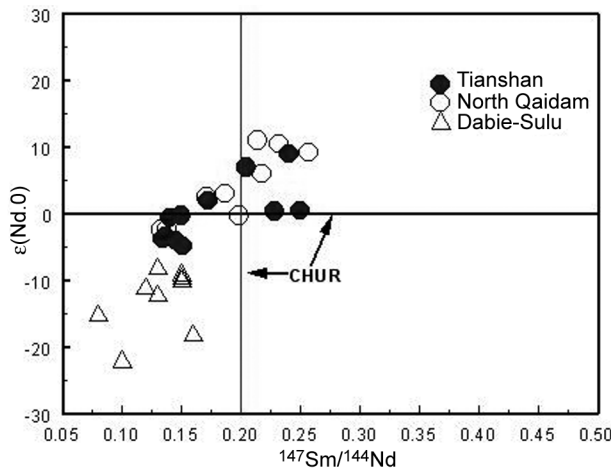


FIG. 6. $\epsilon\text{Nd}(0)$ vs. $^{147}\text{Sm}/^{144}\text{Nd}$ diagram of eclogites from the southwestern Tianshan (Zhang et al., 2005a), Northern Qaidam (after Yang et al., 2003), and Dabie-Sulu (after Jahn et al., 2003).

$\Sigma\text{Y} = 1.43\text{--}1.80$, $(\text{La}/\text{Yb})_n = 2.71\text{--}4.46$, and $\text{La}/\text{chondrite} = 50\text{--}75$. LREE are moderately fractionated, $(\text{La}/\text{Sm})_n = 1.22\text{--}1.93$. No obvious Eu anomalies are observed, $\text{Eu}/\text{Eu}^* = 0.91\text{--}1.06$. $\text{Zr}/\text{Hf} = 42.97\text{--}45.21$, $\text{Nb}/\text{La} = 0.73\text{--}1.30$, and $\text{Nb} = 9.62\text{--}22.00$ (>8 ppm) show resemblance to E-MORB-type basalts (Fig. 5B; Sun and McDonough, 1989). $\epsilon\text{Nd}(t) = -2.5\text{--}3.2$.

Group III protolith assemblages (BS_1) are blueschists and minor carbonate-bearing eclogites, whose SiO_2 contents vary between 47.7 and 50.4 wt%. They are very low in REE contents, $\Sigma\text{REE} = 81\text{--}86$, and are highly depleted in LREE, $\text{La}/\text{Yb} = 0.3\text{--}0.5$, $(\text{La}/\text{Sm})_n = 0.44\text{--}0.52$ (both are obviously below 1), $\text{La}/\text{chondrite} = 8\text{--}11$. Left-inclined REE and relatively flat HREE patterns, average $(\text{Gd}/\text{Yb})_n = 0.76$, and Zr/Hf ratios ($= 36.96\text{--}38.11$) indicate that they may have NMORB affinities (Fig. 5C). Lower Nb/La ($0.53\text{--}0.63$), Nb contents $= 1.25\text{--}1.35$, less than average NMORB (Sun and McDonough, 1989) and higher Pb contents suggest addition of a certain amount of marine sediments. $\epsilon\text{Nd}(t) = 6.7\text{--}7.4$ indicates that they were derived from a mantle source more depleted than CHUR (Ai et al., 2005).

Geochemical characteristics of three protolith groups for the southwestern Tianshan UHP eclogites and blueschists, combined with rarely preserved pillow structure and associations with ophiolitic fragments, indicate that they are affinities of E-MORB, N-MORB, and OIB basalts formed in an oceanic basin (Zhang et al., 2000). Their protoliths

consist of oceanic basaltic assemblages formed at a seamount setting, and were derived from long-evolved, depleted upper mantle mixed with minor sediment, resembling those of UHP eclogites from the western Alps (Rumble et al., 2003) and northern Qaidam (Yang et al., 2003) (Fig. 6). The $\epsilon\text{Nd}(0)$ values of -2.5 to $+7.4$ are significantly different from those (-10 to -20) of Dabie-Sulu UHP eclogites formed in typical continental setting (Jahn et al., 2003).

The metamorphic ages of the southwestern Tianshan eclogite and blueschist have long been hotly debated. Among the early studies, the scientific expedition team of the Chinese Academy (1985) acquired an Rb-Sr isochron age of 729 Ma for the blueschist at Hanjayrak by the Muzart River. Wang (1990) reported a Rb-Sr isochron age of 634 Ma for the blueschist at Changawuzi. Gao et al. (2000) reported $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 364 ± 2 to 401 ± 1 Ma respectively for glaucophane and phengite from the southwestern Tianshan eclogites. Subsequently, Gao and Klemm (2003) reported Sm-Nd isochron ages of $343 \pm 44\text{--}346 \pm 3$ Ma for eclogites and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 334 ± 2 and 347 ± 2 Ma, respectively, for glaucophane and phengite from blueschist. More recently, new Rb-Sr isochron ages of 313–302 Ma and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 323–312 Ma, respectively, were obtained for these rocks by Klemm et al. (2005). These data consistently suggest a Late Paleozoic subduction for the HP/UHP rocks of the southwestern Tianshan.

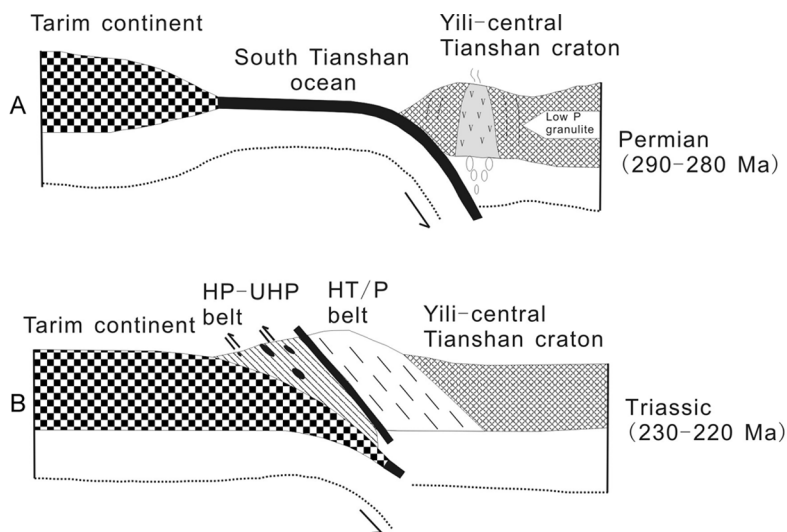


FIG. 7. Tectonic model for the formation of the southwestern Tianshan UHP metamorphic belt in western China. A. Northward subduction of the Paleo-south Tianshan oceanic lithosphere beneath the Yili-central Tianshan plate in the Permian (290–280 Ma) led to island-arc magmatism and formation of low-pressure granulite-facies metamorphism in the active continental margin of the Yili-central Tianshan craton. B. Collision between the Tarim plate and Yili-central Tianshan plate in the Triassic (230–220 Ma) led to the formation and exhumation of UHP eclogites (Zhang et al., 2005a).

Zircon separated from three different types of eclogites were dated by SHRIMP U-Pb dating; we obtained consistent rim ages of 220–230 Ma, and core ages of 310–405 Ma (Zhang et al., 2003c, 2006). We conclude that the 220–230 Ma ages obtained in zircon rims are better representatives of the HP-UHP metamorphic ages of the southwestern Tianshan eclogites. Much uncertainty exists in Rb-Sr isochron dating of metamorphosed rocks, especially for multistage metamorphosed rocks. Sm/Nd internal isochron dating is a useful method for many metamorphosed rocks, but considering the blocking temperature (650–850°C) of garnets in the Sm-Nd isotopic system (Burton et al., 1995; Thoni, 2002), the implication of this method for low-temperature eclogites is prone to the Sm-Nd isotopic disequilibrium between garnet and omphacite in eclogite (Thoni et al., 2002). The 550–600°C peak metamorphic temperatures of the southwestern Tianshan eclogites (Gao et al., 1999; Zhang et al., 2000, 2002a; Wei et al., 2003) are lower than the blocking temperature of garnet in the Sm-Nd isotopic system; this brings a large uncertainty to the Sm-Nd isochron dating. In fact, we have performed six sets of Sm/Nd analyses for garnet-omphacite whole-rock of the southwestern Tianshan eclogites; none has

produced a suitable isochron age. Another important factor affecting the precise Sm/Nd dating for eclogites is that the garnets from the southwestern Tianshan low-T eclogites have pronounced compositional zonation, and contain many mineral inclusions such as zoisite and paragonite in the cores. Hence, the Sm/Nd internal isochron method may not be suitable for dating metamorphic age of low-T eclogite in the southwestern Tianshan.

Because of the difficulty of adjusting the excess argon, the acquired ages are usually older than the real ages when $^{40}\text{Ar}/^{39}\text{Ar}$ step method is brought into use for dating metamorphic ages. The $^{40}\text{Ar}/^{39}\text{Ar}$ dating studies on HP-UHP rocks in recent years show that the excess argon prevails in these rocks (e.g., Dabie UHP rocks by Li et al., 1994; western Alps eclogites by Arnaud and Kelley, 1995 and Scaillet, 1996; and Himalayan HP rocks by Tonarini et al., 1993). Therefore, the most widely accepted method for dating HP-UHP metamorphic rocks at present is zircon U-Pb SHRIMP dating (Rubatto et al., 2003).

Summary

Unlike other UHP metamorphic belts reported in the world, a low P/T granulite-facies metamorphic

belt parallels the UHP belt in the southwestern Tianshan. The low-P belt lies to the north of the UHP belt across the Chagawuzi fault (Fig. 1). SHRIMP dating of zircons from two-pyroxene granulite yields a protolith age of about 298.5 ± 4.9 Ma (Li and Zhang, 2004); this implies that granulite-facies metamorphism took place probably prior to 220–230 Ma UHP metamorphism of eclogites to the south. We conclude that the ancient southwestern Tianshan ocean began to close some time after about 298 Ma, and the Tarim plate was subducted northward underneath the Yili-central Tianshan plate where coeval arc magmatism and granulite-facies metamorphism occurred on the active continental margin (Fig. 7A). In the early Triassic, the oceanic crust and accretionary wedge sediments were further subducted to mantle depth (<150 km) and then exhumed to the surface. Most oceanic materials were subducted to mantle depths; only a small portion of UHP metamorphic rocks were enwrapped in the metamorphosed sediments, and finally were exhumed to crustal levels by buoyant force and to the surface by subsequent thrusting (Fig. 7B).

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