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Magnetic susceptibility of ultrahigh pressure eclogite: The role of retrogression

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ABSTRACT

Retrograde metamorphism played the dominant role in changing the low-field rock magnetic properties and density of 198 specimens of variably retrograded eclogites from the main borehole of the Chinese Continental Scientific Drilling Project (CCSD) and from surface outcrops in the Donghai area in the southern part of the Sulu UHP belt, China. Bulk magnetic susceptibility (κ) of unretrogressed UHP eclogite is controlled by whole-rock chemical composition and ranges from 397 to 2312 μSI with principal magnetic susceptibility carrying minerals paramagnetic garnet, omphacite, rutile and phengite. Partially retrograded eclogites show large variations in magnetic susceptibility between 804 and 24,277 μSI, with high mean magnetic susceptibility values of 4372 ± 4149 μSI caused by appreciable amounts of Fe-Ti oxide minerals such as magnetite, ilmenite and/or titanohematite produced by retrograde metamorphic reactions. Completely retrograded eclogites have lower susceptibilities of 1094 ± 600 μSI and amphibolite facies mineral assemblages lacking high magnetic susceptibility minerals. Jelínek's corrected anisotropy (P_j) of eclogites ranges from 1.001 to 1.540, and shows a positive correlation with low-field magnetic susceptibility (κ). Arithmetic mean bulk density (ρ) shows a steady decrease from 3.54 ± 0.11 g/cm^3 (fresh eclogite) to 2.98 ± 0.06 g/cm^3 (completely retrograded eclogite). Retrograde metamorphic changes in mineral composition during exhumation appear to be the major factor causing variations in low field magnetic susceptibility and anisotropy. Retrograde processes must be taken into account when interpreting magnetic surveys and geophysical well logs in UHP metamorphic terranes, and petrophysical properties such as density and low-field magnetic susceptibility could provide a means for semi-quantifying the degree of retrogression of eclogite during exhumation.

1. Introduction

Anisotropic magnetic susceptibility (AMS) measured in a low strength magnetic field (comparable to the Earth's field) arises from all the mineral grains in a rock. Each type of mineral has a different bulk susceptibility and different susceptibility anisotropy, and therefore the physical and lithological parameters controlling the magnetic susceptibilities of polyphase rocks under *in situ* conditions include properties of individual crystals and integrated properties of the assemblage of mineral grains. Individual crystal properties include: crystal symmetry, structure, size, shape and characteristics of magnetic domains in ferromagnetic minerals, while bulk properties include the types of minerals present and their relative proportions, grain sizes, shape preferred orientations and crystallographic preferred orientations (CPO). In metamorphic rocks, these are in turn determined by the metamorphism and deformation history of the rock including its P-T-t path, kinematic history, stress/strain history and other tectono-metamorphic processes (Tarling and Hrouda, 1993; Dunlop and Özdemir, 1997; Borradaile and Jackson, 2004). Knowledge of magnetic petrology at depth in the Earth allows us to understand the factors controlling the sources of magnetic susceptibilities and their anisotropies, and thus improve our interpretations of magnetic survey data (Clark et al., 1992; Borradaile and Henry, 1997; McEnroe et al., 2004). Previous studies have shown that prograde or retrograde metamorphism results in significant changes in magnetic properties of pre-existing rocks due to changes in mineral parageneses and microstructures caused by recrystallization in response to changes in temperature, pressure, fluid-rock interaction, and strain (Tarling and Hrouda, 1993; Warner and Wasilewski, 1995; Robion et al., 1997; Oufi and Cannat, 2002). Nakamura and Borradaile (2004) have given a detailed account of metamorphic control of the magnetic

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susceptibilities and magnetic fabrics of greywackes, using bulk magnetic susceptibility (κ) and its anisotropy to distinguish between rocks metamorphosed in greenschist, amphibolite and granulite facies.

Eclogite is a metamorphic rock consisting of garnet and omphacite as the two major minerals. It results from high-pressure metamorphism of mafic igneous rock (typically basalt or gabbro) in subduction zones or from crystallization of basaltic magmas that cooled within the mantle or lower continental crust (Ringwood and Green, 1966). The discovery of coesite (Chopin, 1984; Smith, 1984) and microdiamond (Sobolev and Shatsky, 1990; Xu et al., 1992; Dobrzhinetskaya et al., 1995) in eclogites indicate that crustal rocks underwent ultra-high pressure (UHP) metamorphism at depths greater than 100 km and have returned to the surface in orogenic collision zones. During the exhumation process, typical UHP eclogite experienced retrograde metamorphism due to changes in pressure, temperature, stress and fluid action, giving rise to a variety of retrograde metamorphic textures and assemblages (Zhang et al., 2003; Yang, 2004). Characterization and quantification of such retrogression features provides valuable information for understanding the exhumation of UHP rocks (e.g. Yang, 2004; Yang et al., 2004) and also important constrains on their petrophysical properties (Gao et al., 2001; Jin et al., 2004). It is shown that retrograde metamorphism can result in significant anisotropy and shear wave splitting in eclogites due to the strongly anisotropic retrograde minerals such as amphibole, plagioclase and mica (Wang et al., 2005a, b).

Previous studies have measured the magnetic properties of eclogites and discussed their relationship with magnetic anomalies caused by mid- to lower crustal sources (Wasilewski et al., 1979; Wasilewski and Mayhew, 1992; Florio et al., 1993) and retrograde metamorphism of eclogites and related changes in magnetic petrology and magnetic properties have continued to be subjects of recent research (Xu et al., 2004; Pan and Zhu, 2005; Strada et al., 2006; Liu et al., 2007, 2009). Petrophysical surveys of the Sulu UHP belt suggest that eclogite containing rutile, showing especially high magnetic susceptibility and remanent magnetization, may be the source of regional magnetic anomalies (Yu et al., 2001, 2002). Abalos and Aranguren (1998) have pointed out that the paramagnetic mineral fraction of eclogite (garnet, clinopyroxene, ilmenite and rutile) is the principal magnetic susceptibility carrier in eclogites from Cabo Ortegal, NW Spain, and that the anisotropy of magnetic susceptibility is due to crystallographic preferred orientation and spatial organization of polymineralic aggregates.

To better understand the magnetic behaviors of eclogites as well as effects of retrograde metamorphism, we conducted a systematic study of petrology and magnetic properties of variably retrograded UHP eclogites collected from drill cores from the main hole of the Chinese Continental Scientific Drilling Project (CCSD) and from surface outcrops in the Donghai area in the southern part of the Sulu UHP belt. This paper presents statistical analyses of magnetic susceptibilities and anisotropies of unaltered UHP eclogites compared with eclogites displaying different types and degrees of retrograde metamorphism, and discusses the effects of retrograde metamorphism on the magnetic properties of eclogites in relation to magnetic mineralogy and bulk rock chemical composition. Our results clarify the role of retrogression in causing significant changes of magnetic mineralogy and magnetic properties of eclogites during exhumation.

2. Geological setting

The CCSD main hole is located in the southern part of the Sulu UHP metamorphic belt (N34°25′, E118°40′) about 17 km southwest of Donghai County, Jiangsu Province (Fig. 1a). It is 5158 m deep and more than 85% of the core was recovered. Metamorphic rocks from the CCSD main hole include eclogite, amphibolite, orthogneiss, paragneiss, garnet peridotite, schist and quartzite. Eclogites occur mainly between the depths of 0–1100 m and 1600–2050 m (Fig. 1b) and have a total thickness of about 1200 m. Detailed petrological studies indicate that these eclogites have been subjected to various degrees of retrograde metamorphism and show a considerable variety of retrograde textures, mineral assemblages and compositional variations (Zhang et al., 2006a,b; Tong et al., 2007; Zhu et al., 2007). UHP mineral parageneses indicate peak metamorphic *P–T* conditions of 675–816 °C and 3.1–4.4 GPa (Zhang et al., 2006a). SHRIMP U–Pb dating of zoned zircons from the CCSD main hole gives three discrete groups of ages (Liu et al., 2004): Proterozoic ages for protolith formation, 227 ± 2 Ma for the UHP metamorphic event, and 209 ± 3 Ma for amphibolite facies retrogression.

3. Experimental methods

3.1. Sampling

A total of 198 eclogites were studied, including 29 outcrop samples and 169 drill cores from the CCSD main hole (Fig. 1b). Standard cores in the form of 25 mm diameter cylinders 22 mm long were sawn from each rock specimen in a field laboratory. Most of the eclogites have well-marked macroscopic foliation and lineation and standard cores were orientated relative to structural *X*-, *Y*-, and *Z*-axes with *X* parallel to lineation and *Z* to the pole to the foliation.

3.2. Magnetic properties

Anisotropic magnetic susceptibility (AMS) for each specimen was measured in fifteen positions at room temperature using a HKB-3 Digital Kappabridge susceptometer in an alternating low field strength induced magnetic field in the petrophysical laboratory of the CCSD project. The sensitivity of the HKB-3 susceptibility bridge is about 0.05 μSI and allows reliable AMS directions to be determined down to an anisotropy ratio of 1.002. The second-rank tensor of the AMS is represented by an ellipsoid with three orthogonal principal susceptibility axes labeled $\kappa_{max} \geq \kappa_{int} \geq \kappa_{min}$. Bulk magnetic susceptibility (κ) for a single sample is given as $\kappa = (\kappa_{max} + \kappa_{int} + \kappa_{min})/3$ in μSI units. Logarithmic parameters of the corrected anisotropy degree (P_j) and the shape parameter (T_j) are defined according to Jelínek (1981).

Temperature dependence of the magnetic susceptibility was measured in an argon atmosphere using a KLY-3 Kappabridge equipped with a CS-3 high-temperature furnace (AGICO Ltd., Brno) at the paleomagnetism laboratory in the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Measurements of susceptibility were made at a rate of about 9.5 °C/min from room temperature up to maximum temperature of 700 °C, and then back to room temperature.

3.3. Density

Bulk densities (ρ) of the eclogites were measured on the standard samples with a volume of about 11.5 cm^3 using a LP1002 densimeter under ambient conditions by an Archimedes method with a relative error of ± 0.03%.

3.4. Rock and mineral chemistry

Petrochemical data for core samples collected at 1–4 m intervals from 100 to 2050 m of the CCSD main hole have previously been reported by Zhang et al. (2006a), who kindly supplied 127 whole rock major element analyses of rocks with the same drill core numbers as our magnetic samples, from which we have quoted FeO^T, SiO_2 and TiO_2 contents. Mineral analyses were carried out using a JEOL superprobe 733 fitted with a wavelength dispersive system at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan. The experimental conditions were 15 kV accelerating energy,

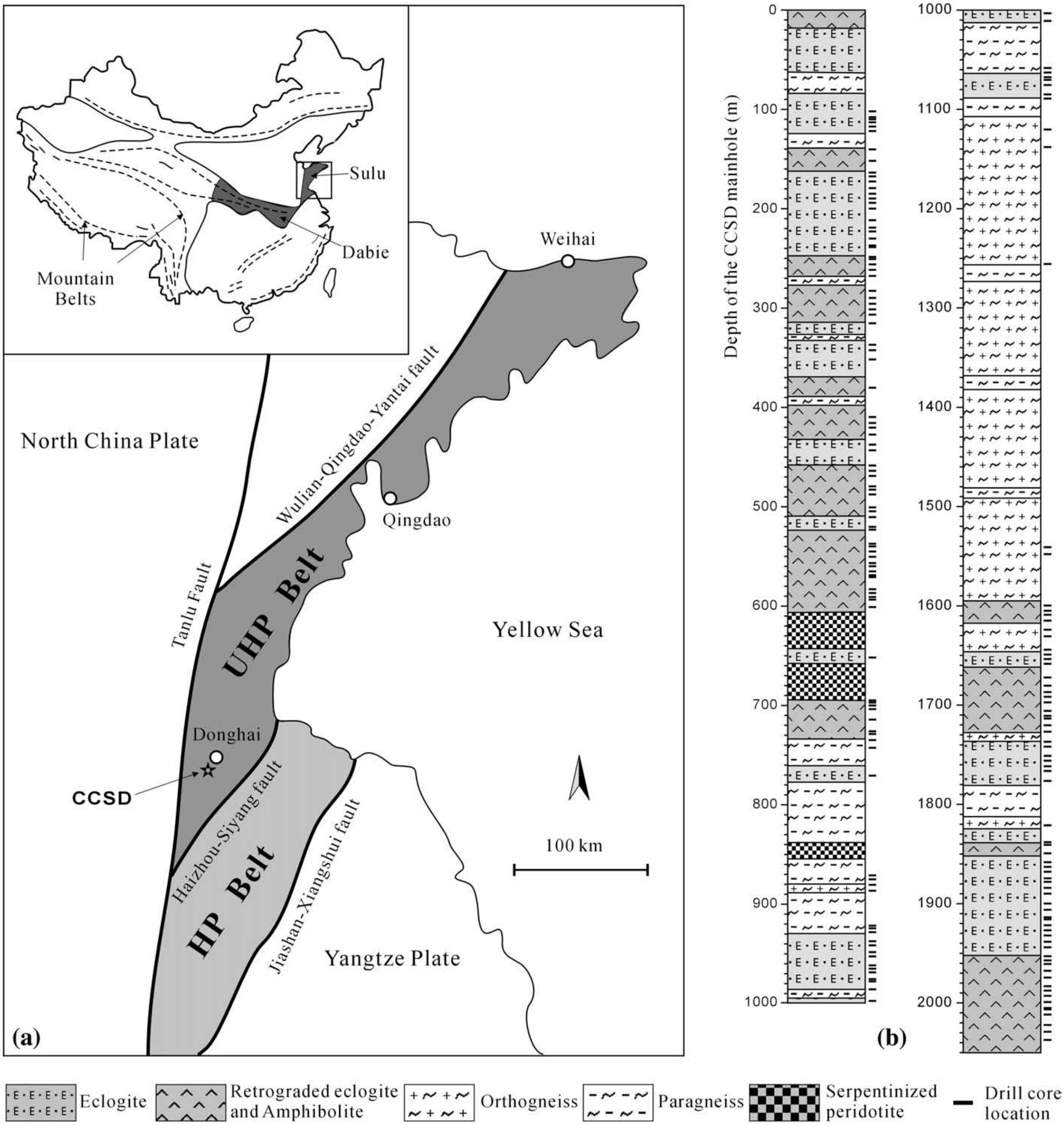


Fig. 1. (a) Simplified map showing UHP and HP units of the Sulu terrane and location of the CCSD drill site (modified after Zhang et al., 1995). (b) Lithological log of the CCSD main hole (0–2050 m), showing recovery depths of drill cores (black bars).

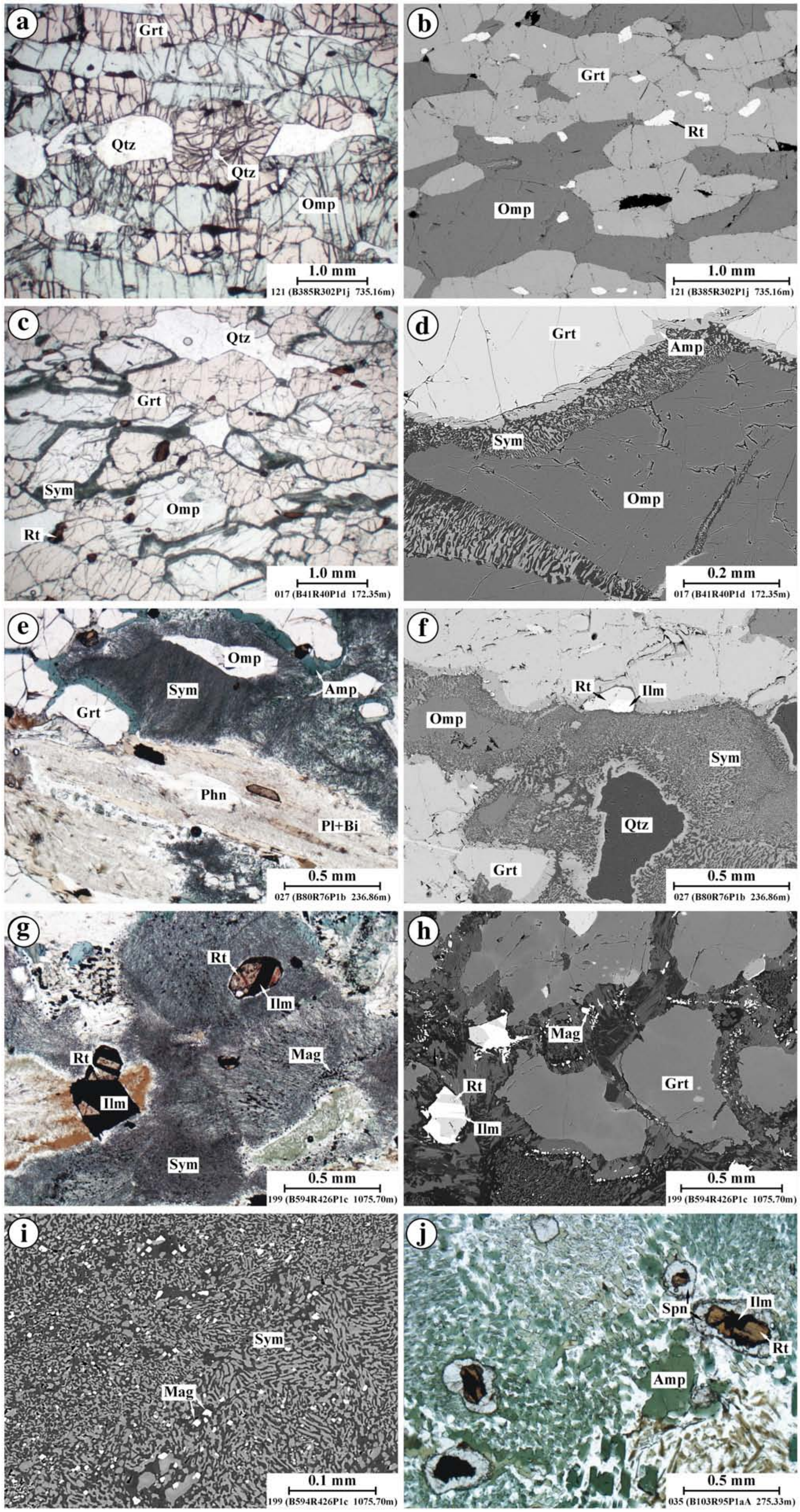
20 nA beam current and a typical beam diameter of 1 μm. Counting times of 30 s per element were used. Analytical precision is estimated at ±0.1 wt.% for oxide components present at the 1 wt.% level.

3.5. Optical and electron microscope images

In order to characterize the mineral assemblages and textures of unaltered eclogites and variably retrograded eclogites, optical studies were undertaken on polished thin sections from each sample. Following optical studies, representative samples were selected for scanning electron microscope (SEM) analysis at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan. SEM backscatter electron images and energy dispersive spectrometer (EDS) semi-quantitative determinations of opaque minerals were performed using an FEI Quanta 200 environmental scanning electron microscope (tungsten filament) with an EDAX 2000 X-ray energy dispersive system operating at 20 kV.

4. Petrography

Eclogites are widespread in the Donghai area but constitute a minor volume of the rock mass. Coesite and other UHP minerals occur


a
Grt
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1.0 mm
121 (B385R302P1j 735.16m)
b
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Rt
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121 (B385R302P1j 735.16m)
c
Qtz
Grt
Sym
Omp
Rt
1.0 mm
017 (B41R40P1d 172.35m)
d
Grt
Amp
Sym
Omp
0.2 mm
017 (B41R40P1d 172.35m)
e
Omp
Sym
Amp
Grt
Phn
Pl+Bi
0.5 mm
027 (B80R76P1b 236.86m)
f
Rt
Ilm
Omp
Sym
Qtz
Grt
0.5 mm
027 (B80R76P1b 236.86m)
g
Rt
Ilm
Mag
Rt
Ilm
Sym
0.5 mm
199 (B594R426P1c 1075.70m)
h
Mag
Rt
Ilm
Grt
0.5 mm
199 (B594R426P1c 1075.70m)
i
Sym
Mag
0.1 mm
199 (B594R426P1c 1075.70m)
j
Ilm
Spn
Rt
Amp
0.5 mm
035 (B103R95P1aA 275.33m)

Table 1
Bulk density (ρ), low field magnetic susceptibility (κ) and corrected anisotropy degree (P_j) of fresh eclogites and variably retrograded eclogites.

	samples	ρ (g/cm^3)			κ (μSI)			P_j		
		Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Fresh eclogite	30	3.35	3.75	3.54 ± 0.11	397	2312	1031 ± 493	1.001	1.257	1.023 ± 0.048
Coronal symplectite bearing eclogite	24	3.27	3.68	3.44 ± 0.11	570	1450	962 ± 209	1.002	1.208	1.049 ± 0.052
Partially retrograded eclogite	87	2.90	3.59	3.22 ± 0.17	804	24277	4372 ± 4149	1.033	1.540	1.216 ± 0.118
Completely retrograded eclogite	57	2.82	3.09	2.98 ± 0.06	461	3675	1094 ± 600	1.007	1.479	1.102 ± 0.096

as inclusions in garnet, omphacite and zircon of eclogites from outcrops and drill holes, indicating that all the eclogites in this area were subjected to UHP metamorphism *in situ* and returned back to the surface (e.g. Zhang et al., 2006a). A few eclogites are fresh and have unaltered UHP parageneses but most have experienced multistage retrograde metamorphism. Some eclogite samples have been completely transformed to amphibolite by extensive amphibolite and greenschist facies retrograde metamorphism (Yang et al., 2003; Yang, 2004).

Fresh eclogites contain major garnet and omphacite and may also contain minor rutile, phengite, kyanite, apatite, zircon, epidote, coesite and quartz. All the minerals in the standard samples crystallized together as equilibrium metamorphic parageneses under peak UHP conditions and therefore the mineral assemblages and modal contents of fresh eclogites are related to whole-rock chemical compositions by the Phase Rule. For example, rutile and rutile-rich eclogites have high modal contents of rutile (4–10%) coupled with high contents of TiO_2 (2.4–5.9%) and total FeO^T (10.9–25.3%) (Zhang et al., 2006b). The eclogites only returned to whole-rock equilibrium and developed metamorphic parageneses that obey the Phase Rule during retrograde amphibolite facies metamorphism seen in completely retrograded eclogites. Between these two end states, the extent of retrogression is extremely heterogeneous on the scales of outcrop and thin section, and differs from mineral to mineral (Zhang et al., 2003). Different metamorphic reactions occurred sequentially between the two equilibrium stages and none went to completion, so partially retrograde eclogites contain a variety of minerals and microstructures that reflect disequilibrium, although small equilibrium domains are possible.

In order to document the relationship between retrogression and rock magnetic properties of eclogites, we collected 198 samples representing a continuum from fresh eclogites through variably retrograded eclogites to amphibolite. We subdivided the eclogites into four categories: fresh eclogite, coronal symplectite bearing eclogite, partially retrograded eclogite and completely retrograded eclogite (i.e. amphibolite). Mineral abbreviations follow Kretz (1983) except Amp = amphibole, Coe = coesite, Phn = phengite and Sym = symplectite.

4.1. Fresh eclogite

Fresh eclogites are generally medium- to fine-grained, pinkish to green rocks of granoblastic texture. Some samples show foliation and lineation marked by shape elongation of omphacite and garnet (Fig. 2a). Rutile generally occurs as an intergranular matrix mineral or as inclusions in garnet and omphacite (Fig. 2b). In some samples, inclusions of coesite and polycrystalline quartz pseudomorphs after coesite are indicated by radiating decompression cracks.

4.2. Coronal symplectite bearing eclogite

Compared with fresh eclogites, coronal symplectite bearing eclogites have ubiquitous narrow rims of symplectite of amphibole and plagioclase with characteristic network symplectite intergrowths along grain boundaries or fractures in omphacite (Fig. 2c). Most garnet grains do not show signs of retrograde metamorphic reactions but a few crystals in contact with symplectite round omphacite are rimmed by thin coronal symplectite of pargasite and minor magnetite (Fig. 2d). Rutile and phengite are unaltered.

4.3. Partially retrograded eclogite

This type of eclogite represents an intermediate stage between coronal symplectite bearing eclogite and completely retrograded eclogite. Eclogites still contain relics of garnet, omphacite, phengite and rutile from the peak UHP paragenesis but they also contain pervasive symplectites after omphacite and phengite that formed successively during retrogression. They show more complex retrograde textures than coronal symplectite bearing eclogites, with secondary symplectitic mineral assemblages of amphibole, plagioclase, quartz, biotite and ilmenite. Relics of omphacite are enclosed by symplectite of amphibole and plagioclase. Phengite is usually replaced by symplectite of biotite and plagioclase (Fig. 2e). Most rutile grains, including intergranular grains and some inclusions in primary garnet and omphacite, have been replaced by secondary ilmenite (Fig. 2g). Garnet grains are extensively replaced by symplectite of amphibole, plagioclase and small magnetite crystals (Fig. 2f, h). Note the large numbers of anhedral to subhedral equigranular small magnetites in symplectite after garnet (Fig. 2i).

4.4. Completely retrograded eclogite (amphibolite)

Completely retrograded eclogites contain amphibolite facies mineral assemblages of amphibole, plagioclase, quartz, zoisite, biotite, sphene and epidote that can be described as amphibolite. The peak UHP metamorphic minerals are almost completely replaced by low pressure mineral assemblages due to extensive amphibolite- and greenschist-facies retrogression although symplectitic pseudomorphs after omphacite, garnet and phengite can still be recognized. Rutile-ilmenite grains are replaced by sphene, with or without relics of rutile-ilmenite in the cores (Fig. 2j).

Fig. 2. Microphotographs and back-scattered electron (BSE) images showing mineral parageneses and textures of eclogites from the CCSD main hole. Sample number, drill core label (BxxxRyyyPzz) and recovery depth of each sample are listed below the scale bar. (a) Fresh eclogite with garnet, omphacite, quartz, rutile and polycrystalline quartz pseudomorphs after coesite in garnet indicated by radiating decompression fractures. Plane polarized light (PPL). (b) Rutile as an intergranular matrix mineral or inclusions in garnet and omphacite. BSE. (c) Eclogite with narrow symplectitic coronas rimming omphacite. PPL. (d) Enlarged view of symplectites. BSE. (e) Eclogite with extensive symplectitic coronas surrounding omphacite and phengite. PPL. (f) Eclogite with narrow coronas of amphibole and magnetite around garnet. Rutile partially replaced by ilmenite, resulting in irregular intergrowths of ilmenite and rutile. (g) Strongly retrograded eclogite with nearly all omphacite replaced by symplectites of amphibole and plagioclase, and rutile relics containing secondary ilmenite. PPL. (h) Strongly retrograded eclogite with small magnetite grains surrounding garnet relics. Most rutile has been replaced by ilmenite. BSE. (i) Symplectite after garnet with equigranular magnetites scattered in the matrix. BSE. (j) Completely retrograded eclogite showing an amphibolite facies metamorphic paragneiss of amphibole, plagioclase, quartz, biotite and epidote with some relict symplectitic pseudomorphs after omphacite, garnet and phengite. Note relics of rutile and ilmenite enclosed by sphene. PPL.

5. Results

5.1. Density

Specimens of variably retrograded eclogites show strong variations in density scattering between 2.82 and 3.75 g/cm^3. Values of bulk density (ρ) for different retrograded eclogites classed according to petrological characters are listed in Table 1. Although each type of retrograded eclogite shows a relative wide range of density, there is a clear tendency for mean density to decrease with increasing retrogression from fresh eclogite ($\rho = 3.54 \pm 0.11$ g/cm^3) through partially retrograded eclogite ($\rho = 3.22 \pm 0.17$ g/cm^3) to completely retrograded eclogite ($\rho = 2.98 \pm 0.06$ g/cm^3). The large variations of bulk density of fresh eclogites reflect their different chemical compositions (Zhang et al., 2006a) and possibly heterogeneous distribution of rock-forming minerals. The significant difference in mean density between fresh eclogites and variably retrograded eclogites indicates that retrogression during exhumation had a profound effect in decreasing rock density, even allowing for different rock chemistry.

5.2. Magnetic susceptibility magnitudes

Table 1 gives statistical results of bulk susceptibility (κ) of the eclogites. Magnetic susceptibility ranges from 397 to 2312 μSI (average 1031 ± 493 μSI) in 30 specimens of fresh eclogite. This result agrees well with published data of eclogite from Maobei area in the southern part of the Sulu UHP belt (Yu et al., 2002) and is close to but a little higher than bulk magnetic susceptibility of the Cabo Ortegal eclogite (Abalos and Aranguren, 1998). Coronal symplectite bearing eclogite and completely retrograded eclogite show similar low arithmetic mean values of magnetic susceptibility of 962 ± 209 μSI and 1094 ± 600 μSI respectively. In contrast, partially retrograded eclogite shows a wider range of magnetic susceptibility between 804 and 24277 μSI and a significantly higher average of 4372 ± 4149 μSI.

Frequency distributions of logarithmic magnetic susceptibility (logκ) for fresh eclogites, variably retrograded eclogites and total specimens are shown in Fig. 3a and show that the logarithmic magnetic susceptibility of all specimens displays multi-modal frequency distributions. The asymmetrical highest peak of the histogram represents the most frequent low magnetic susceptibilities of fresh eclogite, coronal symplectite bearing eclogite and completely retrograded eclogite. In contrast, the logarithmic magnetic susceptibility distribution of partially retrograded eclogite is shifted to higher values. The most likely explanation for the high magnetic susceptibility of partially retrograded eclogite is that a considerable amount of high magnetic susceptibility minerals such as magnetite and ilmenite formed during retrograde metamorphism of UHP eclogites, to be explained in next section.

In a cross-plot of bulk magnetic susceptibility (κ) as a function of density (ρ), we subgrouped the specimens into three (Fig. 3b): (1) fresh- and coronal symplectite bearing eclogite has high density and low magnetic susceptibility; (2) partially retrograded eclogite has higher magnetic susceptibility and lower density; and (3) completely retrograded eclogite has the lowest density and low magnetic susceptibility. Magnetic susceptibility and density might be used as proxies for the degree of retrogression of eclogite.

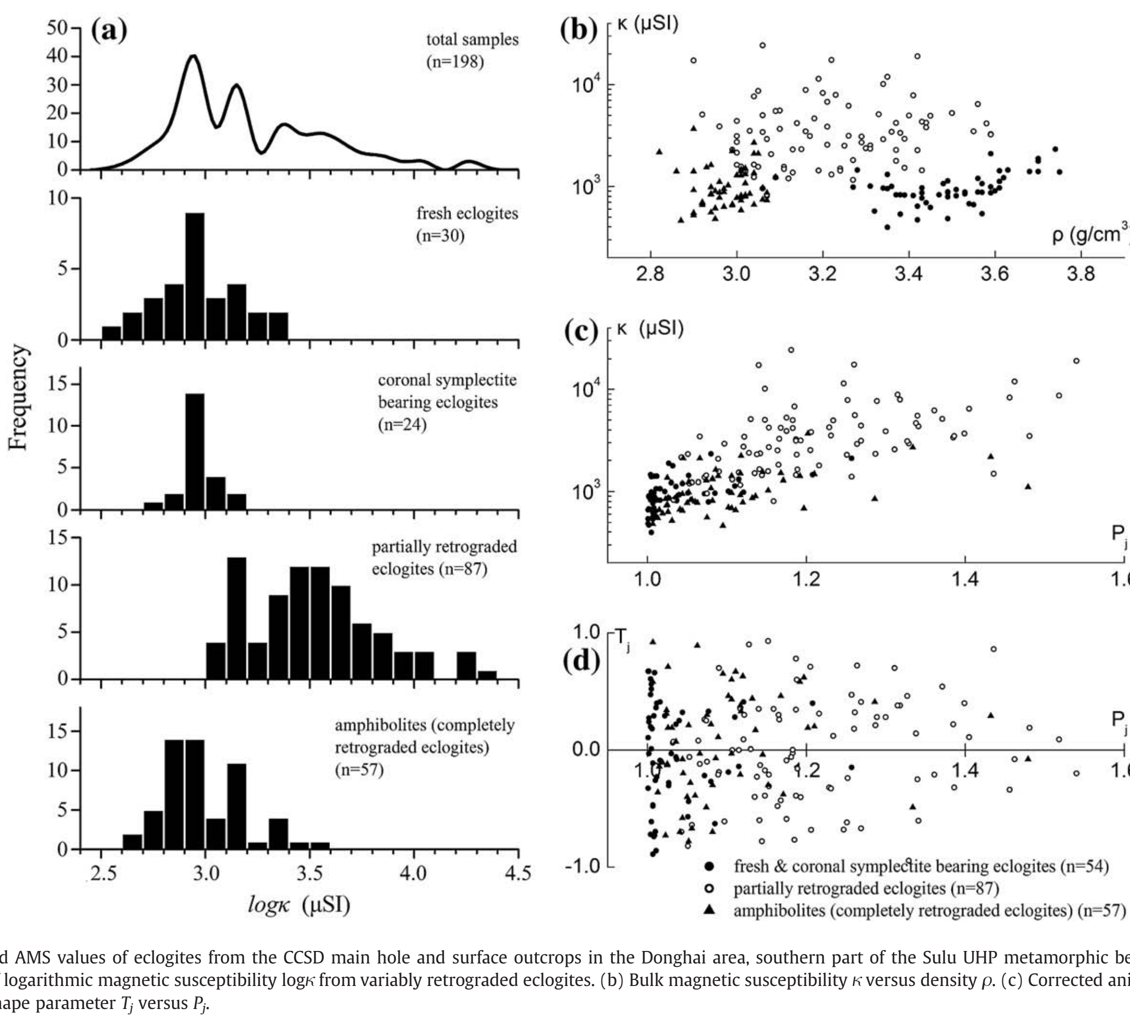

Fig. 3. Low field AMS values of eclogites from the CCSD main hole and surface outcrops in the Donghai area, southern part of the Sulu UHP metamorphic belt. (a) Frequency distributions of logarithmic magnetic susceptibility logκ from variably retrograded eclogites. (b) Bulk magnetic susceptibility κ versus density ρ. (c) Corrected anisotropy degree P_j versus κ. (d) Shape parameter T_j versus P_j.

5.3. Anisotropy of magnetic susceptibility

Corrected Jelínek anisotropy values (P_j) of low field magnetic susceptibility range from 1.001 to 1.540, and their arithmetic mean shows almost the same change as bulk magnetic susceptibility with retrogression of eclogite (Table 1). Fresh eclogite and coronal symplectite bearing eclogite have relatively low P_j of 1.023 ± 0.048 and 1.049 ± 0.052, respectively. In 57 samples of completely retrograded eclogite, P_j shows a wide range of 1.007–1.479 with a moderate average of 1.102 ± 0.096 while partially retrograded eclogite shows relatively higher P_j of 1.216 ± 0.118. There is a clear positive correlation between magnetic susceptibility κ and anisotropy degree P_j, probably indicating control of rock composition on magnetic anisotropy of eclogite (Fig. 3c). Each type of retrograded eclogite shows a wide range of P_j, which can be interpreted by different crystallographic preferred orientations (CPO) and shape preferred orientations (SPO) of polymineralic aggregates resulting from complex retrograde metamorphic processes during exhumation (Abalos and Aranguren, 1998; Borradaile and Jackson, 2004).

Jelínek plots of corrected anisotropy (P_j) versus shape parameter (T_j) for fresh eclogite and variably retrograded eclogite are shown in Fig. 3d. Each type of eclogite shows a scattered distribution, ranging from prolate ($-1<T_j<0$) through neutral ($T_j=0$) to oblate ($0<T_j<1$) with no distinct preferred tendency. There is no consistent correlation between corrected anisotropy degree (P_j) and shape parameter (T_j), suggesting complex deformation regimes during retrogression of eclogite.

5.4. Temperature dependence of susceptibility

Temperature dependence of low field magnetic susceptibility displayed on thermomagnetic curves is sensitive to subtle changes of magnetic minerals during thermal treatment, and thus provides useful information about magnetic susceptibility behavior versus temperature and also for identification of magnetic mineralogy (Dunlop and Özdemir, 1997). All the samples show irreversible thermomagnetic curves during cooling, indicating that new magnetic phases formed during heating. Fig. 4 shows typical heating and cooling thermomagnetic curves of UHP eclogites in argon atmosphere. The values, calibrated against measurements on an empty furnace, are normalized by initial susceptibility. The heating curve of fresh eclogite MB6A ($\kappa = 1445$ μSI) shows a paramagnetic hyperbola between room temperature and the maximum temperature around 700 °C, whereas the cooling curve shows a conspicuous increase in susceptibility below 520 °C with much higher susceptibility, probably indicating the creation of new titanium-bearing magnetic minerals (Fig. 4a). This strongly suggests that it is the paramagnetic fraction that controls the room temperature susceptibility of fresh eclogite. The heating curve of strongly retrograded eclogite JC4A ($\kappa = 7828$ μSI) shows a λ-shaped peak around 270 °C and a distinct Hopkinson-type peak in the vicinity of 580 °C (the Curie point of magnetite), while the cooling curve with much higher susceptibility is relatively constant below 500 °C (Fig. 4b). The disappearance of such a distinct λ-shaped peak in the heating curve around 270 °C during cooling may probably be interpreted as new formation of magnetite from primary ilmenite or titanohematite during heating. This thermomagnetic susceptibility behavior indicates that the dominant magnetic carriers of strongly retrograded eclogite are magnetite and ilmenite-titanohematite, consistent with our petrological analyses (Fig. 2g, h, i) and previous studies (Pan and Zhu, 2005; Liu et al., 2007).

6. Discussion

6.1. Relationship between mineral composition and magnetic susceptibility of eclogite

Eclogites from the Dabie and Sulu terranes are mainly of basaltic or gabbroic compositions, but show a wide range of major (e.g. SiO_2 36 to 60%) and trace element abundances which suggest that they originated from different types of protoliths (Jahn et al., 2003). Recent petrological and geochemical studies have shown that the eclogites from the CCSD main hole probably originated from metamorphosed mafic intrusives, and can be subdivided into quartz-rich eclogite, rutile- and/or ilmenite-rich eclogite, phengite and/or kyanite-rich eclogite, MgO-rich eclogite and normal eclogite. These types of eclogites show distinct differences in whole-rock chemical compositions, mineral compositions and mineral modal abundances (Zhang et al., 2006a). To understand the influence of chemical composition on the magnetic susceptibility of eclogite, we analyzed the relationships between logarithmic bulk magnetic susceptibility logκ and the major oxides FeO^T, TiO_2 and SiO_2 of UHP eclogites from the CCSD main hole (Fig. 5).

In 35 specimens, fresh and coronal symplectite bearing eclogites show large variations in SiO_2 (38.20–52.86%), TiO_2 (0.62–4.88%), and total FeO^T (8.28–22.93%). Clear positive correlations can be seen between logκ and whole-rock FeO^T and TiO_2 composition and a clear negative correlation between logκ and SiO_2 (Fig. 5a) indicating that the mean low field susceptibilities of fresh- and coronal symplectite

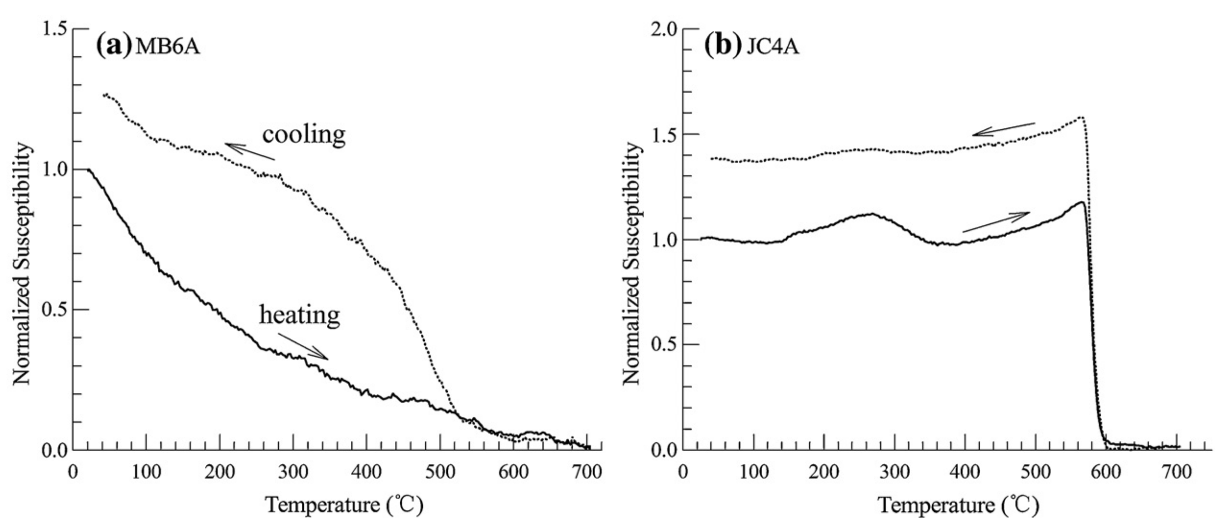

Fig. 4. Normalized thermomagnetic curves in argon, calibrated against an empty furnace: (a) fresh eclogite MB6A; (b) strongly retrograded eclogite JC4A. Heating curves, solid lines; cooling curves, dashed.

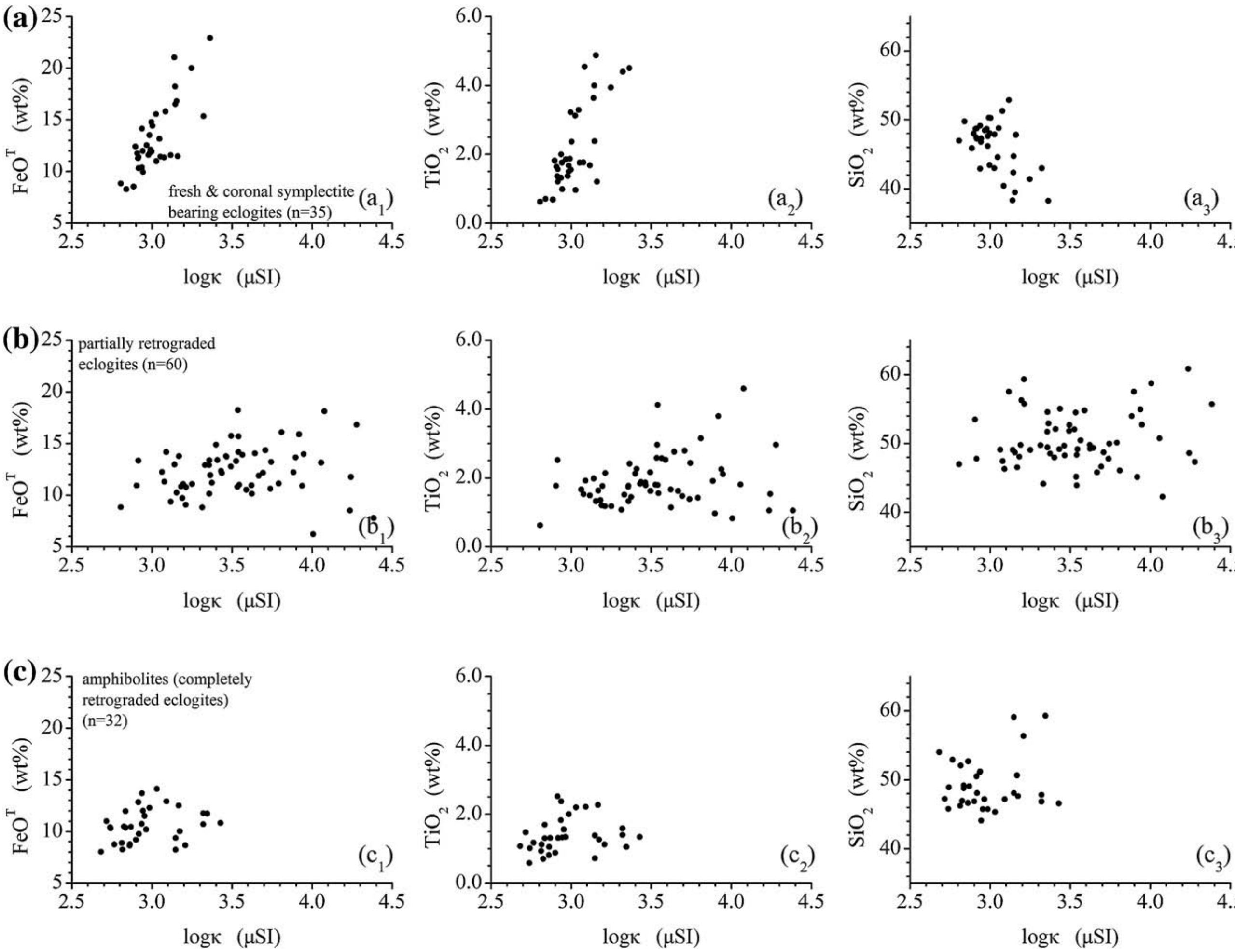

Fig. 5. Major oxides FeO^T, TiO_2 and SiO_2 versus logarithmic bulk magnetic susceptibility (logκ) of eclogites from the CCSD main hole: (a) fresh & coronal symplectite-bearing eclogites, 35 samples; (b) partially retrograded eclogites, 60 samples; (c) amphibolites (completely retrograded eclogites), 32 samples.

bearing eclogites are mostly controlled by whole-rock chemical composition. Further retrogression obscures these relationships. In Fig. 5b, partially retrograded eclogites show scattered distributions, suggesting that retrogression has brought about a profound change in magnetic susceptibility. Completely retrograded eclogites show relatively lower contents of FeO^T (8.01–14.12%) and TiO_2 (0.58–2.52%), which probably indicate that such eclogites experienced local mass balance exchanges during the pervasive amphibolite facies retrogression (Zhang et al., 2003; Yang et al., 2003; Yang, 2004). There are no consistent correlations between chemical compositions (FeO^T, TiO_2 and SiO_2) and magnetic susceptibilities of completely retrograded eclogites and so we argue that whole-rock composition is a key factor controlling the low field magnetic susceptibility of fresh eclogite while retrogression was the dominant control on the rock magnetic properties of retrograded eclogite and masks the effects of bulk rock chemical composition.

6.2. Magnetic mineralogy and the extent of retrogression of eclogite

The low field magnetic susceptibility and its anisotropy of the eclogites were measured in standard cylindrical specimens of ca. 11.5 cm^3 and represent the integrated magnetic properties of all the ferromagnetic, paramagnetic and diamagnetic minerals scattered throughout the samples (Tarling and Hrouda, 1993). If high susceptibility accessory minerals such as magnetite and ilmenite are present they will dominate a rock's magnetic properties (Borradaile and Henry, 1997) and susceptibility due to diamagnetism is entirely swamped by ferromagnetic and paramagnetic susceptibilities. Because the UHP eclogites have experienced different degrees of retrograde metamorphism during exhumation to the surface and show a variety of retrograde textures, mineral assemblages and compositional variations (e.g. Yang, 2004) we need to know the types of mineral present, their relative proportions, their types of magnetic response, microstructures and anisotropies in order to interpret large changes of low field magnetic susceptibility. Table 2 gives selected density (ρ), low field magnetic susceptibility (κ) and anisotropy (P_j) values for common eclogite minerals. From SEM, quantitative SEM-EDS and electron microprobe analyses we can make some generalizations about the main magnetic minerals and their relationships with retrogression.

Garnets and omphacites from eclogites have compositional ranges related to host rock compositions, their FeO contents show positive correlations with whole rock compositions (Zhang et al., 2006a) and they have wide ranges of densities and magnetic susceptibilities (Table 2). We suggest that fractions of the paramagnetic minerals garnet and omphacite, and to a lesser extent rutile, phengite and the rest are the principal magnetic susceptibility controls in fresh eclogites and we are not surprised to see positive relationships between low field magnetic susceptibility (κ) and whole-rock chemical compositions (Fig. 5a).

Partially retrograded eclogites show higher magnetic susceptibilities and anisotropies than fresh eclogite (Table 1, Fig. 3), indicating

Table 2
Selected density (ρ), low field magnetic susceptibility (κ) and anisotropy degree (P_j) data for common eclogite rock-forming minerals.

Mineral	ρ (g/cm^3)	κ (μSI)	P_j	Source
Garnet	3.56–4.25	502–6780	1.001	A, Ba, Bo, H
Pyroxene	3.29–3.42	25–2783	1.2–2.08	A, Ba
Muscovite	2.84	110–140	1.27–1.49	Bo
Biotite	3.00	1042–2900	1.34–1.38	Bo, H
Amphibole	3.12–3.15	490–8920	1.08–1.66	A, Ba
Quartz	2.65	−13 to −17	1.01	Bo, H
Plagioclase	2.54–2.58	−13 to −17	<1.01	Ba, Bo, H
Rutile	4.26	26.3	1.07	A
Ilmenite	4.72	2200–3,800,000	15	A,H
Sphene	3.52	264	–	A
Magnetite	5.18	1,000,000–5,700,000	1.18	A, H

A = (Abalos and Aranguren, 1998); Ba = (Bass, 1995); Bo = (Borradaile and Jackson, 2004); H = (Hunt et al., 1995).

that high susceptibility magnetic minerals appeared during retrograde metamorphism. Previous studies found that such minerals are mainly pseudo-single domain (PSD) and multidomain (MD) magnetite, monoclinic pyrrhotite, titanomagnetite and ilmenite (Pan and Zhu, 2005; Strada et al., 2006; Liu et al., 2007). Our research confirms these findings, but demonstrates that Fe–Ti oxide minerals formed by a variety of retrograde metamorphic reactions and that their modal contents are to some extent related to whole-rock chemical compositions. The most abundant Fe–Ti oxides are described by four compositional end members: magnetite, ulvöspinel, ilmenite and hematite, distinguished by their FeO–Fe_2O_3–TiO_2 ratios. There are two solid solution series: tititanomagnetite between magnetite and ulvöspinel, and titanohematite between ilmenite and hematite. The main Fe–Ti oxides identified in our study are rutile, ilmenite, hematite–ilmenite series and magnetite (Fig. 6). Rutile generally occurs as an intergranular matrix mineral or as inclusions in garnet and omphacite. In rutile eclogites and rutile-rich eclogites, the modal content of rutile can reach 4–10%. During retrogression, primary UHP rutile is transformed successively to ilmenite–titanohematite and finally to sphene in the completely retrograde metamorphic stage (Fig. 2). Small magnetite crystals enclosing garnet relics or scattered in symplectite, mainly appeared as retrograde metamorphic oxidation products of garnet and omphacite. The modal content of secondary magnetite reaches its highest value at the partially retrograde eclogite stage, but decreases significantly or even disappears at the completely retrograde stage. A likely explanation for the decrease of magnetite is that the later amphibolite-facies retrogression was caused by fluid infiltration resulting in significant mass transfer and mass balance changes between amphibolite-facies minerals (Yang et al., 2003). We suggest that the high magnetic susceptibilities and anisotropies of partially retrograded eclogites are mainly caused by the symplectitic minerals magnetite and ilmenite.

Completely retrograded eclogite can be regarded as amphibolite and shows typical amphibolite mineral assemblages of amphibole, plagioclase, quartz, zoisite, biotite, sphene and epidote. Detailed investigations by optical microscopy and SEM show that this type of eclogite only contains rutile-ilmenite relics in the cores of sphene (Fig. 2j) and very little magnetite. Thus the low magnetic susceptibility ($\kappa = 1094 \pm 600$ μSI) and anisotropy ($P_j = 1.102 \pm 0.096$) must mainly be attributed to the amphibolite minerals epidote, zoisite, biotite and relict ilmenite.

Many researchers have investigated retrograde metamorphic processes in eclogites and their relationships with the petrology, chemistry and physical properties of the retrograded rocks (Straume and Austrheim, 1999; Zhang et al., 2003; Yang et al., 2003; Yang, 2004; Zhang et al., 2006a; Tong et al., 2007). Combining the results of these authors with ours, we suggest that varying contents of the high magnetic susceptibility minerals magnetite and ilmenite produced by symplectite forming reactions during retrograde metamorphism account for most of the profound changes of magnetic properties of eclogites during retrogression (Fig. 7a).

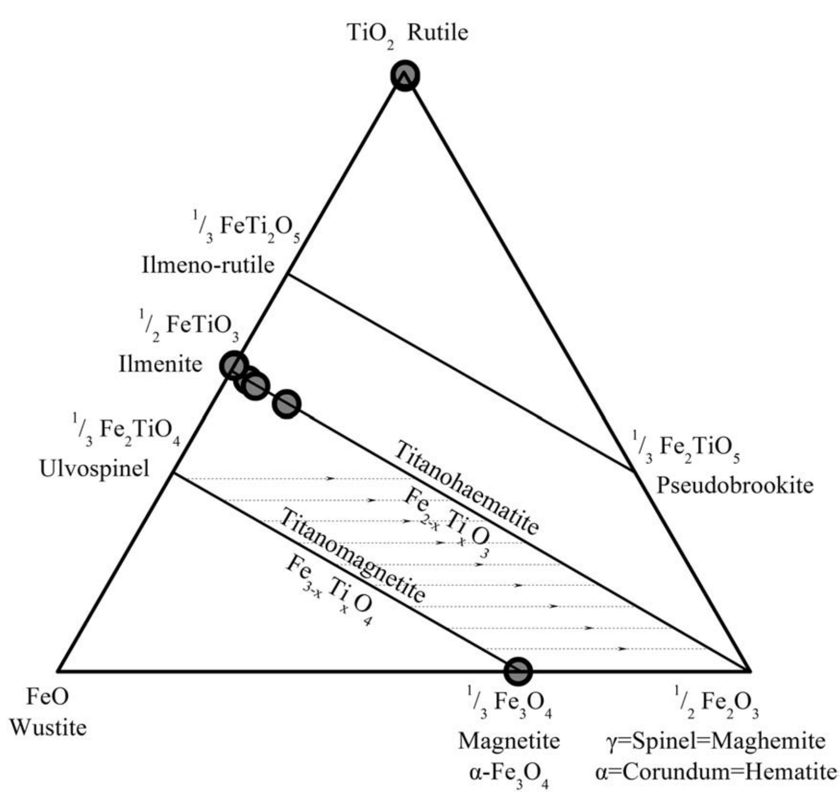

Fig. 6. Ternary FeO–Fe_2O_3–TiO_2 diagram showing compositions of Fe–Ti oxide minerals in eclogites from the CCSD main hole.

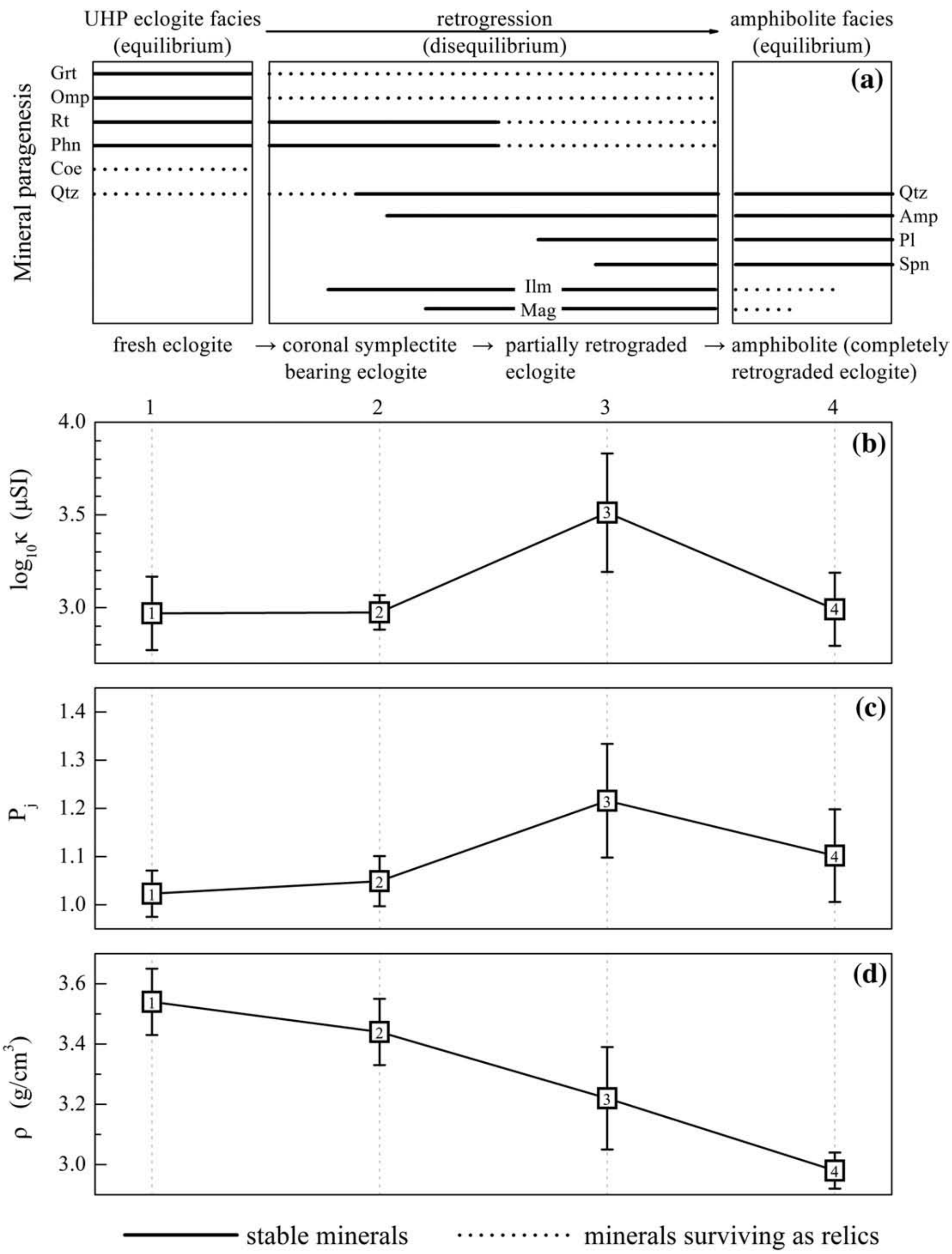

Fig. 7. (a) Summary of retrograde metamorphic evolution of minerals in eclogites; (b) evolution of logarithmic bulk magnetic susceptibility logκ; (c) corrected anisotropy P_j; (d) bulk density ρ; b,c,d, time scale as in a. Samples as in Fig. 3, error bars 1 SD.

6.3. Evolution of density, magnetic susceptibility and anisotropy with mineralogy during retrograde metamorphism of eclogite

Fig. 7 shows the evolutions of bulk density (ρ), logarithmic low field magnetic susceptibility (logκ) and corrected anisotropy degree (P_j) with mineral paragenesis during retrogression of UHP eclogites from the CCSD main hole and its adjacent area. The logarithmic magnetic susceptibility (logκ) of these eclogites does not increase linearly with the degree of retrogression. Instead, logκ remains modest in coronal symplectite bearing eclogites and then increases rapidly at the partially retrograde stages, and finally it shows a sharply decrease at completely retrograde stage (Fig. 7b). The arithmetic mean magnetic susceptibilities of partially retrograded eclogite (κ=4372 μSI) is about 4.24 times of fresh eclogite (κ=1031 μSI). Compared to magnetic susceptibility, corrected magnetic anisotropy degree (P_j) shows almost the same change trend with retrogression degree of eclogite, and it reaches the highest value of 1.216 ± 0.118 corresponding to the partially retrograded eclogite (Fig. 7c). The relative high contents of magnetite and ilmenite, associated with retrograde metamorphism, should be responsible for the high magnetic susceptibility and anisotropy of partially retrograded eclogites. Clearly, the bulk density (ρ) shows a steady decrease from 3.54 ± 0.11 g/cm^3 (fresh eclogite) to 2.98 ± 0.06 g/cm^3 (completely retrograded eclogite) with increasing degree of retrogression

(Fig. 7d). This change can be attributed to the progressively transformations of primary high density minerals of garnet and omphacite to secondary low density minerals such as amphibole, quartz, plagioclase and etc (Table 2).

Other factors, such as deformation mechanisms, finite strain, strain history and stress, also have important effects on the low field magnetic anisotropy (AMS) of a rock (Borradaile and Jackson, 2004). Better interpretation of the AMS data requires a closer liaison between structural geology, metamorphic petrology and rock magnetism, and a better understanding of the relationship between magnetic fabrics and petrofabrics during retrogression of eclogite. Further work is needed to understand the relationships between petrofabrics and magnetic fabrics of eclogite and also the influence of deformation during successively retrogression.

7. Conclusion

Eclogites from the CCSD main hole and outcrops in the southern part of the Sulu UHP metamorphic belt have experienced various degrees of retrogression during exhumation, and show different retrograde mineral assemblages and textures. Retrogression plays a very important role in changing rock magnetic properties and density. In 198 specimens from variably retrograded eclogites, the arithmetic mean of bulk density (ρ) shows a steady decrease with increasing retrogression degree from 3.54 ± 0.11 g/cm^3 (fresh eclogite) to 2.98 ± 0.06 g/cm^3 (completely retrograded eclogite). The bulk magnetic susceptibility (κ) of fresh eclogite is mainly controlled by whole-rock chemical compositions and ranges from 397 to 2312 μSI with an average of 1031 ± 493 μSI due to large variations in SiO_2 (38.20–52.86 wt.%), TiO_2 (0.62–4.88 wt.%) and total FeO^T (8.28–22.93 wt.%). The principal magnetic susceptibility carriers of fresh eclogite are the paramagnetic minerals garnet, omphacite, rutile and phengite. In contrast, partially retrograded eclogites show large variations in magnetic susceptibility with rather high mean magnetic susceptibility values of 4372 ± 4149 μSI. We suggest that the considerable amount of high magnetic susceptibility minerals such as magnetite, ilmenite and/or titanohematite produced by retrograde metamorphic reactions are responsible for the high magnetic susceptibility. The magnetic susceptibility decreases sharply with further retrogression as the rock is transformed to completely retrograded eclogite ($\kappa = 1094 \pm 600$ μSI) with typical amphibolite facies mineral assemblages such as amphibole, plagioclase, quartz, zoisite, biotite, sphene and epidote. The Jelinek's corrected anisotropy degree (P_j) of eclogite ranges from 1.001 to 1.540, and shows a positive correlation with low field magnetic susceptibility (κ).

Changes in eclogite mineral composition by retrograde metamorphism during exhumation appear to be the major factor controlling the low field magnetic susceptibility and its anisotropy. We should consider the role of retrogression in the interpretation of geophysical magnetic surveying and geophysical well logging in UHP metamorphic terranes and petrophysical properties such as density and low field magnetic susceptibility might provide a potential means for semi-quantifying the degree of retrogression of eclogite during exhumation.

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