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# Fabric kinematics of the ultrahigh-pressure metamorphic rocks from the main borehole of the Chinese Continental Scientific Drilling Project: Implications for continental subduction and exhumation

Zhiqin Xu [a], Qin Wang [b,*], Zhemin Tang [a], Fangyuan Chen [a]

[a] *Key Laboratory of Continental Dynamics, Ministry of Land and Resources, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China*
[b] *Department of Earth Sciences, Nanjing University, Nanjing 210093, China*

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A B S T R A C T

The 5158-m-deep main borehole of the Chinese Continental Scientific Drilling Project (CCSD-MH) penetrated granitic gneisses, paragneisses, eclogites, retrograde eclogites, amphibolites and ultramafic rocks in the Sulu ultrahigh-pressure (UHP) metamorphic terrane, eastern China. The CCSD-MH consists of four petro-structural units separated by three SE-dipping ductile shear zones DFa (835–1280 m), DFb (2010–2280 m) and DFc (2920–3225 m), which are correspondent with the regional shear zones in the northern Sulu UHP supracrustal zone. Using the electron backscatter diffraction (EBSD) technique, we investigated the lattice-preferred orientations (LPOs) of omphacite, diopside and quartz in core samples from the CCSD-MH. Omphacite from eclogites and diopside from garnet pyroxenites display very strong LPOs, which are characterized by the maximum concentration of [001]-axes parallel to the lineation and (010)-poles normal to the foliation. Quartz in para- and granitic mylonites/gneisses from the shear zones DFa, DFb and DFc developed multiple slip systems. $^{40}Ar/^{39}Ar$ dating of biotite in para- and granitic gneisses from the CCSD-MH yields 223–202 Ma, which constrains the formation ages of the quartz high-temperature prism slip systems {m}<a> and {m}[c]. The asymmetric LPOs of omphacite, diopside, olivine and quartz with respect to the structural frame reveal three deformation phases in the Sulu terrane. In the Middle Triassic, the northward subduction of the Yangtze plate to depths >100 km produced a top-to-the-south shear sense in LPOs of omphacite, diopside and olivine, and a nearly N–S-striking foliation and a subhorizontal N–S-trending lineation in eclogites and ultramafic rocks. In the Late Triassic, the UHP rocks were exhumed to the lower crust and quartz developed high-temperature slip systems with a top-to-the-NW shear sense, which is consistent with the regional SE-dipping foliation and SE-plunging lineation in the ductile shear zones. In the Cretaceous the UHP rocks were exhumed to the middle crust when the migmatization and granitic intrusion formed a NE-striking antiform structure. As a result, the activation of quartz low-temperature basal slip (0001)<a> is characterized by a top-to-the-SE shear sense in the south, but a top-to-the-NW shear sense in the north.


## 1. Introduction

Discovery of microdiamond- and coesite-bearing ultrahigh-pressure (UHP) metamorphic rocks opened a new window to explore the evolution of continental collision orogens and the material recycling between the crust and upper mantle (e.g., Chopin, 1984; Smith, 1984; Xu, 1987; Wang et al., 1989; Sobolev and Shatsky, 1990; Xu et al., 1992). More than twenty UHP terranes have been documented in the past two decades, demonstrating that low-density continental material could be rapidly subducted to depths greater than 100 km and then exhumed to the surface (Liou et al., 1998; Carswell and Compagnoni, 2003; Chopin, 2003; and references therein). Hence continental subduction should be as important as continental collision in plate tectonics. These findings, which rely on extensive studies of mineralogy, petrology and isotope geochemistry, require new mechanical and geodynamic models to understand the continental collision zones (e.g., Chemenda et al., 1995; Ernst and Peacock, 1996; Gerya and Stöckhert, 2002). Unfortunately, the retrograde metamorphism, post-collisional deformation, recrystallization and migmatization significantly overprinted or even erased the early UHP assemblages, which hampers our recognition and tectonic reconstruction of the UHP terranes.

As the largest (>30,000 $km^2$) and one of the best-preserved UHP terranes, the Dabie–Sulu orogen in east central China was formed by the Triassic collision between the Sino-Korean and Yangtze plates. The occurrence of coesite, microdiamond, UHP hydrous phases and exsolution textures in eclogites, garnet peridotites, orthogneisses and metasediments indicates that the Yangtze continental crust has been subducted to depths >120 km at extremely low geotherms (Xu

* Corresponding author. Tel.: +86 25 8359 6887; fax: +86 25 8368 6016.
*E-mail address:* qwang@nju.edu.cn (Q. Wang).

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et al., 1992; Liou et al., 1998; Ye et al., 2000; Zhang et al., 2003; Liu et al., 2004). From August 2001 to March 2005, the Chinese Continental Scientific Drilling Project (CCSD) completed a 5158-m-deep main borehole (CCSD-MH) in the Sulu terrane. The UHP index minerals have been found in zircons from the surface to 5158 m depth in core samples of the CCSD-MH (Liu et al., 2007), suggesting that the CCSD-MH provides a superdeep telescope into the subducted continental crust.

Formation of a lattice-preferred orientation (LPO) depends on the active slip systems of a mineral under certain thermal–mechanical conditions. Non-coaxial deformation tends to produce asymmetric fabrics in minerals with respect of the structural reference frame (i.e., foliation and lineation), which allow us to determine the shear sense of plastically deformed rocks. Metabasaltic eclogites containing predominantly garnet and omphacite occur in all known UHP terranes. Garnet generally produces very weak LPO whereas omphacite develops strong LPO in eclogites (e.g., Boundy et al., 1992; Mauler et al., 2001; Ji et al., 2003; Wang et al., 2008, this issue). Dislocation creep of omphacite takes place above 1.2–1.4 GPa and 450–550 °C (Buatier et al., 1991; Philippot and van Roermund, 1992), implying that the granulite and amphibolite facies retrograde metamorphism cannot significantly change the omphacite LPO formed under the UHP conditions. Both theoretical modeling (Bascou et al., 2002) and experimental studies (Zhang et al., 2006) demonstrate that the omphacite LPO patterns are only controlled by changes in deformation regime, therefore the asymmetric LPO of omphacite permit shear-sense determination of eclogites during the UHP metamorphism (Ábalos, 1997). In contrast, the quartz fabrics have been widely used to infer the deformation history of quartz-rich tectonites in the middle and lower crust (e.g., Mainprice et al., 1986; Stipp et al., 2002; Otani and Wallis, 2006).

To clarify the relationships between petrofabrics and deformation history of the UHP metamorphic rocks, this paper presents an integrated study of petrology, microstructure and geochronology on the core samples from the CCSD-MH. A petro-structural profile of the CCSD-MH was constructed and correlated with regional structures in the Sulu terrane. The LPOs of omphacite, diopside and quartz from eclogites, garnet pyroxenites, para- and granitic gneisses/mylonites were measured using the electron backscatter diffraction (EBSD) technique. $^{40}Ar/^{39}Ar$ dating was carried out on biotite from para- and granitic gneisses to constrain the formation age of quartz LPO. Combined with previous data, fabric kinematics of the UHP metamorphic rocks were used to reconstruct the tectonic evolution of the Sulu terrane.

## 2. Geological setting

### 2.1. The Dabie–Sulu orogen

As the continental collision zone between the Sino-Korean and Yangtze plates, the Dabie–Sulu orogen was offset by the NE-striking Tan–Lu fault about 500 km (Fig. 1). In the Dabie Mountains and the Sulu terrane, quartzofeldspathic and pelitic gneisses, marbles and quartzites, together with minor eclogites and garnet peridotites, were subjected to in situ UHP metamorphism of $P > 2.6$ GPa and $T = 600$–900 °C (e.g., Xu, 1987; Wang and Liou, 1991; Liou et al., 1998; Zhang et al., 2000a,b; Liu et al., 2004). Most UHP metamorphic rocks in the Dabie–Sulu orogen yield the Neoproterozoic protolith ages of 740–780 Ma (Zheng, 2008, and references therein), which suggests their tectonic affinity to the Yangtze plate because the basement of the North China craton was formed in the Late Archean to Paleoproterozoic (Zhao et al., 2005). In addition, a north-dipping slab-like high velocity anomaly was found in the upper mantle beneath the Dabie–Sulu orogen and interpreted as a remnant of the subducted Yangtze plate (Xu et al., 2001).

The bulk continental subduction and exhumation under the UHP regime took place from 245–240 Ma to 225–220 Ma in the Dabie Mountains (e.g., Hacker et al., 1998; Li et al., 1999; Hacker et al., 2000; Li et al., 2004). Recent SHRIMP U–Pb analysis on coesite-bearing para- and orthogneisses from the Sulu terrane obtained $231 \pm 4$ Ma and $211 \pm 3$ Ma for the peak UHP metamorphism and the amphibolite facies retrogression, respectively (Liu et al., 2004). The extremely low $\delta^{18}O$ values in the Dabie–Sulu UHP metamorphic rocks also requires very short duration of 10–20 Ma for the bulk UHP metamorphism (Zheng et al., 1998, 2001). The foreland of the Dabie–Sulu orogen constitutes the lower Yangtze fold-thrust belt, which were formed by N–S contraction in the Middle to Late Triassic. After the rapid syn-collisional early exhumation at mantle depths, during 210 to 180 Ma a regional top-to-the-NW thrusting under amphibolite facies conditions occurred in the Dabie Mountains (Hacker et al., 2000; Faure et al., 2003b) and the Sulu terrane (Wallis et al., 1999; Faure et al., 2003a; Xu et al., 2003, 2006b). In the Early Cretaceous the migmatization took place in the central Dabie Mountains (Faure et al., 2003b; Wu et al., 2007) and the northern Sulu terrane (Faure et al., 2003a; Xu et al., 2006b), and resulted in the SE-ESE dipping foliation and SE-plunging stretching lineation in the south and the NW-WNW dipping foliation and NW-plunging stretching lineation in the north. Finally, the intense magmatism and crustal extension in the Cretaceous and Cenozoic overprinted the early structures and brought the UHP rocks to the surface (Ratschbacher et al., 2000; Faure et al., 2003a).

### 2.2. The Sulu HP and UHP slices

East of the Tan–Lu fault, the Sulu terrane is bounded by the Wulian–Yantai fault in the north and the Jiashan–Xiangshui fault in the south (Fig. 1). The Wulian–Yantai fault is a steeply NW-dipping normal fault that separates the Sulu terrane from the Cretaceous Laiyang basin. Although the Wulian–Yantai fault is often assumed to represent the boundary between the Sino-Korean and Yangtze plates, field surveys (Faure et al., 2003b; Xu et al., 2006b) and seismic reflection profiles (Yang, 2002) reveal that the Wulian–Yantai fault developed above a gently NW-dipping ductile detachment, i.e., the Wulian–Yantai detachment (Fig. 1b). The Wulian–Yantai detachment preserved a top-to-the-NW shearing under greenschist facies conditions at ~147 Ma, which was coeval with the formation of the Laiyang basin and the migmatitic doming in the northern Sulu terrane. The Cretaceous red continental sandstones and volcanic layers in the Laiyang basin probably overlie the Sulu migmatites, retrograded granulites, eclogites and garnet peridotites, implying a further north suture zone between the Sino-Korean and Yangtze plates. Discovery of Neoproterozoic granitoids (738–758 Ma) in the Laiyang basin also supports a suture zone to the north of the Wulian–Yantai fault (Wu et al., 2004). In the south, the Jiashan–Xiangshui fault is a steeply SE-dipping sinistral normal fault that bounds the North Jiangsu basin. Due to the crustal extension and lithospheric thinning since the Late Jurassic, the North Jiangsu basin is a continental rift developed along some existing faults, e.g., the Jiashan–Xiangshui fault, during the Late Cretaceous to Neogene (Yang, 2002).

The Sulu terrane consists of a series of high-pressure (HP) and UHP metamorphic slices separated by wide shear zones. Four tectonometamorphic zones are identified with increasing metamorphic grades from south to north (Fig. 1). The southern and uppermost zone (Zone I) is a low-temperature (LT) and HP zone where glaucophane- and kyanite-bearing paragneisses, quartzites and marbles experienced blueschist facies metamorphism at 0.7–0.85 GPa and 300–360 °C (Qiu et al., 2002). The Zone II is a medium temperature (MT) and very high pressure (VHP) zone characterized by the occurrence of hydroxyl-rich topaz in kyanite quartzites, which suggests the metamorphism at 1.5–2.5 GPa and 500–600 °C (Zhang et al., 2002). The northern UHP supracrustal zone (Zone III) is predominantly composed of coesite-bearing supracrustal gneisses, quartzites, mica