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# Chemical geodynamics of continental subduction-zone metamorphism: Insights from studies of the Chinese Continental Scientific Drilling (CCSD) core samples

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ABSTRACT

The Dabie–Sulu orogenic belt of east-central China has long been a type location for the study of geodynamic processes associated with ultrahigh-pressure (UHP) tectonics. Much of our understanding of the world's most enigmatic processes in continental deep-subduction zones has been deduced from various records in this belt. By taking advantage of having depth profiles from core samples of the Chinese Continental Scientific Drilling (CCSD) project in the Sulu orogen, a series of combined studies were carried out for UHP metamorphic rocks from the main hole (MH) at continuous depths of 100 to 5000 m. The results provide new insights into the chemical geodynamics of continental subduction-zone metamorphism, especially on the issues that are not able to be resolved from the surface outcrops. Available results from our geochemical studies of CCSD-MH core samples can be outlined as follows. (1) An O isotope profile of 100 to 5000 m is established for the UHP metamorphic minerals, with finding of $^{18}O$ depletion as deep as 3300 m. Along with areal $^{18}O$ depletion of over 30,000 $km^2$ along the Dabie–Sulu orogenic belt, three-dimensional $^{18}O$ depletion of over 100,000 $km^3$ occurs along the northern margin of the South China Block. (2) Changes in mineral O isotope, H isotope and water content occur in eclogite-gneiss transitions, concordant with petrographic changes. The contact between different lithologies is thus the most favorable place for fluid action; fluid for retrogression of the eclogites away from the eclogite-gneiss boundary was derived from the decompression exsolution. For the eclogites adjacent to gneiss, in contrast, the retrograde metamorphism was principally caused by aqueous fluid from the gneiss that is relatively rich in water. Inspection of the relationship between the distance, petrography and $\delta^{18}O$ values of adjacent samples shows O isotope heterogeneities between the different and same lithologies on scales of 20 to 50 cm, corresponding to the maximum scales of fluid mobility during the continental collision. (3) Studies of major and trace elements in the two continuous core segments indicate high mobility of LILE and LREE but immobility of HFSE and HREE. Some eclogites have andesitic compositions with high $SiO_2$, alkalis, LREE and LILE but low CaO, MgO and FeO contents. These features likely result from chemical exchange with gneisses, possibly due to the metasomatism of felsic melt produced by partial melting of the associated gneisses during the exhumation. On the other hand, some eclogites appear to have geochemical affinity to refractory rocks formed by melt extraction as evidence by strong LREE and LILE depletion and the absence of hydrous minerals. These results provide evidence for melt-induced element mobility in the UHP metamorphic rocks, and thus the possible presence of supercritical fluid during exhumation. In particular, large variations in the abundance of such elements as $SiO_2$, LREE and LILE occur at the contact between eclogite and gneiss. This indicates their mobility between different slab components, although it only occurs on small scales and is thus limited in local open-systems. (4) Despite the widespread retrogression, retrograde fluid was internally buffered in stable isotope compositions, and the retrograde fluid was of deuteric origin and thus was derived from the decompression exsolution of structural hydroxyl and molecular water in nominally anhydrous minerals. (5) A combined study of petrography and geochronology reveals the episode of HP eclogite-facies recrystallization at 216 ± 3 Ma, with timescale of 1.9 to 9.3 Myr or less. Collectively, the Dabie–Sulu UHP terrenes underwent the protracted exhumation (2–3 mm/yr) in the HP-UHP regime. (6) Zircon U–Pb ages and Hf isotopes indicate that mid-Neoproterozoic protoliths of bimodal UHP metaigneous rocks formed during supercontinental rifting along preexisting arc-continent collision orogen, corresponding to dual bimodal magmatism in response to the attempted breakup of the supercontinent Rodinia at about 780 Ma. The first type of bimodal magmatism was formed by reworking of juvenile Late Mesoproterozoic crust, whereas the second type of bimodal magmatism was principally generated by rifting anatexis of ancient Middle Paleoproterozoic crust. In conclusion, the geochemical studies of CCSD-MH core samples have placed important constraints on the nature and scale of fluid action and element mobility during the continental subduction and UHP metamorphism.



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## 1. Introduction

Since findings of coesite and diamond in the supercrustal rocks, it has been recognized that the continental crust can be subducted to mantle depths over 100 km to form ultrahigh-pressure (UHP) metamorphic rocks. During the deep subduction of continental crust, a great deal of geological processes occurs due to increases of temperature and pressure (e.g., Chopin, 2003; Liou et al., 2004; Ernst, 2006). Geochemical studies of the processes have significantly contributed to our understanding of UHP metamorphism and continental collision (e.g., Jahn et al., 2003; Rumble et al., 2003; Zheng et al., 2003a). The ubiquitous presence of a larger volume of UHP metamorphic rocks of continental affinity than the volume of more dense mafic-ultramafic rocks strongly suggests that the buoyancy of the continental material, once "unstuck" from the subducting slab, is sufficient to exhume it back to the surface. Each UHP slab is a multicomponent system that is heterogeneous in composition. Thus, variations in metamorphic lithology are controlled by changes in pressure and temperature during subduction and exhumation. This has great bearing on availability of metamorphic fluid in deep subduction zones, with significant effects on density, water content, fertility, melting conditions and so on.

The Dabie–Sulu orogenic belt is UHP metamorphic terranes that formed by the Triassic continental collision between the South China Block and the North China Block (Cong, 1996; Liou et al., 1996; Li et al., 1999; Hacker et al., 2000; Faure et al., 2003; Zheng et al., 2005a; Xu et al., 2006). It contains one of the largest (>30,000 $km^2$) and best-exposed UHP terranes on the earth and thus has long been a type location for the study of geodynamic processes associated with continental deep-subduction. In the past two decades, many studies have been devoted to the geodynamics of continental subduction and exhumation from various aspects of mineralogy, petrology, geochronology, geochemistry, geophysics, structural geology, and tectonics (Zheng, 2008, and references therein). Identification of coesite and diamond in eclogites and their country gneisses and marbles from this belt demonstrates that supracrustal materials were subducted to mantle depths of at least 120 km to undergo UHP metamorphism (e.g., Okay et al., 1989; Wang et al., 1989, 1992; Xu et al., 1992, 2003, 2005). Findings of coesite inclusions in zircon from granitic gneisses (Tabata et al., 1998; Ye et al., 2000; Liu et al., 2001, 2002) further indicate that the UHP terranes, few hundreds of kilometers in width and a few hundreds of kilometers in length, may have retained basically complete coherence during subduction and exhumation.

Anomalously low $\delta^{18}O$ values of −11 to −4‰ were found in UHP eclogites and gneisses (e.g., Yui et al., 1995; Zheng et al., 1996, 1998, 1999; Rumble and Yui, 1998; Fu et al., 1999). Zircon U–Pb dating for low $\delta^{18}O$ zircons gave ages of 740 to 780 Ma (Rumble et al., 2002; Zheng et al., 2004, 2007a; Wu et al., 2007; Tang et al., 2008a,b). Thus, O isotope exchange of high-T meteoric water with their protoliths is demonstrated to occur in the Middle Neoproterozoic, with genetic links not only to the tectonic advance from supercontinental rift to breakup but also to the tectonic driving of cold paleoclimate prior to and during the snowball Earth event. The isotopic signature of meteoric water would be transported by the UHP metamorphic minerals in subducting the continental crust into the diamond stability field through the cold subduction-zone. Perverse preservation of such low $\delta^{18}O$ signatures indicates very weak fluid action during the bulk processes of the subduction and exhumation of the continental crust (Liou et al., 1997; Fu et al., 2001; Zheng et al., 2003a).

Starting with the O isotope geodynamics of UHP metamorphic rocks (Zheng et al., 1998, 1999, 2003a), we have made successful links to the following geochemical issues: (1) nominally anhydrous mineral H isotopes and water concentrations in order to decipher fluid action during continental collision and UHP metamorphism (Chen et al., 2007a; Gong et al., 2007a,b; Zhao et al., 2007a), (2) whole-rock major and trace elements in order to recognize element mobility during continental subduction-zone metamorphism (Zhao et al., 2007b; Xia et al., 2008), (3) mineral Sm–Nd and Rb–Sr isochrons in order to test the assumption of isotopic equilibrium (Zheng et al., 2002, 2003b,c; Li et al., 2004; Xie et al., 2004; Zhao et al., 2006a; Gong et al., 2007a), (4) zircon Lu–Hf isotopes in order to trace protolith origin and metamorphic modification (Zheng et al., 2005b, 2006, 2007b; Wu et al., 2006a,b; Chen et al., 2007b), (5) zircon U–Pb ages in order to date water-rock interaction, low $\delta^{18}O$ magmatism and metamorphic fluid flow (Zheng et al., 2003d, 2004, 2007a,c, 2008a; Wu et al., 2007; Tang et al., 2008a,b), and (6) zircon U–Pb ages and Lu–Hf isotopes in order to constrain the crustal architecture of a collision orogen (Zhao et al., 2008). In particular, petrographic identification of, with geochemical support to, partial melting has been obtained for the first time from UHP metamorphic rocks in the Dabie–Sulu orogenic belt (Zhao et al., 2007b; Xia et al., 2008). The results highlight the importance of integrating the stable isotopes, which are capable of characterizing the origin and transport of aqueous fluid, with radiogenic isotopes and trace elements in the same targets for the purpose of interpreting the tectonic evolution in the processes of continental collision and UHP metamorphism. It also provides an important complement to chemical geodynamics of oceanic subduction-zone metamorphism (Bebout, 2007).

The Chinese Continental Scientific Drilling (CCSD) project at Donghai in the Dabie–Sulu orogenic belt is aiming to reconstruct the formation and exhumation mechanisms of UHP metamorphic terranes (Xu et al., 1998). It provides an advantageous and rare chance for collecting UHP rock samples continuously from the surface downward to 5 km. This allows us to determine scales of fluid action and its effect on elememt mobility during continental subduction-zone metamorphism. On the other hand, more and more experimental data for the pressure dependence of water solubility in nominally anhydrous minerals become available (Lu and Keppler, 1997; Withers et al., 1998; Mosenfelder, 2000; Rauch and Keppler, 2002; Koch-Muller et al., 2003; Bromiley et al., 2004a,b; Mierdel and Keppler, 2004). This offers us with the opportunity to test previous hypothesis concerning the origin of retrograde fluid during exhumation. In addition, determining the state of continental crust before subduction is crucial for understanding how different lithologies evolve during the bulk processes of subduction and exhumation. By taking advantage of having depth profiles from CCSD core samples, we have accomplished a series of integrated studies of petrography, whole-rock major and trace elements, whole-rock Sr–Nd isotopes, mineral O and H isotopes and water content, and zircon U–Pb ages and Hf isotopes. The results provide new insights into the chemical geodynamics of continental subduction-zone metamorphism, especially on the issues that are not able to be resolved from discrete surface outcrops.

## 2. Geological setting and samples

The Dabie–Sulu orogenic belt was formed by the Triassic subduction of the South China Block beneath the North China Block (e.g., Cong, 1996; Liou et al., 1996; Li et al., 1999; Zheng et al., 2005a; Xu et al., 2006). It is separated into two terranes by approximately 500 km of left-lateral strike-slip displacement along the Tan–Lu fault (Fig. 1). The Sulu orogen in the east is separated from the North China Block to the NW by the Wulian–Qingdao–Yantai Fault (WQYF), and the South China Block to the SE by the Jiashan–Xiangshui Fault (JXF). The Sulu orogen can be divided into fault-bounded UHP and HP metamorphic zones (Xu et al., 2006). The UHP zone is defined by occurrence of coesite inclusions in metamorphic minerals (Zhang et al., 1995; Liou and Zhang, 1996; Ye et al., 2000; Liu et al., 2002, 2004a,b, 2005b).

Dabie–Sulu UHP metamorphic rocks are mainly composed of granitic gneiss, with minor proportions of other rock types that are enclosed as pods and layers within the regional granitic gneiss. They show the following characteristics (Cong, 1996; Jahn, 1998; Liou et al.,