Microstructures, petrofabrics and seismic properties of ultra high-pressure eclogites from Sulu region, China: implications for rheology of subducted continental crust and origin of mantle reflections

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Abstract

Ultra high-pressure (UHP) eclogites from Sulu region (China) represent mafic components of the continental crust, which were first subducted to mantle depths greater than 100 km and then exhumed to the earth’s surface. Detailed investigation of microstructures, chemical compositions, petrofabrics and seismic properties of the UHP eclogites can provide important information on the operating deformation mechanisms and rheology of subducted continental crust and on the origin of seismic reflections within the upper mantle. We present here results from field, optical and TEM observations, electron back-scattered diffraction (EBSD) measurements and numerical computations of the seismic properties of UHP eclogites collected from fresh surface outcrops at the drill site (Maobei, Donghai County, Jiangsu Province) of the Chinese Continental Scientific Drilling Program (CCSD). Two types of eclogites have been distinguished: Type-1 (coarse-grained) eclogites deformed by recovery-accommodated dislocation creep at the peak metamorphic conditions, and Type-2 (fine-grained) eclogites which are composed of reworked Type-1 materials during recrystallization-accommodated dislocation creep in shear zones which were active during the exhumation of the UHP metamorphic rocks. Both garnet and omphacite in these eclogites deformed plastically and the flow strength contrast between these two constituent minerals is apparently much less than an order of magnitude under the UHP metamorphic conditions. Plasticity of eclogites under UHP conditions can effectively facilitate channeled flow along the interplate shear zone. The
preservation of the relict crustal materials within the continental lithosphere may produce regionally extensive, strong, seismic reflections in the upper mantle. This may explain the origin of mantle reflections observed in many areas of the world.

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1. Introduction

Whereas the upper crust is accessible to geological sampling and mapping, the deeper portions of the crust and the upper mantle are relatively inaccessible. Much of our understanding about the composition, structure and evolution of the deep crust and upper mantle beneath continents has been derived from various seismic refraction and reflection measurements. Interpretation of these seismic data is mainly based on our knowledge of the elastic properties of rocks and rock-forming minerals, the latter obtained largely from laboratory measurements of ultrasonic velocities and density (e.g., Christensen, 1965; Kern and Richter, 1981; Kern, 1990; Ji and Salisbury, 1993; Christensen and Mooney, 1995; Burlini and Tancredi, 1998; see Ji et al., 2002, for summary). However, it is not easy to simulate the pressure and temperature environments of the earth’s mantle in the laboratory. Thus, theoretical calculations of seismic properties based on the elastic theory (Crosson and Lin, 1971; Ji and Mainprice, 1988; Mainprice, 1990) become another way to estimate the anisotropic seismic properties of any kind of possible rocks when all the physical properties such as elastic constants, density and crystallographic preferred orientation (CPO) are known for each constituent mineral (e.g., Mainprice and Silver, 1993; Ji et al., 1994; Mainprice et al., 2000; Mauler et al., 2000; Saruwatari et al., 2001). The CPO measurement of ultrahigh pressure (UHP) eclogites from former continental subduction zones has recently been made possible by technological developments of SEM-based measurements of minerals of any symmetry, such as cubic garnet (Prior et al., 2000) and omphacite (Mauler et al., 2000; Bascou et al., 2002).

The Qinling–Dabie–Sulu ultrahigh pressure (UHP) metamorphic belt, which is about 1000 km long and 120 km wide, is the largest among seven well-recognized UHP belts in the world and has been investigated extensively since the discovery of coesite (Xu, 1987; Wang and Liou, 1991) and diamond (Xu et al., 1992) from the region. The UHP rocks were a part of lithospheric slab subducted at the intracontinental collision zone between the Sino-Korean and Yangtze blocks in the Late Triassic or Early Jurassic (e.g., Cong, 1996; Liou, 1999). Previous studies (e.g., Hirajima et al., 1992; Yang et al., 1993; Zhang et al., 1994) suggest that the UHP rocks from Dabie and Sulu region was subducted to a depth up to about 150 km before being rapidly exhumed to the earth’s surface. Petrologic, mineralogical and geochemical aspects of these UHP rocks have already been thoroughly investigated during last decade (e.g., Zhang et al., 1994; Cong, 1996; Liou, 1999). However, deformation microstructures of these UHP rocks have received little attention although such investigations may provide important information on deformation mechanisms, rheological and petrophysical properties of the continental lithosphere first subducted into and then exhumed from the upper mantle. In this paper, we report the results of our investigations on microstructures, crystallographic preferred orientation (CPO) and calculated seismic properties of the UHP-eclogites from the Sulu UHP metamorphic terrane. These results are then applied to constrain deformation mechanism and rheological behavior of subducted slab and origin of seismic reflections in the upper mantle.

2. Geological setting

The Sulu UHP metamorphic terrane, which has been displaced about 530 km by the sinistral, strike–slip Tanlu fault, is an eastern extension of the Triassic Qinling–Dabie collision zone (e.g., Wang and Liou, 1991; Wang et al., 1992). On the north, the UHP metamorphic terrane is bounded by the Yantai–Qingdao–Wulian fault with the Proterozoic–Archean basement (Fig. 1), which is overlain by
Paleozoic cratonal cover and the Mesozoic volcaniclastic rocks (Zhang et al., 1994). On its southern limit, the high-pressure (HP) terrane includes blueschists bounded by the Haizhou–Siyang fault. The UHP terrane consists of eclogite, gneiss, marble, quartzite and meta-ultramafic rocks. The eclogite occurs as sheared lenses, pods and layers ranging from tens of centimeters to hundreds of meters in size within foliated ultramafic blocks, metapelites (garnet-quartz-jadeite gneisses), kyanite quartzites and marbles. These eclogitic blocks are obviously tectonic boudins. The age of UHP metamorphism and the time of collision between the Sino-Korean and Yangtze blocks is about 210–220 Ma (see Cong, 1996 for summary), as derived from independent studies including Sm–Nd isochrons (Li et al., 1989, 1992), U–Pb zircon ages (Ames et al., 1993; Li et al., 1993a,b), 40Ar/39Ar dating (Hacker and Wang, 1995) and Rb–Sr dating (Cong, 1996). The protolith of the UHP rocks are considered to be Archean (=1.66 Ga, Jahn et al., 1996) or Proterozoic (~800 Ma, Li et al., 1993a,b; Jahn et al., 1996).

The present-day crustal structures under the Dabie–Sulu region are divided into four-layer structures (i.e., upper, middle, upper lower-crust and lowermost crust) with an average total thickness of 34 km that is much thinner than the crust (45–70 km) of western China (Li and Mooney, 1998; Kern et al., 2003).
Fig. 2. Microstructures of the UHP eclogites from Maobei, Donghai, China. (a) Field photograph of compositional banding with alternating garnet-and omphacite-rich layers. (b) Optical microphotograph of a typical garnetite layer. \(XZ\) sections. (c) Optical microphotograph of a coarse-grained eclogite. Both garnet (Grt) and omphacite (Omp) are flattened and elongated. \(XZ\) sections.
Both the crustal thinning and exhumation of the UHP rocks are attributed to an intensive tectonic extension immediately after the collision between the Sino-Korean and Yangtze cratons.

P-wave refraction and reflection profiles across the Sulu UHP terrane from Tangchen to Lianshui (Yang et al., 1999; Yang and Yu, 2001) have a series of northwest-dipping reflectors at 0–500, 900–1100 and 3000–4000 m depth. These highly reflective layers have an average P-wave velocity varying from 6.8 to 7.3 km/s, probably corresponding to a series of sheared slices of UHP eclogite- and/or garnet lherzolite-bearing felsic gneisses as exposed at the surface. A high portion of eclogite/lherzolite (30–40 vol.%) is needed to explain such high P-wave velocities (Kern et al., 2002).

The studied samples of eclogites were collected from fresh surface outcrops in stone pits at the drill site (Maobei, Donghai County, Jiangsu Province) of the Chinese Continental Scientific Drilling Program (CCSD). This drill site is located in the southern part of the Sulu UHP metamorphic terrane, about 30 km east of the Tanlu fault and approximately 70 km west of the Yellow sea (Fig. 1). The CCSD drilling started in July 2001, has reached the depth of 3000 m, and planned to reach a depth of 5000 m in the year of 2004, penetrating through all the observed seismic reflectors and high Vp layers within the upper crust of the region. Petrophysical properties of the studied coesite-bearing eclogites may provide critical constraints on geological interpretations of the seismic refraction and reflection data obtained from the CCSD, and further shed light upon the deformation mechanisms of the subducted slab and exhumation of UHP metamorphic rocks.

3. Microstructures

3.1. Field, optical and SEM observations

In the field, the UHP eclogites reveal a strong planar fabric defined by a compositional banding with alternating garnet- and omphacite-rich layers (Fig. 2a). These garnet-rich layers, containing more than 85–90 vol.% garnet, can be referred to as garnetite. The omphacite-rich compositional layers are dominated by omphacite (>80 vol.%) and can be referred to as pyroxenite. These layers are 5–80 cm thick. On a given outcrop, garnetite layers are usually thicker than pyroxenite layers (Fig. 2a). The stretching lineation is defined by the elongation of garnet and particularly omphacite. In thin sections, both garnet and omphacite are flattened and elongated in the eclogites (Fig. 2b and c). The compositional layering (Fig. 2a) is believed to originate from mass-transfer-related metamorphic differentiation.

In thin sections cut parallel to the XZ plane, where X is parallel to the stretching lineation and Z is normal to the flattened foliation, garnet grains generally show a shape of elongate lenses with two smoothly curved boundaries subparallel to the foliation (Fig. 2b and c). Intersections of these two boundaries form two-outward-pointing cusps extending into the foliation plane. Some garnet grains show a well-developed pinch-and-swell structure. These microstructural...
characteristics provide unambiguous evidence for garnet plasticity. In the XZ sections, omphacite shows a mean aspect ratio (2.5–5.0) larger than garnet (2.0–3.5). In the XY and YZ sections, omphacite also shows a mean aspect ratio larger than garnet. The larger aspect ratio of omphacite could be due to a fact that garnet grains were equidimensional while omphacite crystals had a columnar shape prior to de-

Fig. 5. Flinn diagram showing the garnet shape fabrics of Type-1 (solid circle) and Type-2 (open circle) eclogites. X, Y and Z are the mean crystal lengths in the directions parallel to the stretching lineation, perpendicular to the stretching lineation and in the foliation plane and normal to the foliation, respectively.

Fig. 4. Grain size distributions of garnet and omphacite in Type-1 (sample 96-MB3C) and Type-2 (sample 96-MB4) eclogites.

Fig. 6. SEM orientation contrast (OC) images showing porphyroclastic texture of garnetite layers in Type-2 eclogite (sample 96-MB20D).
formation. It is necessary to note that no strong deflection of the foliation and layering defined by flattened omphacite grains has been observed around garnet crystals (Fig. 2b and c). This fact suggests that the rheological contrast between garnet and clinopyroxene is much less under the UHP conditions than those in amphibolite- and granulite-facies mylonites from the deep crust.

Thin sections which were first polished mechanically and chemically, then coated with carbon and were examined in a Philips XL30 SEM using a foescatter detector system to collect orientation contrast (OC) images. On these OC images (Fig. 3), grain boundaries and fractures can be clearly distinguished. Internal structure such as cellular subdomains of different crystallographic orientations (Prior et al.,

Fig. 7. TEM microphotographs of dislocation substructures in deformed garnet grains. (a and b) Dislocation walls defined by well-organized and regularly spaced, linear array of straight dislocations. Bright field. Sample 96-MB3 (Type-1 eclogite). (c and d) Dislocation networks defined by polygonal array of dislocations of two (d) or three (c) discrete orientations. Bright field (c) and dark field (d). Sample 96-MB1 (Type-2 eclogite).
2000) were occasionally detected in some garnet grains (Fig. 6b).

Based on grain size, two characteristic types of UHP eclogites can be identified. The first, referred to as “Type-1 eclogites”, is characterized by coarse-grained garnet and omphacite. Garnet ranges from 0.15 to 1.4 mm with an average grain size of 0.52 mm, and omphacite (0.32–3.0 mm) has a mean grain size of 0.93 mm (Fig. 4). Measurements made on thin sections parallel to $XY$ planes show that garnet and omphacite have average aspect ratios of 2.06 and 2.58, respectively. On $YZ$ sections, omphacite has a slightly higher average aspect ratio (1.68) than garnet (1.46). The garnet grains in Type-1 eclogites have thus prolate shapes with a Flinn coefficient $K=1.4$ (Fig. 5). The second type of eclogites, referred to as “Type-2 eclogites”, is characterized by relatively fine-grained garnet and omphacite (Fig. 4). Garnet grain size ranges from 0.03 to 1.4 mm with an average grain size of 0.28 mm, and omphacite (0.03–1.5 mm) has a mean grain size of 0.41 mm. Garnet and omphacite on the $XY$ sections have average aspect ratios of 1.4 and 1.78, respectively. On $YZ$ sections, the average aspect ratio is 1.56 for omphacite and 1.46 for garnet. The garnet grains are characterized by quasi-plane-strain shape with $K=1$ in Flinn diagram (Fig. 5). Thus, Type-1 and Type-2 eclogites can be considered as $L \gg S$ and LS tectonites (Helmstaedt et al., 1972), respectively. The $L \gg S$ tectonites deformed in the field of apparent constriction while the LS tectonites deformed in the field of plane strain and probably indicates a simple shear deformation (Philippot and van Roermund, 1992; Godard and van Roermund, 1995; Abalos, 1997; Zulauf, 1997).

Both types of eclogites consist of the same assemblage of garnet (57 ± 6 vol.%), omphacite (∼39 ± 10 vol.%), rutile (∼1–3%) and phengite (∼0.5%), and minor amounts (less than 3 vol.%) of secondary minerals such as amphibole and epidote. Rutile occurs either as interstitial grains between garnet and omphacite or as inclusions in these minerals. Coesite relics and their quartz pseudomorphs occur as inclusions in garnet and omphacite in Type-1 eclogites. Radial extensional fractures from these inclusions are found in both garnet and omphacite. Some omphacite grains are rimmed by a very fine-
grained symplectite of plagioclase and Ca-pyroxene or omphacite with a lower jadeite content. Amphibole and epidote are the retrograde products which are restricted to some fractures. Both types of eclogites are pervasively cracked by extensional fractures which are predominantly perpendicular to the stretching lineation (Figs. 2 and 3). These lineation-normal fractures are very common in granulite facies mylonites and UHP metamorphic rocks and thought to be formed during the latest stages of the exhumation (Ji et al., 1997).

When both types of eclogites coexist in the same blocks, the coarse-grained Type-1 eclogites are bounded by the fine-grained Type-2 eclogite layers. The latter represent localized shear zones which overprinted on the early coarse-grained Type-1 eclogite. The shear zones are approximately parallel to the regional penetrative mylonitic foliation in the strongly deformed wall rocks such as garnet-bearing ultramafic rocks, UHP paragneiss, quartzite and marble. Fore-scatter orientation contrast imaging showed that the garnetite layers from Type-2 eclogites developed porphyroclastic texture with large porphyroclasts enclosed in a fine-grained matrix (Fig. 6a). The latter developed a foam structure where grain boundaries are smoothly curved and aligned 120° triple junctions (Fig. 6b). No coesite relicts were observed in either garnet or omphacite from Type-2 eclogites, and quartz occurs as elongated polycrystalline aggregates between fine-grained garnet/garnet, garnet/omphacite or omphacite/omphacite grains. It is thus likely that Type-2 eclogites resulted from dynamic recrystallization of Type-1 eclogites along shear zones which were active during the exhumation of the UHP metamorphic rocks.

3.2. TEM observations

A Philips CM200 transmission electron microscope (TEM, GFZ-Potsdam) operating at 200 kV was used to characterize the dislocation microstructures in the eclogites. Dislocation microstructures are

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<th>FeO+Fe₂O₃</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
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<td>0.13</td>
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<td>11.57</td>
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<td>0.12</td>
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<td>15.61</td>
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<td>8.47</td>
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*a Major oxides are expressed as wt.%.
similar in garnets from both types of eclogites. Garnets developed extensively regular dislocation arrays and dislocation networks. The dislocation arrays (Fig. 7a and b) can be interpreted as tilt subgrain boundaries while the dislocation networks (Fig. 7c and d) imply an activation of more than two active slip systems. Those well-organized dislocation microstructures indicate that diffusion-assisted recovery mechanism such as dislocation climb and cross-slip efficiently occurred. Within the subgrains surrounded by dislocation walls, free dislocations were imaged with a density in the range from $10^{11}$ to $10^{12}$ m$^{-2}$ (Fig. 8a). Dislocation junctions, which are complex intersections (tangles) of several dislocations, were also observed in both types of eclogites (Fig. 8b and c). The presence of dislocation junctions indicates that dislocation interactions and consequently the operation of multiple slip systems took

![Diagram](image)

Fig. 9. Compositional profiles of pyrope (Prp), grossular (Grs), almandine (Alm) and spessartine (Sps) contents along two orthogonal profiles of lenticular garnets. (a) Sample 96-MB3C (Type-1 eclogite). (b) Sample 96-MB4 (Type-2 eclogite). Sketch maps based on backscattered electron imageries.
place in the deformed garnet (Voegelé et al., 1998; Wang and Ji, 1999). The above observations agree with previous TEM investigations on other naturally deformed garnets (Ando et al., 1993; Ji and Martignole, 1994; Doukhan et al., 1994; Voegelé et al., 1998; Prior et al., 2000), all suggesting that the garnet can be deformed plastically as long as temperature, pressure, differential stress and strain rate are appropriate.

4. Chemical compositions and the metamorphic temperature

Major elements of 27 UHP eclogites collected from the region were determined by the X-ray fluorescence (XRF) in McGill University. The results of 12 representative samples are listed in Table 1. Analytical precision is better than ±1%. The UHP eclogites have significantly lower contents of K₂O, Na₂O and SiO₂ compared with typical basalts, indicating that these relatively mobile components have immigrated into fluids during the eclogitization. The above chemical composition also reflects a fact that the UHP eclogites, which have subjected to little retrograde metamorphism, are mainly bimineralic aggregates of garnet and omphacite and contains <1–2% coesite and/or quartz.

Chemical compositions of garnet and omphacite were measured using a JEOL 8700 Super-probe, with an accelerating voltage of 15 kV, a beam current of 20 nA and a beam diameter of 5 μm. Each estimation of elements was performed with 20 s counting time on peaks and 10 s on background. The precision in the chemical compositions is about ±1%. Garnet composition varies from sample to sample; such differences are related to differences in bulk composition of protoliths. In one garnet-rich
layer and in one textural situation in the sample scale, the garnet grains generally have nearly constant compositions, varying only by ±3%. For example, microprobe analyses of 209 garnet grains from sample 96-MB3C, which is a typical Type-1 eclogite, yield the ranges of pyrope (38.7–44.5%), grossular (30.7–36.0%), almandine (22.6–25.6%) and spessartine (0.3–0.7%) with an average composition

\[
\text{Alm}_{24.0} \pm 0.3 \text{Prp}_{41.7} \pm 1.1 \text{Grs}_{33.7} \pm 1.1 \text{Spe}_{0.5} \pm 0.1.
\]

Four typical lenticular garnet grains with length/width ratios larger than 2 were selected from Type-1 eclogite for compositional X-ray maps of Mg, Ca and Fe using the electron microprobe. These maps (not illustrated here) show that each lenticular crystal is rather homogeneous in compositions and do not show any clear compositional zoning. Zoning profiles from rim to rim through the core were also carried out along two mutually perpendicular directions which coincide with the major and minor axes of several elongated garnet grains in the XZ sections. These profiles (Fig. 9a) show only slight compositional variations with respect to the uncertainties of measurements, providing no evidence for the existence of compositional zoning in garnet grains from Type-1 eclogites. The absence of compositional zoning in the garnet grains from Type-1 eclogites can be attributed to homogenization by diffusion at peak metamorphic conditions \((T\sim800 \text{ °C and } P>3 \text{ GPa}, \text{ Zhang et al., 1994})\) and to the absence of effective retrogression from the eclogite to granulate or amphibolite facies.

In Type-2 eclogites, most of garnet porphyroclasts do not show significant compositional zoning (Fig. 9b) with some rare exceptions (Fig. 10). When the compositional zoning occurs, it is characterized by a relatively low pyrope component at both the center and the rims while the variation of grossular component is reverse (Fig. 10). Higher pyrope component and lower grossular component occur between the center and the rims. The almandine and spessartine components remain generally constant. The zoning pattern can be interpreted as growth zoning during the exhumation of the UHP metamorphic terrane. Rapid exhumation and resultant strain localization might result in grain boundary migration of garnet and formation of the compositional zones with distinct pyrope and grossular components. The radial fracturing around coesite inclusions in Type-1 eclogites and recrystallization of Type-2 eclogites were probably contemporaneous with this tectonic uplift. However, omphacite grains are nearly homogeneous with jadeite components of \(X_{\text{jad}} = 0.25–0.60\) and show no specific compositional distinction between these two types of eclogites.

Equilibrium temperatures were estimated from the empirical relationship between Ca-content in garnet \(X_{\text{Ca}} = \text{Ca}/(\text{Ca} + \text{Fe} + \text{Mg} + \text{Mn})\) and Fe–Mg partitioning \((K_D)\) between coexisting homogeneous garnet and omphacite. \(K_D\) is defined as the ratio of \(\text{Fe}^{2+}/\text{Mg}\) for garnet to that for omphacite. Since the existence of coesite pseudomorphs implies that the garnet and omphacite assemblage was stable in the coesite stability field, the peak temperature can be estimated at a pressure of 3 GPa using the garnet-clinopyroxene geothermometers of Ellis and Green (1979) and Powell (1985). These geothermometers generally give reasonable temperature estimates with garnets of low to medium grossular components \((X_{\text{Grs}} < 0.5, \text{ Koziol and Newton, 1989})\). As shown in Fig. 11, the results suggest that both types of the eclogites from Maobei drilling site were equilibrated at the similar temperature range of \(850 \pm 50 \text{ °C\), consistent with previous

![Fig. 11. Plots of the \(K_D\) values \([\text{Fe}^{2+}/\text{Mg}]_g/(\text{Fe}^{2+}/\text{Mg})_m\) of eclogite samples versus the grossular content \([X_{\text{Ca}} = \text{Ca}/(\text{Ca} + \text{Fe} + \text{Mg} + \text{Mn})] \) of garnet. Also shown are the 3.0 GPa isotherms of Ellis and Green (1979, continuous lines) and Powell (1985, broken lines).}](image-url)
Fig. 12. Garnet compositional variations in an old porphyroclast (profiles AB and CD) and the adjacent matrix of recrystallized new grains (profiles EF and GH). Type-2 eclogite (sample 96-MB20D).
estimates for eclogites from other localities of the Sulu regions (Zhang et al., 1994).

Compositional variations of garnet relict porphyroclasts and polygonal recrystallized grains were investigated in sample 96-MB20D, which is a typical Type-2 eclogite. The results (Fig. 12) are presented in terms of pyrope, grossular, almandine and spessartine components. The line drawing (Fig. 12a), which was based on an electron backscattered image, shows a typical site chosen for microprobe measurements. The porphyroclast has a serrated boundary, which is interpreted as the result of grain boundary migration. The recrystallized matrix surrounding the porphyroclast is characterized by a mosaic of polygonal fine grains. The pyrope, grossular, almandine and spessartine components display no variations within the range of uncertainties of microprobe measurements along two orthogonal profiles AB and CD in the garnet porphyroclast (Fig. 12b and c). Along profiles EF and GH, which started from the rims of the porphyroclast and then extended progressively to the recrystallized matrix, a marked continuous decrease in pyrope component and an increase in both grossular and almandine components are detected while spessartine content remains constant (Fig. 12d and e). The observed tendency of compositional variations has two implications: (1) the dynamic recrystallization of garnet took place during uplift of the UHP metamorphic terrane with continuous decreasing in $T$ and $P$; and (2) the dynamic recrystallization of garnet in the UHP eclogites, which probably occurred through grain boundary migration, was driven by not only dislocation strain energy but also by chemical-free energy.

5. Density data

Densities of the eclogites were measured using Archimedes methods at ambient conditions. The densities obtained vary from 3.46 to 4.10 g/cm$^3$ (Fig. 13). The Type-2 eclogites have an average density of 3.76 g/cm$^3$, which is higher than that (3.54 g/cm$^3$) of Type-1 eclogites. These mean densities are consistent with the bulk densities of eclogites from Dabie UHP belt (Kern et al., 1999), but higher than those compiled by Rudnick and Fountain (1995) (3.43 g/cm$^3$) and Christensen and Mooney (1995) (3.48 g/cm$^3$).

6. Crystallographic preferred orientations

CPOs were measured on garnet, omphacite and rutile using electron backscattered diffraction (EBSD), JEOL JSM 5600 SEM, at Laboratoire de Tectonophysics, Université de Montpellier II. The CPO diagrams were projected in equal area and lower hemisphere respect to the $X$, $Y$ and $Z$ directions of the tectonic framework (Fig. 14).

6.1. Garnet CPO

Each EBSD measurement with more than two hundreds of garnet grains shows that garnets from both types of eclogites have weak strengths and complex CPO patterns with numerous maxima of $\langle 100 \rangle$, $\langle 111 \rangle$ and $\langle 110 \rangle$ (Fig. 14). Bulk patterns of those CPOs cannot be interpreted simply by assuming the activation of any single slip system. The complex patterns may result from multiple slip of many systems such as those of $1/2 \langle 111 \rangle \{110\}$, $\{112\}$ or $\{123\}$, $\langle 100 \rangle \{010\}$ and $\langle 100 \rangle \{011\}$. Activation of these slip systems has been documented by previous deformation experiments of garnet single crystals (Garem et al., 1982; Rabier et al., 1976; Karato et al., 1995; Voegelé et al., 1998; Wang and Ji, 1999). We are not surprised by observing such weak and complex CPOs for garnets because for a...
Fig. 14. Stereographic projections (lower hemisphere equal area) of crystallographic preferred orientations of garnet, omphacite and rutile, determined by EBSD system. X, Y and Z are defined in the text.
given finite strain produced by dislocation slip, crystals with more active independent slip systems should develop more complex and weaker CPOs than those with only single or two active slip systems. During slip, an unconstrained crystal with five or more independent slip systems changes its shape but its lattice may subject to little rotation with respect to the instantaneous stretching axes of bulk flow. Unlike triclinic minerals such as plagioclase (Ji and Mainprice, 1988), the bcc garnet has high symmetry and 12 potential slip systems, there is a wide choice of slip systems. The slip plane does not have to undergo much rotation before the resolved shear stress becomes high on another 1/2 \{111\} \{110\} slip system, for example. Even though the slip occurs predominantly on the \{110\} planes, it is important to realize that three \{110\}-type planes intersect in a [111] direction and screw dislocations with a 1/2 (111) Burgers vector may move at random on the \{111\} planes with high resolved shear stress. Thus, the weakness of the garnet LPOs cannot provide any unequivocal evidence for diffusion creep or against dislocation creep as a deformation mechanism of the garnet grains in the UHP eclogites (Ji and Martignole, 1996).

Of note are the data of crystallographic misorientation between two adjacent grains, which may provide some information for the prevailing deformation mechanism (Mainprice et al., 1993; Jiang et al., 2000). The distributions of minimum misorientation (some times called disorientation) angles and rotation axes between adjacent garnet grains are presented in Fig. 15a and b, respectively. There is no clear distinction between Type-1 and Type-2 eclogites. In both types of eclogites, the rotation axes are almost randomly distributed, with no special correlation with

Fig. 15. Misorientation angle distributions (a) and pole figures of the misorientation axes (b) of garnet grains in Type-1 and Type-2 eclogites.
the tectonic framework (X–Y–Z axes). The histograms shown in Fig. 15a display a maximum frequency at a disorientation angle of about 45°. For a random distribution of cubic crystals such as garnet, the distribution of disorientations has a maximum peak at exactly 45° (Mackenzie, 1958). Hence, it is further argument to say that these garnets have a very weak CPO.

6.2. Omphacite

Both types of eclogites developed strong CPOs (Fig. 14) with similar preferred orientations of [001], which is subparallel to the stretching lineation (X). Both [100] and [010] direction forms girdles perpendicular to the lineation. However, the maximum concentrations of the [010] are different for Type-1 and Type-2 eclogites. The [010] maxima are close to the Z-direction for Type-1 eclogite while they are located middle way between the Y and Z directions in the plane normal to the lineation for Type-2 eclogite. The omphacite CPO pattern of Type-1 eclogite is very similar to those of so-called L-type eclogites subjected to a constrictional or coaxial extensional strain (e.g., Godard and van Roermund, 1995; Abalos, 1997; Mauler et al., 2000). The omphacite CPO pattern of Type-2 eclogite is similar to those observed by Abalos (1997). Both patterns of the omphacite CPOs have been reported for eclogites from Western Norway (Boundy et al., 1992), Western Alps (Philippot and van Roermund, 1992; Piepenbreier and Stöckhert, 2001), Swedish Caledonids and Western France (Godard and van Roermund, 1995), NW Spain (Abalos, 1997) and for eclogites xenoliths from East Corolado Plateau (Kumazawa et al., 1971).

The omphacite CPOs of eclogites (Fig. 14) can be readily explained according to the recent viscoplastic self-consistent (VPSC) numerical simulations of Bascou et al. (2002). The simulations were made using the slip systems observed by TEM in naturally deformed omphacite. Slip has been observed on 1/2 \( \{110\} \{101\} \) and \( \{001\} \{100\} \) by van Roermund and Boland (1981), Buatier et al. (1991), Ji et al. (1993) and Godard and van Roermund (1995). Type-1 eclogite has strong point maximum of [001] with a density of 11.3 m.u.d. subparallel to the lineation, a girdle of [010] in the YZ plane with a maximum of 7.6 m.u.d. normal to the foliation (Z) and more dispersed distribution of [100] in the YZ plane with a maximum of 3.9 m.u.d. between Y and Z. Both simple shear and pure shear simulations have these general characteristics. Deformation of Type-1 eclogite was probably in the constrictional field given the prolate shape data for omphacite. Type-2 has stronger point maximum of [001] with a density of 12.9 m.u.d. subparallel to the lineation, a weaker girdle of [010] in the YZ plane with a maximum of 6.0 m.u.d. between Y and Z and stronger concentration of [100] in the YZ plane with a maximum of 4.7 m.u.d. near Z. The transtension simulation (Bascou et al., 2002) has these general characteristics. The transtension used in the simulation has a kinematic vorticity number of \( W_k = 0.9 \), that is about 90% simple shear with a small component of tension parallel to the lineation. The shape data on omphacite for Type-2 is nearly plane strain which is entirely compatible with a transtension deformation.

6.3. Rutile

Rutile CPOs are shown in Fig. 14. [001] directions of rutile in both types of eclogites are concentrated near the lineation. As rutile is of tetragonal symmetry where [100] and [010] axes are crystallographically equal, those axes show similar patterns. [100] and [010] in Type-1 eclogite show clear girdles perpendicular to the lineation, whereas both these axes in Type-2 eclogite show relatively dispersing fabric patterns. Stoichiometric rutile has two principal glide systems, \( \{101\} \{101\} \) is active above 600 °C and \( \{001\} \{110\} \) above 900 °C (Blanchin et al., 1990). However, \( \{001\} \{110\} \) has a critical resolved shear stress that is twice as high as \( \{101\} \{101\} \), hence is difficult to activate at laboratory strain rates (Blanchin and Faisant, 1979). As \( \{101\} \{101\} \) provides only four slip systems, rutile is extremely difficult to be fully plastic below 900 °C. Hence, it is likely that the observed rutile CPO is due either to anisotropic crystal growth or to the passive rotation of elongate crystals in the ductile matrix.

7. Seismic wave properties

We calculated the seismic velocities (Vp is referred to P-wave velocity, and Vs1 and Vs2 are,
respectively, the velocities of the first and second arrived S-waves), shear-wave anisotropy \(A(V_s)\) and polarization direction of \(V_{s1}\) on the basis of the CPO, density, volume fraction and elastic stiffness coefficients of each constituent mineral. The elastic stiffness coefficients of garnet, omphacite and rutile are derived from Chai et al. (1997), Bhagat et al. (1992) and Bass (1995), respectively. The seismic velocities and anisotropies (Fig. 16) have been calculated for each type of eclogite using the Voigt–Reuss–Hill average. Both types of eclogites yield comparable \(V_p\) anisotropies (1.4–1.5%) with similar minimum (8.67–8.70 km/s) \(V_p\) and maximum (8.79–8.84 km/s) \(V_p\) values. The maximum \(V_p\) occurs at the direction subparallel to the lineation while the minimum \(V_p\) occurs at a high angle to the lineation. Kern et al. (2002) carried out laboratory measurements on three fresh UHP eclogite samples from the same locality as our samples and obtained mean \(V_p\) values at 600 MPa ranging from 8.48 to 8.64 km/s and \(V_p\) anisotropies from 1.0% to 2.0% (Table 2). Although the calculated and measured \(V_p\) anisotropy values are almost the same, the calculated zero-pressure \(V_p\) values of crack-free and retrogression-free eclogite aggregates are slightly higher than those values measured at 600 MPa (Table 2). This fact indicates that the calculated velocity actually corresponds to a velocity measured at a pressure above 600 MPa for eclogites. It is not surprising because the critical pressure over which all pores and cracks existent within hard rocks such as mantle xenoliths and eclogites are closed at room temperature should be significantly higher than 600 MPa (e.g., Christensen, 1965; Manghnani et al., 1974; Kern et al., 1999; Wang and Ji, 2001).

Both types of eclogites have almost identical calculated mean \(V_{s1}\) (4.98–5.00 km/s) and \(V_{s2}\) (4.96–4.97 km/s) values, yielding weak \(V_s\) anisotropies (<1.5%). The low values of \(A(V_s)\) are mainly caused by the volumical predominance of cubic garnet which is elastically quasi-isotropic. The calculated values (Fig. 16) are slightly higher than those values measured by Kern et al. (2002) at 600 MPa. They yielded

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Fig. 16. Seismic properties of typical Type-1 and Type-2 eclogites from the Sulu UHP metamorphic terrane. All the properties were calculated for the zero-porosity and ambient conditions. Lower hemisphere projections. Contours for P-wave velocity (\(V_p\)), fast S-wave velocity (\(V_{s1}\)) and slow S-wave velocity (\(V_{s2}\)) are in km/s, S-wave velocity anisotropy \(A(V_s)\) is in %. Vs polarization is indicated by the trace of the fast S-wave vibration plane.
the eclogites mean Vs values ranging from 4.80 to 4.93 km/s at this pressure (Table 2). Vs1 fast polarization directions, as shown in Fig. 16, are similar for Type-1 and Type-2 eclogites except at the Y-direction. The fast polarization directions are subparallel to the X-direction for rays parallel to the XY-plane in Type-2 eclogite, whereas those are oblique to the X-direction for rays parallel to the Y-direction in Type-1 eclogite.

8. Discussion

8.1. Transition between constriction and plane strain

In the coarse-grained Type-1 eclogites, both garnet and omphacite are of prolate shape \((L > S)\), indicating an apparent constrictional strain (e.g., Godard and van Roermund, 1995; Zulauf, 1997). In the fine-grained Type-2 eclogites, however, shapes of either garnet or omphacite display a plane-strain (LS) which was most likely related to a non-coaxial shear (e.g., Philippot and van Roermund, 1992; Abalos, 1997) or trans-tension as suggested here. It is interesting to discuss the possible origin of these two types of eclogites.

Field observations show that the deformation fabrics of coarse-grained Type-1 eclogite and fine-grained Type-2 eclogite were not coeval: the early coaxial fabrics \((L > S)\) were overprinted by the late simple shear (LS) along the localized shear zones. This feature implies that the variable microstructures of the UHP eclogites were not due to heterogeneous and strongly partitioned deformation—a mechanism proposed by Henry et al. (1993) for the UHP rocks from the Dora–Maira massif, Western Alps, Italy. Thus, the distinct deformation fabrics of the Sulu UHP eclogites should be formed at different periods of tectonic history and most likely at different depths (Fig. 17).

![Fig. 17. Tentative P–T paths for Type-1 and Type-2 eclogites. Type-1 eclogite deformed under the peak metamorphic conditions within the wide subduction shear zone at the greater depth while Type-2 eclogite resulted from reworking of Type-1 eclogite during the exhumation along some localized narrow shear zones.](image-url)
Systematic analyses of seismic focal mechanisms led geophysicists to recognize three tectonic strain regimes along subducting slabs (Isacks and Molnar, 1969, 1971): simple shear at shallow depths (<100 km), down-dip extension at intermediate depths (100–400 km) and down-dip compression at deep upper mantle depths (400–660 km). The boundaries between these regimes correspond approximately to those of phase transformations. At depths greater than 400 km, olivine of the subducting slab is transformed to spinel while clinopyroxene progressively dissolves into the garnet structure and finally eclogite completely transforms to garnetite. Both spinel and garnetite are denser than olivine and eclogite, resultant negative buoyancy causes an additional pulling force on the subducting slab at 100–400 km depth. As the subducting slab is less dense than perovskite-dominant lower mantle below the 660 km discontinuity, the resultant buoyancy will resist against penetration of the slab into the lower mantle. As a result, the subducting slab is subject to down-dip compression at 400–660 km depth. The non-coaxial strain regime is prevailing along the boundary thrust shear zone between the subducting slab and its overlying lithosphere at depth of the slab bend (<100 km). Although eclogitization of crustal rocks such as amphibolite, anorthosite and granulite-facies gneiss can start from a depth of ~40 km, the transformation may not be fully completed until a depth of ~80 km if the materials are relatively dry (e.g., Austrheim, 1987; Andersen et al., 1991).

Type-1 eclogites recorded an apparent constrictional strain which could be driven by a slab-pull mechanism at the depth deeper than the slab bend (~100 km), whereas Type-2 eclogites recorded a plane, non-coaxial strain, predominantly simple shear which could take place a depths shallower than 100 km deep. This also reasonably explains why both garnet and omphacite are coarser in Type-1 eclogites than in Type-2 eclogites and why inclusions of coesite pseudomorphs surrounded by radial fractures are observed in Type-1 eclogites rather than in the recrystallized matrix of Type-2 eclogites. If the above conclusion is correct, Type-2 eclogites might be reworked and recrystallized Type-1 eclogites from shear zones resulted from strain localization during the uplift of the UHP metamorphic rocks, possibly in extension as indicated by the transtension interpretation of omphacite CPOs. It is thus reasonable to assume that Type-1 eclogite was equilibrated above the critical pressure for the quartz/coesite transformation while Type-2 eclogite was equilibrated near or below this pressure. As the deformation temperatures estimated from geothermometric mineral assemblages for both types of eclogites are almost the same (Fig. 11) within the certainties of the geothermometers, the initial uplift of the UHP metamorphic terrane appeared to be nearly isothermal (Okay, 1993; Zhang et al., 1994; Wang and Cong, 1999). The existence of some zoning garnet grains from Type-2 eclogites may indicate depressurization of these rocks. Furthermore, the transition from plane, non-coaxial strain (L−S) to constrictional strain (L ≫ S) within the subducting slab is believed to occur approximately at the depth of the transformation of quartz to coesite (~100 km). This fabric transition depth, which may depend on tectonic setting and geothermal gradient, varies from region to region and may be as shallow as about 40 km depth (e.g., in central European Variscides: Zulauf, 1997; south Norwegian Caledonides: Andersen et al., 1991).

Previous TEM investigations of the bcc garnets (e.g., Voegelé et al., 1998) revealed that the dislocation slip occurs on several planes, {110}, {111}, {112} and {123} but predominantly in the close-packed (111) direction. The (111) dislocations are extensively dissociated into two partials 1/2 (111), between which a stacking fault is produced. An extended screw dislocation cannot cross slip unless the partial dislocations recombine into a perfect dislocation. The greater the width of the stacking fault, the difficult it is to produce constrictions in the stacking fault. An increase in hydrostatic pressure will tend to reduce partial dislocation separation and increase the possibility of cross-slip (Poirier and Vergobbi, 1978; Montardi and Mainprice, 1987). Because recovery and recrystallization are two antagonist (competing) processes, a decrease in hydrostatic pressure due to tectonic exhumation will reduce the ability of dislocations to cross-slip so that the dislocation density rises and recrystallization occurs. This may explain why recovery-accommodated creep is prevalent in garnet from Type-1 eclogites which deformed likely at higher P (≈3.2 GPa), while recrystallization occurs in garnet from Type-2 eclogite which deformed likely at lower (P = 2.8 GPa, Fig. 17).
8.2. Rheological contrast between garnet and omphacite

The studied UHP eclogites are typically two-phase rocks that are mainly composed of garnet and omphacite. Microstructural observations suggested that the eclogites can be plastically deformed and are not as rigid as thought previously. Moreover, plastic flow of eclogites under UHP conditions may effectively facilitate channeled flow within the shear zone between two lithospheric plates. The enhanced counterflow within a wedge-shaped flow channel can force the UHP metamorphic rocks to be rapidly exhumed. The rapid exhumation in turn precludes effective heat transfer from the surrounding mantle to the wedge, rendering a cool thermal structure within the subducted crustal materials (5–10 °C/km, Fig. 17). This makes the subducted crust possible to preserve the mineralogic assemblages and deformation microstructures formed at UHP metamorphic conditions.

Our microstructural observations suggest that the rheological contrast between garnet and omphacite under the UHP conditions is lower than that commonly observed between garnet and clinopyroxene in typical deep crustal rocks such as amphibolite or granulite facies metamorphic rocks (e.g., Ji et al., 1993). Garnet is most likely several times rather than several orders stronger than omphacite in UHP eclogites where both garnet and omphacite plastically deform.

Using a Griggs apparatus, Jin et al. (2001) deformed hot-pressed quartz eclogite (50% garnet, 40% omphacite and 10% quartz), garnet aggregate and omphacite aggregate. They found that “the flow properties of eclogite are very similar to those of peridotite”. However, garnet grains in their deformed samples are extensively fractured rather than flattened, indicating little plastic deformation of garnet. Eclogites from the Sulu UHP metamorphic terrane show remarkable evidence of plastic deformation: well-developed foliation, pronounced stretching lineation and deformation-metamorphism-induced, alternating garnet-and omphacite-rich compositional layers (Fig. 2). Both garnet and omphacite grains are flattened and elongated in the eclogites (Fig. 3). TEM observations of deformed garnets from the UHP eclogites (Figs. 7 and 8) display well-organized dislocations and regularly spaced subgrain boundaries. EBSD measurements demonstrated that garnet developed complex CPOs. Furthermore, recrystallization-induced porphyroclastic texture is observed in Type-2 eclogites (Fig. 6). The above observations indicate that garnet grains in Type-1 and Type-2 eclogites deformed viably by recovery- and recrystallization-accommodated dislocation creep, respectively.

It is well known that the mechanical strength of a material strongly depends on operating deformation mechanisms (e.g., Stöckhert and Renner, 1998; Wang and Ji, 2000). For example, quartz is stronger than feldspar when quartz deforms by dislocation creep while feldspar by microfracturing and cataclastic flow, whereas quartz is weaker than feldspar when both quartz and feldspar deform by dislocation creep (Dell’Angelo and Tullis, 1996). Jin et al. (2001) experiments failed to duplicate the typical microstructures observed optically and with the TEM in naturally deformed UHP eclogites. Deformation mechanisms in their deformed samples are not the same type as those operated in natural UHP eclogites from former subducting slabs. Thus, the mechanical strength data of the eclogite deformed in the non-steady-state semibrittle regime cannot be reliably extrapolated to the UHP eclogites deformed plastically at much lower natural strain-rate and temperature.

The UHP eclogites from the Sulu region contain < 50% SiO₂ (Table 1) and < 1-2% coesite or quartz pseudomorphs as inclusions in strong minerals such as garnet. However, the eclogite specimens studied by Jin et al. (2001) contain of 10 wt.% intergranular quartz. The quartz, which did not enter in the stability field of coesite under their experimental conditions, is the weakest phase in the eclogite samples and takes the much greater part of the strain with reference to its volume fraction. The addition of 10 wt.% quartz into eclogites as intergranular “lubricant” results in considerable weakening. Therefore, the “flow” strength of quartz eclogite, reported by Jin et al. (2001), cannot represent that of bimineralic (garnet and omphacite) eclogites in the subducting slab.

8.3. Geophysical implications

Seismic reflectors have been observed in the upper mantle beneath many areas of the world, for example, the Northwest Territories of Canada (Cook et al., 1999), the Abitibi–Opatica of the Canadian Superior
Province (Calvert et al., 1995) and the north coast of Scotland (Warner and McGeary, 1987; Warner et al., 1996). These mantle reflectors are generally gently dipping and extend from the Moho to at least 110 km depth. The mantle reflectors display the following characteristics: (1) Reflection coefficients (Rc) higher than around 0.1 are needed to cause such reflections within the upper mantle overlaid by the 40-km-thick crust (Warner and McGeary, 1987). (2) Seismic reflectors represent the sharp boundaries (Morgan et al., 1994; Bostock, 1997). (3) Because seismic reflection methods have a vertical and horizontal resolution of about 75 and 3000 m, respectively, at depths of 40 km (assuming average crustal velocities of 6 km/s and a dominant frequency of 20 Hz), each mantle reflector must be considered as a zone composed of layered rocks with high impedance contrast. Such a zone should be regionally extensive, have a thickness of several hundreds meters to several kilometers and have a sharp, well-defined, continuous upper surface.

Several models, as discussed below, have been proposed to interpret the origin of mantle reflections.

(1) Ductile shear zone. The deformed peridotites in a mantle shear zone have developed strong CPOs of olivine and pyroxenes and are thus anisotropic, while the wall rocks are undeformed, have no CPO and therefore isotropic. The boundary between deformed and undeformed rocks can be seismically reflective if the resulting reflection coefficient is large enough (i.e., Rc >0.5–0.10). Previous investigations (e.g., Kern et al., 1996; Ji et al., 1994; Ben Ismaïl and Mainprice, 1998) show that most of peridotites have a CPO-induced P-wave anisotropy <7% with an average value of ~4%. A simple calculation, assuming that both deformed and undeformed peridotites have the same density, can readily demonstrate that the reflection coefficient related to such an anisotropy is generally <0.03. Therefore, the boundary between sheared (anisotropic) peridotites and their undeformed (isotropic) protoliths cannot be a candidate for the observed mantle reflections.

(2) Lithological interfaces between typical mantle rocks. The presence of water-rich fluids may cause the upper mantle partially melted. The melts may crystallize into wehrlite, websterite and pyroxenite, leaving a residue (harzburgite and dunite) from partial melting. Although these lithological units can be interlayered and sufficiently thick (up to several hundred meters), the boundaries between them will have low reflectivity for the following reasons: (a) Dunite and pyroxenite have almost same density although they are different in average P-wave velocity: 8.40 km/s for dunite and 7.94 km/s for pyroxenite (at a confining pressure equivalent to 40 km depth, Christensen and Mooney, 1995). The reflection coefficient between these two rocks is thus <0.04. (b) The wehrlite, websterite and pyroxenite occur commonly as subvertical dykes or veins (Wilshire and Kirby, 1989) which are difficult to be imaged at mantle depths using conventional reflection techniques. (c) Contacts between the lithologic units may not be sharp enough to be seismically reflective. Furthermore, spinel lherzolite and garnet harzburgite have almost the same density, same P-wave velocity and same anisotropy. The reflection coefficient between these two rocks is <0.01. Thus, the transition boundary from spinel to garnet in peridotite should not be as reflective, as suggested by O’Reilly and Griffin (1985).

(3) Transition zone between dislocation and diffusion creep. Dislocation creep is considered to produce CPO and thus anisotropy while neither diffusion nor superplastic process can form CPO and anisotropy (e.g., Karato and Wu, 1993). However, the transition zone between the dislocation and diffusion creep regimes does not cause the strong reflectivity for the following reasons: (a) typical maximum seismic anisotropies formed by dislocation creep in the mantle rocks are ~3–5% (Mainprice and Silver, 1993; Ji et al., 1994; Kern et al., 1996; Ben Ismaïl and Mainprice, 1998; Saruwatari et al., 2001). Even though the assumption that no CPO is formed in the diffusion regime is fully correct, the boundary between the two regimes has a reflection coefficient <0.02. (b) Because the average grain size of olivine is commonly larger than 0.5 mm, as demonstrated by upper mantle xenoliths, dislocation creep should be dominated over a thickness of at least 250–300 km (Ji et al., 1994). The transition zone between dislocation and diffusion creep regimes
should not appear in the depth range of upper mantle reflectors. (c) The transition zone between dislocation and diffusion or superplastic creep regimes may not be sharp enough to produce the interface transition widths \(<200\,\text{m}\) required by the seismic reflection data (Bostock, 1997).

(4) Metasomatized shear zones. Mantle shear zones developed parallel to a subducting slab in the mantle wedge above the subducting slab would provide a favorable conduit for fluids to migrate upwards. Under high temperature and high pressure conditions, the fluids react with rocks, forming seismically slower, less dense hydrated minerals such as phlogopite and amphibole (e.g., Francis, 1976). If the concentration of these hydrated minerals is higher than about 40\% in metasomatized shear zones, the boundary between the metasomatized shear zones and their wall rock has impedance contrasts large enough to be seismic reflective (Warner and McGeeary, 1987; Calvert et al., 1995). Then the metasomatized shear zones should be low velocity zones. However, studies of Morgan et al. (1994), Warner et al. (1996) and Bostock (1997) suggest that the mantle reflectors are most likely the faster and denser layers embedded in the slower and less dense rocks. Moreover, evidence from mantle xenoliths (e.g., Francis, 1976) shows that the concentration of hydrated minerals in metasomatized zones is typically only several percent and much lower than the critical value needed for causing mantle reflections. All the facts described above exclude metasomatized shear zones from the common candidates for the origin of mantle reflectors.

(5) Boundary between eclogite and peridotite. Previous researchers (Morgan et al., 1994; Warner et al., 1996; Calvert et al., 1995) believe that mantle reflectors represent relict fragments of eclogitic oceanic crust embedded within the subducted lithosphere. However, this assumption has not been fully supported by published petrophysical data (Ji et al., 2002). According to Christensen and Mooney (1995), laboratory measurements of 54 mafic eclogite samples at a confining pressure equivalent to 40 km depth yield an average density of 3.51 g/cm\(^3\) and an average P-wave velocity of 8.19 km/s, while measurements of 51 peridotite samples under the same conditions gave an average density of 3.33 and an average V\(_p\) of 8.40 km/s. These average values give a reflection coefficient \(<0.02\) for the boundary between eclogite and peridotite, making it unlikely a candidate for the strong mantle reflectors. Thus, Fountain and Christensen (1989), Gubbins et al. (1994), Hynes and Snyder (1995) concluded that eclogites transformed from mafic rocks are indistinguishable in both densities and velocities from peridotitic upper mantle.

![Fig. 18. Contents of garnet in HP (high pressure) and UHP (ultrahigh pressure) eclogites. Data compiled from Birch (1960), Boundy et al. (1992), Kern and Richter (1981), Kern et al. (1999, 2002), Mauler et al. (2000), Manghnani et al. (1974) and this study. See Ji et al. (2002) for summary.](image)
Eclogites are generally classified into high pressure (HP) and ultrahigh pressure (UHP) ones that are separated by the quartz-coesite equilibrium (e.g., Cong, 1996). The HP and UHP eclogites are also called “cold eclogite” and “hot eclogite” (Chopin et al., 1991), respectively. The UHP eclogites (Kern et al., 1999; Kern et al., 2002; this study) have a higher mean density and a higher mean Vp than the HP eclogites (e.g., Fountain et al., 1994; Mauler et al., 2000) because the first have higher contents of garnet (Fig. 18) and lower contents of quartz, amphibole, zoisite and mica than the latter. Thus, mafic UHP eclogites are believed to be denser and faster in Vp than typical peridotites while HP eclogites have similar densities and velocities as the peridotites.

Field and laboratory studies on lithology, deformation structures and seismic properties of the Dabie–Sulu UHP metamorphic terrane can provide some important hints for understanding the origin of mantle reflections. As stated above, the metamorphic terrane consists of interlayered pelitic and felsic gneisses, quartzite, eclogite, garnet-peridotite and marble. All these rocks contain coesite as inclusions in garnet, omphacite, jadeite and zoisite (Wang et al., 1993; Cong, 1996; Zhang and Liou, 1996; Wang and Cong, 1999). This suggests that all these rocks, which could represent continental shelf limestone, quartzofeldspathic sandstone (grewacke) and mafic volcanoclastic sediments, were subducted into the upper mantle at great depths (>90–100 km) and then tectonically exhumed to the earth’s surface, during the continental collision and post-collision extension. Garnet peridotite, on the other hand, may be from the mantle wedge immediately overriding the subducting slab.

The UHP eclogites are tectonic boudins since they occur as pods, layers and blocks, ranging in size from tens of centimeters to hundreds of meters, within garnet-peridotite, metapelites (garnet-quartz-jadeite gneisses), coesite-bearing quartzite and marble. All the rocks show well-developed foliation, stretching lineation and compositional layering. These foliations or compositional layers are generally subparallel in ultramafic rocks, eclogite layers and country rocks (gneisses, quartzite and marble), indicating that in-situ contact relations between these rocks were not considerably disturbed during tectonic emplacement. When such a package of interlayered crustal materials was once subducted and remains in the upper mantle, a large reflection coefficient (>0.10) should occur at interfaces between UHP eclogite or garnet peridotite and their wall rocks such as quartzite, marble, pelitic and felsic gneisses. Therefore, the regionally extensive mantle reflectors probably indicate the preservation of subducted crustal materials in the lithospheric upper mantle.

9. Conclusions

The major conclusions of this study are listed below.

(1) Eclogites from the Sulu region deformed plastically under the UHP metamorphic conditions and are not rheologically rigid as thought previously. Plasticity of eclogites under UHP conditions may effectively facilitate channeled flow within the interplate shear zone. The enhanced counterflow within a wedge-shaped flow channel may force the subducted crustal rocks to be rapidly exhumed.

(2) Observations of optical microstructures, petrofabrics and TEM structures suggest that the coarse-grained (Type-1) and fine-grained (Type-2) eclogites recorded two distinct plastic deformations: constrictional strain ($L \gg S$) in Type-1 eclogites while plane strain in Type-2 eclogites. Omphacite, which could be only a few times lower in flow strength than garnet, deformed mainly by dislocation creep as demonstrated by the occurrence of CPOs. Plastic deformation of garnet in Type-1 eclogites was dominated by recovery-accommodated dislocation creep as testified by the pervasive presence of dislocation walls and networks, whereas garnet in Type-2 eclogites was deformed by recrystallization-accommodated dislocation creep as indicated by the presence of porphyroclastic texture. As $\langle 111 \rangle$ dislocations are commonly dissociated into two partials $1/2 \langle 111 \rangle$ in bcc garnet (e.g., Voegelé et al., 1998), the cross slip of $\langle 111 \rangle$ dislocations, which is sensitive to the hydrostatic pressure, may be the factor that controls the transition
from recovery-accommodated dislocation creep at higher pressures ($P > \sim 3.2$ GPa) to recrystallization-accommodated dislocation creep at lower pressures ($P < \sim 2.8$ GPa). Thus, Type-1 eclogites represent the subducted mafic rocks deformed at the peak metamorphic conditions while Type-2 eclogites resulted from recrystallization of Type-1 eclogites along some shear zones which were active during the exhumation of the UHP metamorphic rocks.

(3) It is widely accepted that the packages of interlayered eclogite, marble, quartzite, pelitic and felsic gneisses from the Dabie–Sulu belt, which were pieces of the continental crust, were subducted to mantle depths greater than 80–100 km and then tectonically exhumed to the earth’s surface (e.g., Cong, 1996; Liou, 1999; Wang and Cong, 1999). Field and laboratory studies of these UHP metamorphic rocks provided some important hints for understanding the origin of mantle reflections. As long as these interlayered UHP rocks remain within the present upper mantle, the interfaces between eclogite (or peridotite) and their wall rocks such as quartzite, marble, pelitic and felsic gneisses should be strong seismic reflectors. The continuous boundaries between garnet- and omphacite-rich layers or between peridotite and garnet-rich eclogite layers can also be seismically reflective. Thus, the regionally extensive seismic reflectors from the upper mantle may indicate the preservation of relict crustal materials subducted within the continental lithosphere.

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