Ultrahigh-pressure metamorphic rocks in the Dabie–Sulu orogenic belt: compositional inheritance and metamorphic modification

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Abstract: The Dabie–Sulu orogenic belt in east-central China contains one of the largest ultrahigh-pressure (UHP) metamorphic terranes in the world. The UHP eclogites are associated with gneiss, peridotite and marble. But all these rocks underwent *in situ* UHP metamorphism during the continental collision in the Triassic. Although fluid action is not significant during cold subduction, it becomes prominent during hot exhumation of UHP slices. Whereas the composition of UHP metamorphic rocks is primarily inherited from their protoliths, they were locally modified by partial melting to varying extents. The partial melting of UHP rocks is highly heterogeneous along the collisional orogen, and achieves a maximum during rifting orogeny at the post-collisional stage. This paper outlines the petrographical features and geochemical compositions of UHP metamorphic rocks, and presents an overview of collisional modification and post-collisional reworking of the subducted continental crust. Further discussions are devoted to continental subduction tectonics, as well as to subduction style, subduction polarity and exhumation mechanism. The results also provide insights into the initiation of continental rifting in a Wilson cycle. Consequently, studies of the Dabie–Sulu orogenic belt have contributed greatly to our understanding of tectonic processes, fluid regime and chemical geodynamics in continental subduction zones.

The recognition of continental deep subduction responsible for the formation and subsequent return of ultrahigh-pressure (UHP) metamorphic rocks to the surface from depths >80 km in collisional orogens has enriched the plate tectonics theory (Chopin 2003; Ernst 2006; Zheng 2012; Hermann & Rubatto 2014). So far, more than 20 coesite-bearing, 10 diamond-bearing and three majoritic garnet-bearing UHP terranes have been documented on Earth (Liou *et al.* 2009, 2014). The occurrence of crustal rocks metamorphosed under mantle *P–T* conditions has extended our understanding of tectonism at convergent plate boundaries (Ernst & Liou 1995; Chopin 2003; Zheng & Chen 2016). Intensive interest in studies of global UHP terranes reflects their significance with regard to not only the evolution of continental crust during subduction, collision and exhumation (Rumble *et al.* 2003; Zheng *et al.* 2009; Hermann & Rubatto 2014) but also the slab–mantle interaction and geochemical recycling in continental subduction zones (Malaspina *et al.* 2009; Zheng 2012; Zhao Z.-F. *et al.* 2013, 2015).

Since findings of coesite (Okay *et al.* 1989; Wang *et al.* 1989) and microdiamond (Xu *et al.* 1992) as crystal inclusions in metamorphic minerals from eclogites and surrounding gneisses in the Dabie orogen in east-central China, the Dabie–Sulu orogenic belt has become a type locality of UHP terranes on Earth (Coleman & Wang 1995; Hacker & Liou 1998; Carswell & Compagnoni 2003; Chopin 2003; Rumble *et al.* 2003; Liou *et al.* 2004, 2009, 2014; Ernst 2006; Zheng 2012; Hermann & Rubatto 2014). A great deal of studies have been devoted to Dabie–Sulu UHP metamorphic rocks in the past three decades (see reviews by Cong 1996; Liou *et al.* 2000, 2009, 2012; Zheng *et al.* 2003, 2009, 2012; Ernst *et al.* 2007; Zheng 2008, 2009, 2012; Zhang R.Y. *et al.* 2009; Liu & Liou 2011). The results demonstrate that eclogites, garnet peridotites, and surrounding country rock gneisses and marbles were all subjected to the *in situ* UHP metamorphism. There are three very important geochemical anomalies in the Dabie–Sulu UHP metamorphic rocks: (1) excess argon in phengite (Li *et al.* 1994); (2) a negative oxygen isotope anomaly (Yui *et al.* 1995; Zheng *et al.* 1996); and (3) a positive Nd isotope anomaly (Jahn *et al.* 1996). Although these anomalies only occur in small amounts of the UHP rocks,

From: Zhang, L. F., Zhang, Z., Schertl, H.-P. & Wei, C. (eds) 2019. *HP–UHP Metamorphism and Tectonic Evolution of Orogenic Belts*. Geological Society, London, Special Publications, **474**, 89–132.
First published online May 15, 2018, https://doi.org/10.1144/SP474.9

they have important implications for both geochronology and geochemistry. Specifically, the negative $\delta^{18}O$ anomaly in the UHP metamorphic rocks makes them a unique tracer to decipher the reworking and recycling of the deeply subducted continental crust (Zheng *et al.* 2003, 2009; Zheng 2012; Zhao Z.-F. *et al.* 2013, 2015).

The study of UHP metamorphic rocks from the Dabie–Sulu orogenic belt has contributed greatly to our understanding of continental subduction zones (e.g. Rumble *et al.* 2003; Zheng *et al.* 2003; Liou *et al.* 2004, 2012; Ernst *et al.* 2007; Zhang R.Y. *et al.* 2009; Hermann & Rubatto 2014). In particular, it provides insights into the fluid regime and chemical geodynamics of continental subduction zones (Zheng 2009, 2012; Zhang *et al.* 2011; Zheng & Hermann 2014), the structures and processes of subduction zones (Zheng 2012; Zheng & Chen 2016), metamorphic zirconology (Liu & Liou 2011; Chen & Zheng 2017), crustal anatexis during collisional orogeny (Zheng *et al.* 2011*b*; Chen *et al.* 2017; Gao *et al.* 2017*a*; Xia & Zhou 2017), extreme metamorphism and orogenic tectonism at convergent plate margins (Zheng & Chen 2017; Zheng & Zhao 2017), and post-collisional reworking of the deeply subducted continental crust (Zhao *et al.* 2017*a*). This paper presents an overview of the geochemistry of Dabie–Sulu UHP metamorphic rocks, with more focus on tectonic implications. The available results are outlined in the three aspects of geochemical composition, collisional modification and post-collisional reworking. It attempts to highlight some important advances in the study of continental subduction zones with respect to the tectonic evolution from collisional orogeny to rifting orogeny, with insights into the Wilson cycle.

Geological setting

The Dabie–Sulu orogenic belt is located between the South China Block and the North China Block (Fig. 1). Eclogite, peridotite, paragneiss, marble and quartzite are enclosed as pods and layers within the regional granitic orthogneiss in the orogenic belt (e.g. Cong 1996; Liou *et al.* 2000; Zheng *et al.* 2003, 2005; Xu *et al.* 2006; Liu & Liou 2011). The UHP metamorphism is identified by the occurrence of rare but widespread coesite inclusions in eclogitic minerals and in metamorphic zircons in the country rocks. It is estimated that the UHP metamorphic rocks have an outcrop area of *c.* 30 000 km^2 in the

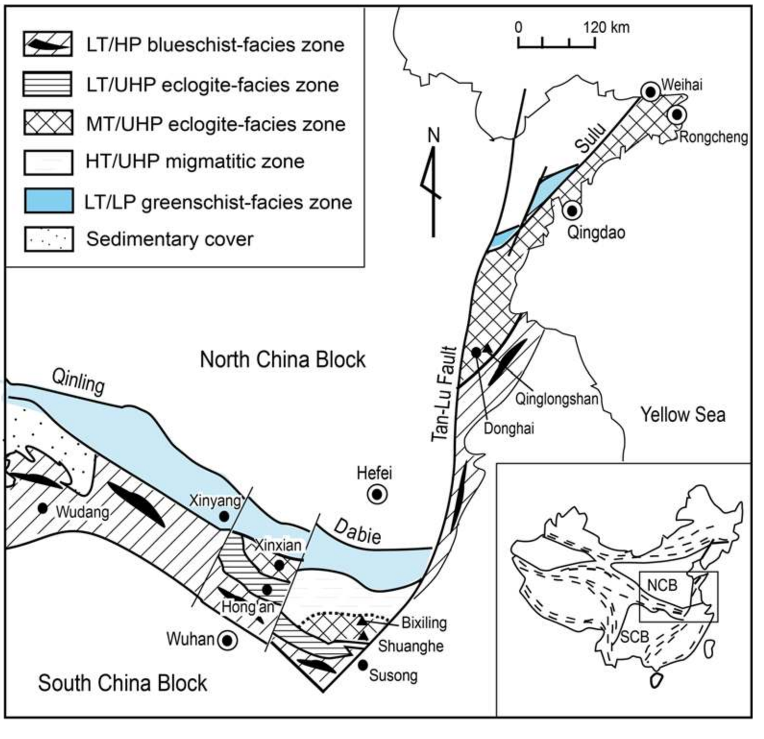

Fig. 1. A sketch map of the tectonic framework for the Dabie–Sulu orogenic belt in east-central China (revised after Zheng *et al.* 2003). NCB and SCB in the inset denote the North China Block and the South China Block, respectively.

Dabie–Sulu orogenic belt, making it one of the largest and best-exposed UHP metamorphic terranes in the world (Carswell & Compagnoni 2003; Liou *et al.* 2009). The continuous occurrence of coesite is documented in core samples from the 5158 m-deep Chinese Continental Scientific Drilling Project (CCSD) in the Sulu orogen (Liu F.L. *et al.* 2007). Therefore, a huge amount of the crustal rocks were subducted to subarc depths of 80–160 km for *in situ* UHP metamorphism. There are virtually identical metamorphic ages of Triassic for various UHP lithologies, indicating *in situ* UHP metamorphism at the subarc depths.

The Dabie–Sulu orogenic belt is separated by the Tan-Lu Fault into the Dabie orogen in the west and the Sulu orogen in the east (Fig. 1). As illustrated in Figure 2, the Dabie orogen is divided into five east–west-orientated zones from south to north (Zheng *et al.* 2005), respectively: (I) the Susong low-temperature/high-pressure blueschist facies zone; (II) the South Dabie low-temperature/UHP zone dominated by paragneiss with eclogite lenses; (III) the Central Dabie mid-temperature/UHP zone composed of coesite-bearing eclogite, gneiss and marble; (IV) the North Dabie high-temperature/UHP zone composed of amphibolite- to granulite-facies orthogneiss and migmatite with a few lenses of garnet pyroxenite and peridotite; and (V) the North Huaiyang low-temperature/low-pressure greenschist facies zone composed of Neoproterozoic igneous rocks and Neoproterozoic–pre-Triassic sedimentary rocks. A similar division is also applied to the Sulu orogen, where five NE–SW-striking zones are recognized from south to north (Zheng *et al.* 2005; Xu *et al.* 2006): (I) the Zhangbaling low-temperature/high-pressure blueschist facies zone; (II) the Subei low-temperature/UHP zone dominated by paragneiss with eclogite lenses; (III) the Jiaonan mid-temperature/UHP zone composed of coesite-bearing eclogite, gneiss and marble; (IV) the Weihai high-temperature/UHP zone consisting of amphibolite- to granulite-facies orthogneiss and migmatite with a few eclogite lenses; and (V) the Wulian low-temperature/low-pressure greenschist facies zone consisting of Neoproterozoic igneous rocks and Neoproterozoic–pre-Triassic sedimentary rocks. The maximum pressure in the three UHP zones lies in the diamond stability field (>3.3 GPa), and the maximum temperature varied from 730 to 880°C during the continental collision. The three UHP zones share similarly clockwise *P–T* paths despite the difference in the maximum pressure and temperature (Fig. 3).

Except for UHP metasedimentary rocks that have Archean–Paleoproterozoic protoliths, UHP meta-igneous rocks in the Dabie–Sulu orogenic belt have Neoproterozoic protolith ages of 780–740 Ma (Zheng *et al.* 2009; Liu & Liou 2011). The latter ages indicate that the deeply subducted continental crust has a tectonic affinity to the South China Block rather than the North China Block (Zheng 2012; Zhang & Zheng 2013). While these rocks underwent peak UHP metamorphism at temperatures of *c.* 670–780°C and pressures of >2.8 GPa,

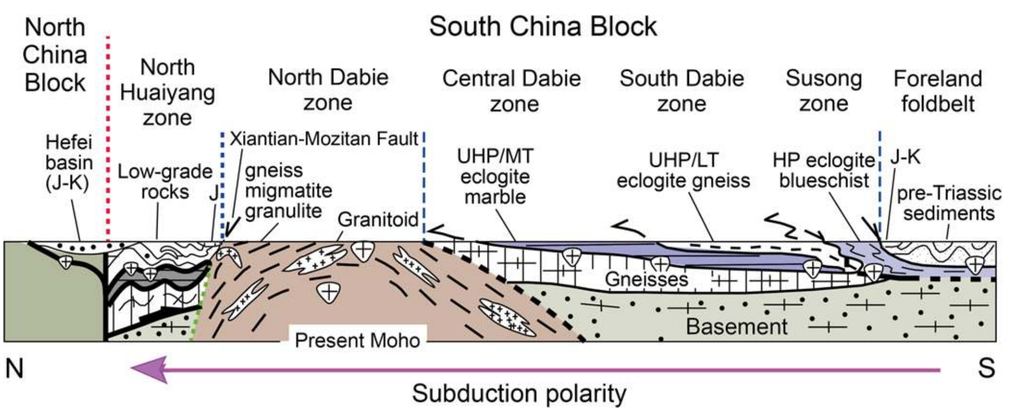

Fig. 2. Schematic diagram showing a crustal-scale cross-profile for the surface geology and lithotectonic units in the Dabie orogen (adapted from Faure *et al.* 1999). With northwards subduction of the South China Block beneath the North China Block in the Triassic, crustal rocks in the subducting continental lithosphere were sequentially detached at different depths and then exhumed in the following order along a continental subduction channel (Zheng *et al.* 2005, 2013*b*): (1) greenschist-facies low-grade zone in North Huaiyang; (2) LT/HP zone in Susong; (3) LT/UHP zone in South Dabie; (4) MT/UHP zone in Central Dabie; and (5) HT/UHP zone in North Dabie. Whereas the three UHP zones experienced eclogite-facies metamorphism in the Triassic, the North Dabie zone suffered granulite-facies overprinting in the Early Cretaceous (Gao *et al.* 2017*b*). Subduction polarity is indicated by a progressive increase in metamorphic grade from HP to UHP.

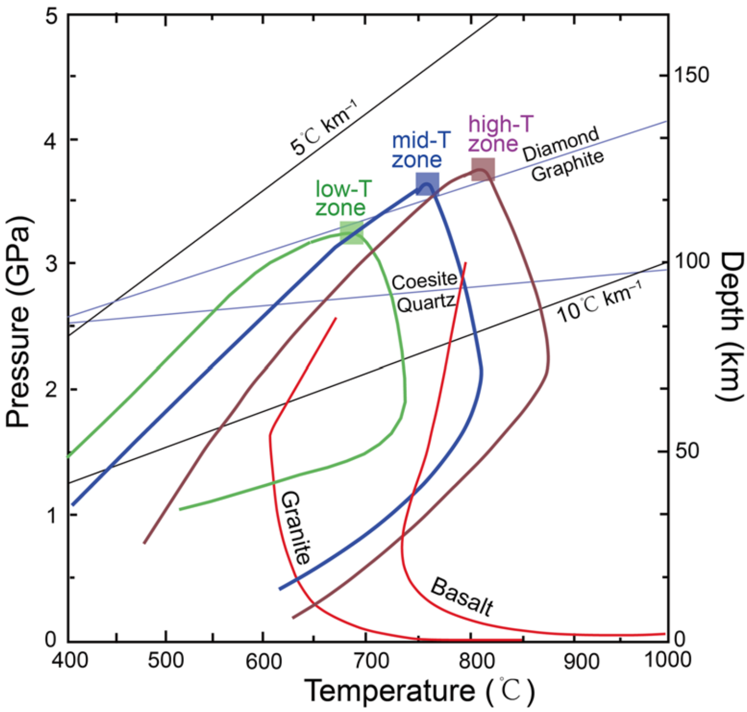

Fig. 3. Schematic diagram showing the clockwise *P*–*T* paths of three UHP metamorphic zones in the Dabie–Sulu orogenic belt. Data sources: the LT/UHP zone (Li X.-P. *et al.* 2004; Zheng *et al.* 2011*a*), the MT/UHP zone (Cong *et al.* 1995; Carswell & Zhang 1999; Gao *et al.* 2011) and the HT/UHP zone (Liu & Li 2008; Liu *et al.* 2015). Red curves denote the wet solidi of crustal rocks. A prominent feature is that these UHP slices were produced by continental subduction in low geothermal gradients of 5–10°C km^{-1}, but were exhumed at elevated temperatures from mantle depths to lower crust levels.

their exhumation is marked by elevated temperatures at reduced pressures (Fig. 3). This suggests that the UHP metamorphic rocks would have reached the maximum pressure in the last stage of subduction, whereas the maximum temperature was reached during the exhumation (Zheng 2012). Geochronological studies indicate that the high pressure (HP)–UHP eclogite-facies metamorphism may have lasted from *c.* 245 to *c.* 205 Ma, but the UHP metamorphism in the coesite stability field would have taken place between 240 and 225 Ma (Hacker *et al.* 2006; Liu *et al.* 2006; Wu Y.-B. *et al.* 2006; Zheng *et al.* 2009; Liu & Liou 2011). Whereas secondary-ion mass spectrometry (SIMS) zircon U–Pb dating of coesite-bearing domains yields a range of ages from 239 ± 3 to 218 ± 3 Ma for the UHP metamorphic event (Fig. 4a), all SIMS and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) zircon U–Pb dating of metamorphic zircon has bracketed the UHP eclogite-facies metamorphic episode between 242 ± 2 and 226 ± 2 Ma (Fig. 4b).

It is noteworthy that no Late Paleozoic–Early Mesozoic arc volcanics occur along the southern margin of the North China Block (Rumble *et al.* 2003; Zheng *et al.* 2003). Nevertheless, syn-exhumation magmatism is prominent in the Sulu orogen (Chen *et al.* 2003; Yang *et al.* 2005; Zhao *et al.* 2012, 2017*b*). In fact, partial melting of the UHP metamorphic rocks during exhumation is widespread in the Dabie–Sulu orogenic belt (Zheng *et al.* 2011*b*; Chen *et al.* 2017; Gao *et al.* 2017*a*; Xia & Zhou 2017). This is recorded by different degrees of migmatization at 225–215 Ma (Chen R.-X. *et al.* 2015; Li W.-C. *et al.* 2016; Chen *et al.* 2017). Amphibolite-facies retrogression is also widespread at 215–205 Ma (e.g. Hacker *et al.* 2000; Faure *et al.* 2003; Zhao *et al.* 2006).

The Early Cretaceous magmatic doming is prominent in the North Dabie zone (Hacker *et al.* 1998, 2000; Wu *et al.* 2007*b*; Zhao *et al.* 2008) and the NE Sulu zone (Wallis *et al.* 2005; Zhao *et al.* 2012), leading to crustal extension in response to the removal of the orogenic root from the continental collision zone (Gao *et al.* 2017*b*; Zhao *et al.* 2017*a*). Partial melting of the UHP metamorphic rocks is significant in the Early Cretaceous (Xu & Zhang 2017; Zhao *et al.* 2017*a*), which has overprinted the Triassic

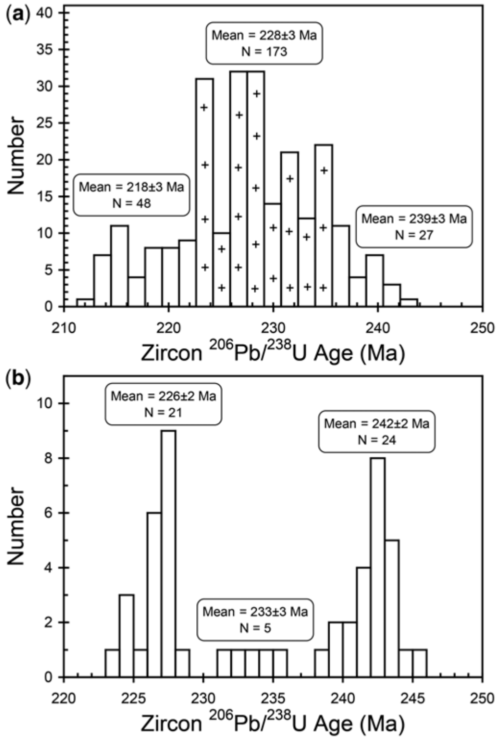

Fig. 4. Histograms of microbeam *in situ* U–Pb ages for zircon from UHP metamorphic rocks in the Dabie–Sulu orogenic belt, east-central China (revised after Zheng 2012). (**a**) SHRIMP U–Pb spot dates for the coesite-bearing domain of the metamorphically grown zircon; and (**b**) SIMS and LA-ICP-MS U–Pb dates for metamorphically grown zircons without identification of the coesite inclusion in the dating domain.

metamorphic structures. The buoyant ascent of melting products has brought the UHP rocks to the surface (Ratschbacher *et al.* 2000; Faure *et al.* 2003), a process similar to emplacement of metamorphic core complexes in rifting orogens (Zheng & Chen 2017). Although seismic tomography shows the absence of a relict continental slab at lower lithospheric depths beneath the collisional orogen (Dong *et al.* 2008; Luo *et al.* 2012; He *et al.* 2014), it does not mean that there has been no subduction of the continental crust to subarc depths in the Triassic (He & Zheng 2018). Therefore, there are three stages of exhumation for the Dabie–Sulu UHP rocks: (1) early exhumation of the HP blueschist- to eclogite-facies rocks in the Middle Triassic (247–235 Ma) from lower crust depths to upper crust depths; (2) peak exhumation of the UHP eclogite-facies rocks in the Late Triassic (235–220 Ma) from the subarc depths to forearc depths of 40–80 km; and (3) late exhumation of the UHP terranes to upper crust depths in the Early Cretaceous.

The petrographical features of UHP metamorphic rocks

A great deal of petrological studies have been devoted to UHP metamorphic rocks from the Dabie–Sulu orogenic belt (e.g. Wang *et al.* 1995; Cong 1996; Liou *et al.* 2000; Xu *et al.* 2006; Zhang Z.M. *et al.* 2008, 2009; Zheng *et al.* 2009; Liu & Liou 2011; Chen *et al.* 2017; Gao *et al.* 2017*a*; Xia & Zhou 2017). Based on field occurrence and wallrock association, three types of eclogite are recognized in the orogenic belt (Zheng *et al.* 2003, 2009): (a) G-type (Fig. 5), principally within granitic orthogneiss, and only minors interlayered with paragneiss – while the granitic gneiss was metamorphosed from granitic protoliths of Middle Neoproterozoic age, the paragneiss was metamorphosed from terrigenous sediments that contain detrital zircon of Paleoproterozoic–Archean age; (b) P-type (Fig. 6), in association with ultramafic rocks such as peridotite and pyroxenite; and (c) M-type (Fig. 7), interlayers with or enclaves within marble or calc-silicate rocks.

The G-type eclogite is most abundant because granitic orthogneiss is a predominant lithology in the bulk orogenic belt. The inclusions of coesite and quartz pseudomorphs after coesite are common in nominally anhydrous minerals such as garnet and omphacite (right-hand panels in Fig. 5). Some coesite grains are rimmed by a thin palisade layer of quartz aggregates, whereas others are totally replaced by a mosaic of coarser-grained quartz aggregates. The majority of host minerals for coesite inclusions show characteristic radiating fractures. In addition to garnet, omphacite/jadeite, coesite/quartz, kyanite, apatite and rutile, minor hydrous phases including phengite, epidote/zoisite, talc and nyböite also occur as UHP minerals. Although microdiamond has been reported as an inclusion in Dabie eclogites (Xu *et al.* 1992; Okay 1993), its occurrence has not been confirmed by others. At the Yangkou Beach in the middle Sulu zone, progressive mineral transformation from gabbro to coesite eclogite occurs in a subrounded UHP slice 30 m in diameter (Liou & Zhang 1996). While a relict gabbro assemblage of plagioclase + augite + orthopyroxene + quartz ± biotite + ilmenite/Ti-magnesite and ophitic textures are preserved in the core of the eclogitic block, coesite eclogite occurs along the block margins; rocks with transitional assemblages occur in-between. The preservation of relict igneous minerals and textures in gabbros, low-pressure assemblages in transitional rocks, and the occurrence of intergranular coesite in eclogite indicate the absence of free water for fluid infiltration during the subduction and exhumation of this piece of continental crust. The adjacent metagranitic slice also shows a similar relict igneous assemblage in the core and a coesite-bearing assemblage in the block margins (e.g. Wallis *et al.* 1997).

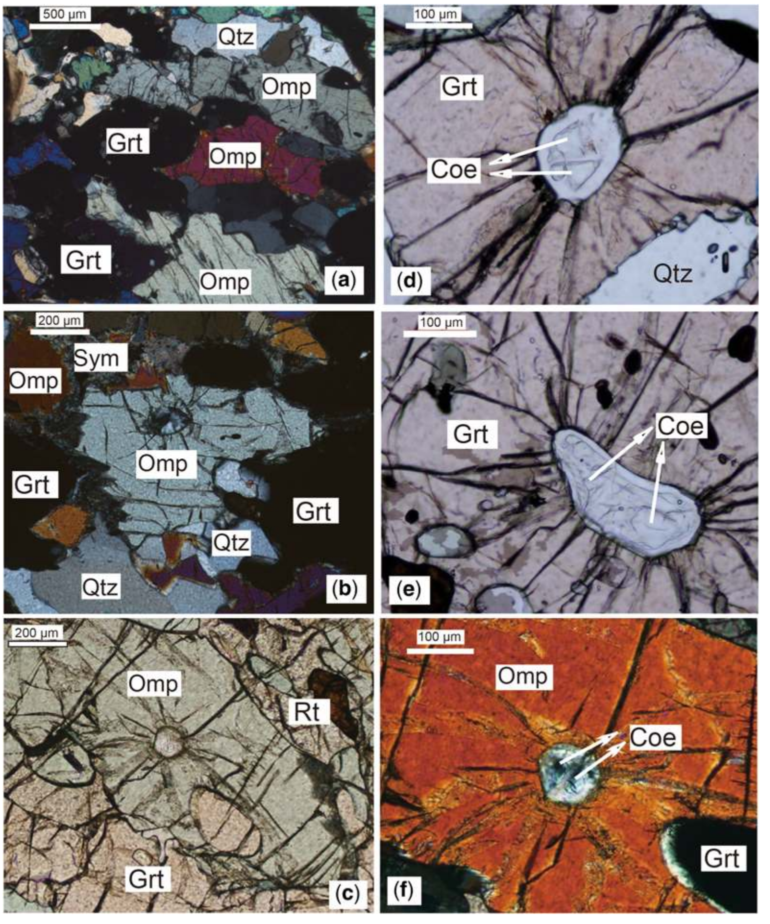

Fig. 5. Photomicrographs from G-type UHP eclogite at Shuanghe in the Dabie orogen. (**a**), (**b**) and (**c**) Eclogites composed of garnet, omphacite, quartz and rutile. (**d**), (**e**) and (**f**) Coesite plus polycrystalline quartz inclusion in garnet with radial cracks. Note the high relief of the coesite relicts surrounded by polycrystalline quartz. Mineral abbreviations are after Whitney & Evans (2010).

The P-type eclogite is mainly bimineralic, primarily composed of garnet and omphacite. It is often either dark-coloured, with more rutile (left-hand panels in Fig. 6), or light-coloured with more quartz, muscovite and kyanite (right-hand panels in Fig. 6). Round to oval-shaped inclusions of polycrystalline quartz aggregates after coesite occur in garnet and omphacite with well-developed radial fractures in eclogites from the Sulu orogen (Liou *et al.* 2000), including outcrops at Chijiadian in Rongcheng, Xugou in Donghai and Houshuichegou in Rizhao. Minute K-feldspar inclusions were identified in eclogitic garnet (Yang *et al.* 1998). Rare corundum-bearing garnetite and eclogite occur as lenses in garnet lherzolite from Zhimafang in Donghai (Enami & Zang 1988).

The M-type eclogite occurs mainly as small boudins and has sharp contacts with the marble; some are concordant layers within banded marble and calc-silicate rocks. A representative assemblage is garnet + omphcite + rutile ± zoisite ± high-Al titanite (Fig. 7). Some eclogites in marble from Dabie contain magnesite and dolomite. Mineralogical evidence for UHP metamorphism of the Dabie marble comes from Wumiao, where calcite pseudomorphs after aragonite are present in garnet (Wang & Liou 1993) and inclusions of coesite are present in dolomite crystals of calc-silicate rocks (Schertl & Okay 1994; Zhang & Liou 1996). Eclogite-bearing UHP marbles were also studied in detail for several outcrops: for instance, those at Kongjiadian in the Sulu orogen (Kato *et al.* 1997; Ogasawara *et al.* 1998) and at Xinyan in the Dabie orogen (Omori *et al.* 1998). The Kongjiadian marble exhibits several parageneses: magnesite-calcite + Ti-clinohumite ± dolomite ± diopside; magnesite-calcite + dolomite ± olivine ± diopside; and

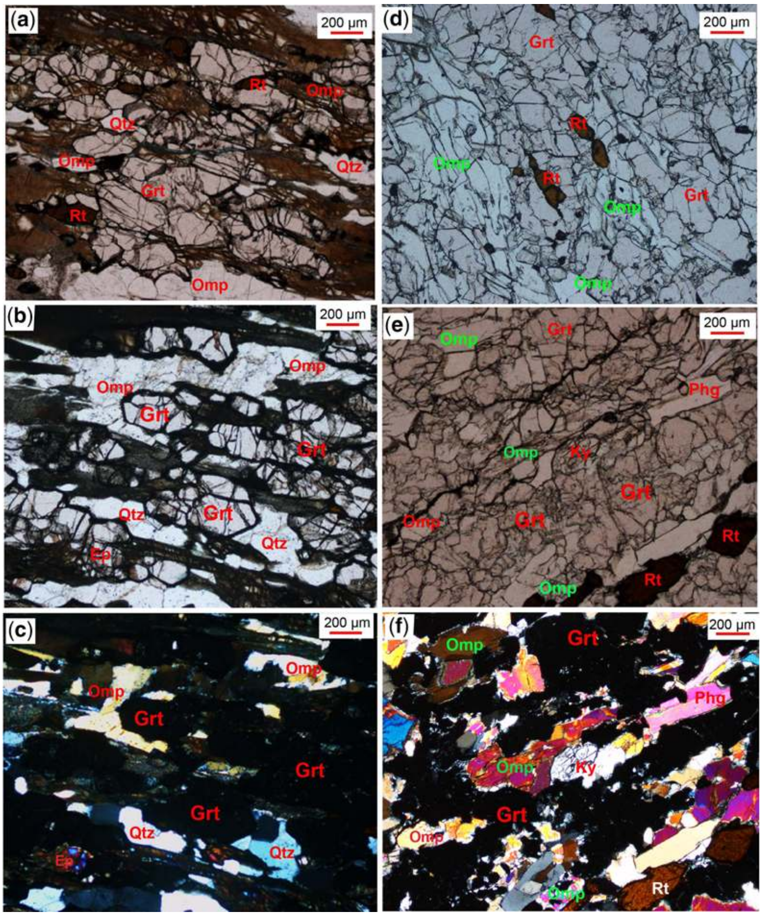

Fig. 6. Photomicrographs from P-type UHP eclogite at Bixiling in the Dabie orogen. (**a**), (**b**) and (**c**) Dark-coloured eclogite that is primarily composed of garnet and omphacite, with minor amounts of rutile, epidote and quartz. (**d**), (**e**) and (**f**) Light-coloured eclogite that is primarily composed of garnet and omphacite, with minor amounts of quartz, muscovite, kyanite and rutile. Mineral abbreviations are after Whitney & Evans (2010).

magnesite-calcite + dolomite + olivine + diopside + Ti-clinohumite (Ogasawara *et al.* 1998). Although inclusions of quartz pseudomorphs after coesite have not been found in the marble, *P*–*T* estimates of 2.5–3.5 GPa and 610–660°C were obtained by phase equilibria and thermodynamic calculations (Kato *et al.* 1997; Ogasawara *et al.* 1998), suggesting that the Kongjiadian marble also experienced UHP metamorphism.

Regardless of their occurrence, the three types of eclogite exhibit various degrees of retrograde metamorphism under amphibolite-facies conditions, with local granulite-facies overprinting in the North Dabie zone (Liu Y.C. *et al.* 2011*a*; Jian *et al.* 2012; Wang S.-J. *et al.* 2012; Groppo *et al.* 2015) and the Weihai zone (Zong *et al.* 2010; Liu F.L. *et al.* 2012; Li W.-C. *et al.* 2016). One typical example of granulite-facies overprinting is coesite eclogite at Weihai in the NE Sulu zone, which shows corona replacement of garnet by orthopyroxene, clinopyroxene and plagioclase, and intergrowths of diopside and plagioclase after omphacite (e.g. Wang *et al.* 1993; Zhang *et al.* 1995*b*). In contrast, amphibolite-facies-overprinted eclogites show symplectic intergrowths of plagioclase + amphibole after omphacite and tarametic amphibole after garnet (e.g. Wang *et al.* 1995). Thin, dark retrograde bands commonly occur at the contacts between the eclogite and its host rock. Moreover, exsolution textures are common in some UHP minerals from various eclogites; these include quartz rods in omphacite, rutile lamellae in garnet, and lamellae of an unknown phase in apatite (Liou *et al.* 2000).

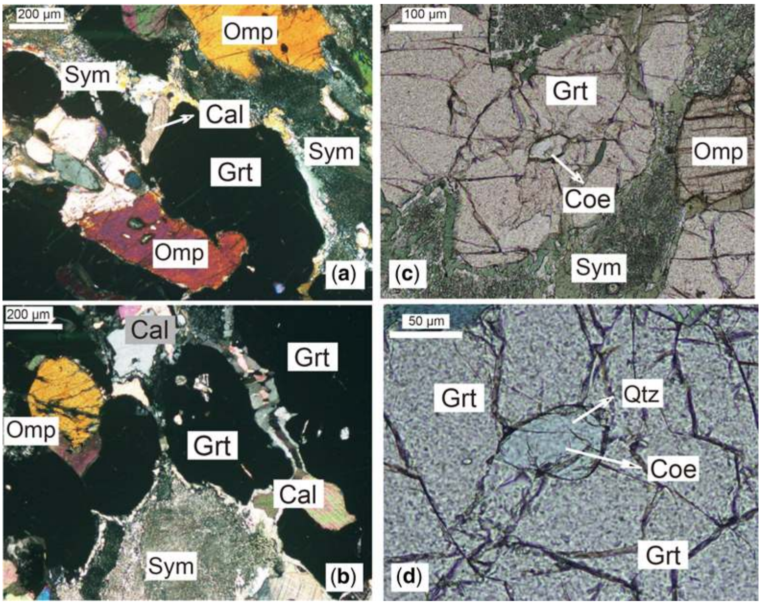

Fig. 7. Photomicrographs from M-type UHP eclogite at Shuanghe in the Dabie orogen. (**a**) and (**b**) Eclogites composed of garnet, omphacite and quartz. (**c**) and (**d**) Coesite inclusion in garnet with radial cracks. Mineral abbreviations are after Whitney & Evans (2010).

In addition to the marbles, metasedimentary rocks that carry the UHP metamorphic signature include kyanite quartzite, jadeite quartzite, pelite and paragneiss. These metasediments occur as interlayers with eclogite or as the country rock enclosing eclogite. Some kyanite quartzites are composed of quartz (>80 vol%), kyanite, pyrite, rutile and topaz (Zhang R.Y. *et al.* 2002); other quartzites interlayered with eclogite are composed of quartz (>60–70 vol%) and kyanite, subordinate zoisite ± phengite ± omphacite ± epidote, and minor garnet and rutile (Zhang *et al.* 1995*a*). Coesite-bearing jadeite quartzite from Shuanghe in the Dabie orogen occurs as intercalated layers with marble and mafic eclogite, and is composed of 35–40 vol% jadeite, 45–60% quartz, 5% garnet and a trace of rutile (Liou *et al.* 1997). Crystal inclusions of coesite and quartz pseudomorphs after coesite are present in garnet, jadeite, epidote and kyanite in jadeite quartzite and in kyanite quartzite.

Orogenic peridotites and pyroxenites, including garnet-bearing lherzolite, harzburgite, wehrlite, websterite and pyroxenites, occur as blocks with diameters up to 1 km in size, as well as thin layers within felsic gneisses. They contain eclogite lenses (or nodules) and layers with minor inclusions of coesite and coesite pseudomorphs in garnet and omphacite. Although the peridotites are partially to completely serpentinized, they can be reconstructed to be mainly composed of olivine, enstatite, diopside and garnet, with minor phlogopite, amphibole, Ti-clinohumite, chlorite, magnesite and Fe–Ti oxides. Two distinct types of garnet peridotite were identified according to the mode of their occurrence and geochemical characteristics (Zhang R.Y. *et al.* 2000). M-type peridotites were offscrapped from the overlying subcontinental lithospheric mantle (SCLM) wedge base by tectonic erosion during continental subduction, and C-type peridotites were part of ultramafic intrusions that were emplaced into the continental crust before continental subduction. Both types of garnet peridotites were subjected to the Triassic UHP metamorphism in the continental subduction zone with cold geotherms. Mineral exsolution textures are common, including ilmenite rods and magnetite lamellae in olivine, Mg–Al–Cr titanomagnetite and/or ilmenite and garnet rods in clinopyroxene, and rutile lamellae in garnet.

The geochemical composition of UHP metamorphic rocks

A large number of geochemical analyses have been devoted to UHP metamorphic rocks from the Dabie–Sulu orogenic belt. We have compiled these geochemical data for the purpose of reconstructing the protolith composition of these rocks. It is known that crustal rocks underwent significant dehydration during their subduction from the forearc to subarc depths (Zheng *et al.* 2016), and these dehydrated UHP rocks may have suffered partial melting during their initial exhumation from the subarc to forearc depths (Zheng *et al.* 2011*b*). The metamorphic dehydration may have released water-soluble incompatible elements such as large ion lithophile elements (LILEs) from subducting rocks, and partial melting may have mobilized melt-mobile incompatible elements such as LILE and light rare earth elements (LREEs) to different extents (Zheng *et al.* 2009; Zheng & Hermann 2014). Nevertheless, either water-soluble or melt-mobile elements would have been lost in very low amounts relative to UHP rocks in the deeply subducted continental crust. As a consequence, the UHP metamorphic rocks have mainly preserved their protolith compositions despite the metamorphic dehydration and partial melting (Zheng *et al.* 2009, 2011*b*).

As shown in the total alkalis v. silica (TAS) diagram (Fig. 8), both UHP eclogite and gneiss exhibit variable SiO_2 and alkaline contents. The eclogites have low SiO_2 contents and variable $Na_2O + K_2O$ contents from subalkaline to alkaline, mainly falling in the mafic domains of gabbro, gabbroic diorite and diorite. Both granitic gneiss and paragneiss have relatively high SiO_2 contents and are almost subalkaline, mainly lying in the felsic domains of granite, granodiorite and diorite. As shown in Figure 9, the eclogites show much larger variations in both major and trace elements. There are good correlations between Mg# and fluid-immobile/refractory elements such as FeO, TiO_2, Cr and Ni; whereas there are no clear correlations between Mg# (= the molecular proportion of MgO/(MgO + FeO), assuming 90% of total iron is ferrous iron) and fluid-mobile/fusible elements such as SiO_2, Al_2O_3, CaO, K_2O, Sr and Ba. The gneisses also exhibit large variations in both major and trace elements (Fig. 10). In contrast to the eclogites, the gneisses show regular changes with SiO_2 for most of the major elements. With increasing SiO_2 contents, there are decreases in CaO, TiO_2, Al_2O_3, FeO, MgO and P_2O_5. However, SiO_2 is not correlated with fluid-mobile elements (i.e. K_2O, Rb, Sr and Ba). Despite this, most of the gneisses have relatively high K_2O contents and fall in the domains of calc-alkaline and high-K calc-alkaline (Fig. 10f).

Most of the eclogites show relatively small variations in heavy rare earth element (HREE) contents and flat HREE distribution patterns on the chondrite-normalized REE diagram (Fig. 11a). Most of the eclogites show insignificant Eu anomalies. However, their LREE contents exhibit significant variations. They vary from pronounced LREE depletion, LREE flat to significant LREE enrichment with $(La/Yb)_N$ ratios of 0.10–27.47 (Fig. 11a). In terms of their REE distribution patters, all of the UHP eclogites can be categorized into three groups: (1) LREE

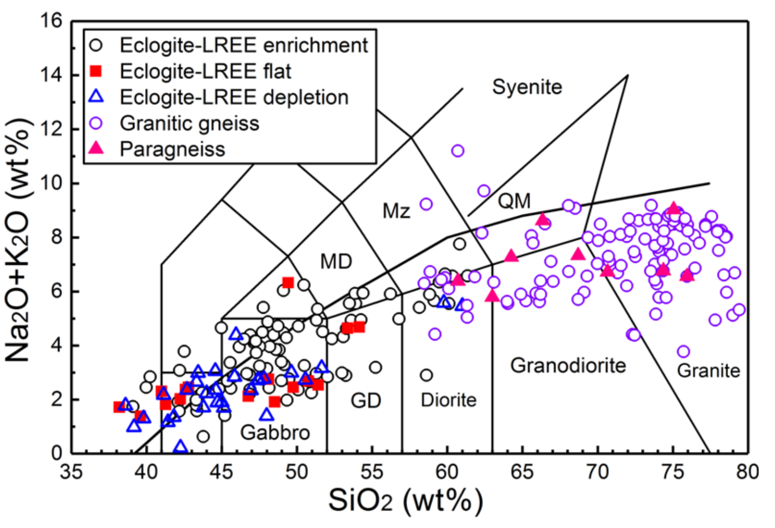

Fig. 8. Total alkali v. SiO_2 (TAS) diagram for UHP eclogites and gneisses from the Dabie–Sulu orogenic belt. The classification is after Irvine & Baragar (1971) and Middlemost (1994). Rock abbreviations: GD, gabbroic diorite; MD, monzodiorite; QM, quartz monzonite; Mz, monzonite. Data sources: Chavagnac & Jahn (1996), Jahn (1998), Zheng *et al.* (1999), Li *et al.* (2000), Ma *et al.* (2000), Zhang Z.M. *et al.* (2000, 2004, 2005, 2006*a*, *b*, 2009), Chen *et al.* (2002), Bryant *et al.* (2004), Liu F.L. *et al.* (2004, 2007), Tang H.-F. *et al.* (2007), Tang *et al.* (2008*b*), Xue *et al.* (2007), Zhao *et al.* (2007*a*), Schmidt *et al.* (2008, 2011), Xia *et al.* (2008), Yang *et al.* (2009) and Chen Y.-X. *et al.* (2016).

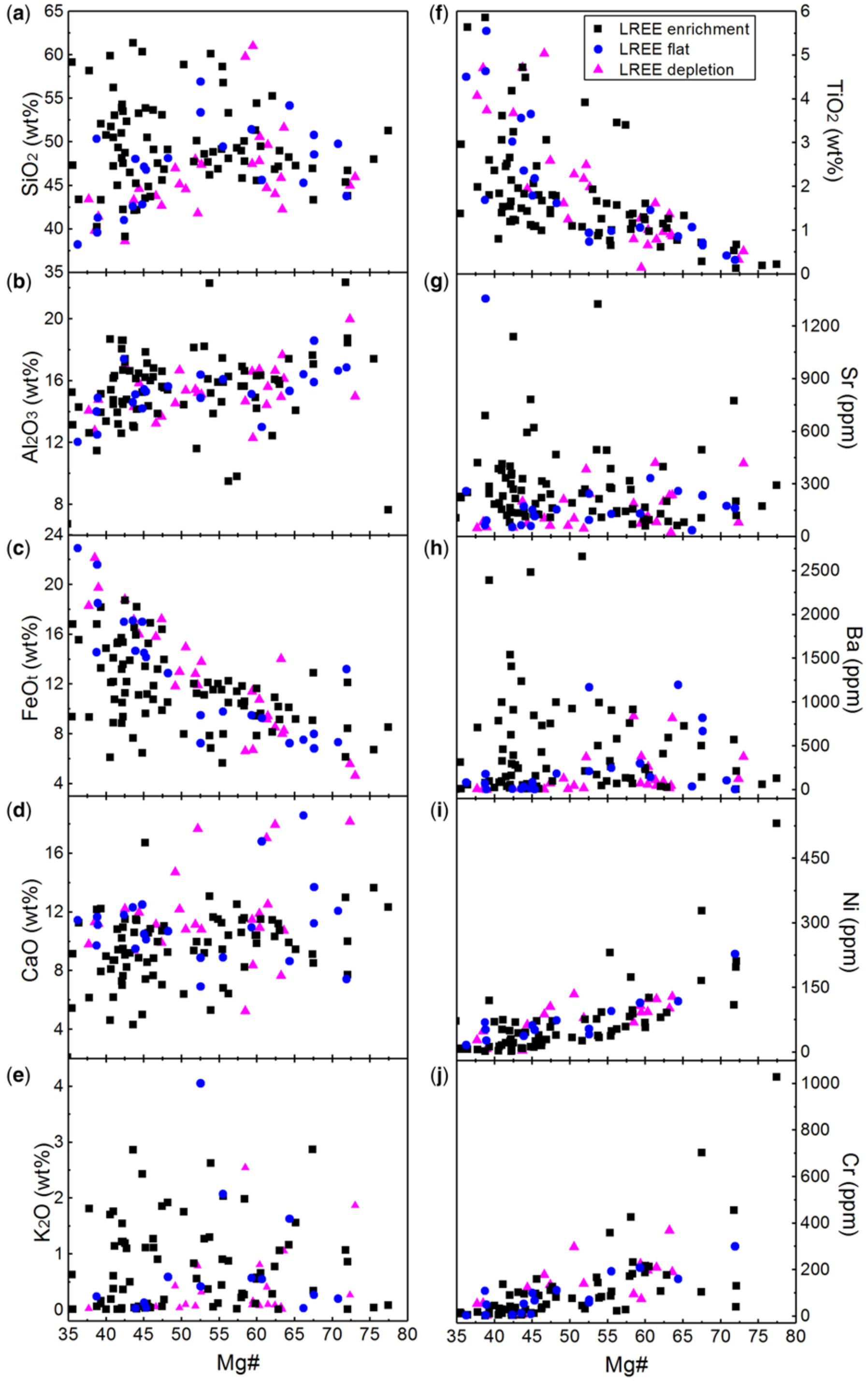

Fig. 9. Geochemical variation diagrams of major and trace elements as a function of Mg numbers for UHP eclogites from the Dabie–Sulu orogenic belt. Data sources: Chavagnac & Jahn (1996), Jahn (1998), Li *et al.* (2000), Zhang Z.M. *et al.* (2000, 2004, 2005, 2006*a*, *b*, 2009), Chen *et al.* (2002), Liu Y.-H. *et al.* (2007), Tang H.-F. *et al.* (2007), Tang *et al.* (2008*b*), Zhao *et al.* (2007*a*), Schmidt *et al.* (2008, 2011), Yang *et al.* (2009) and Chen Y.-X. *et al.* (2016).

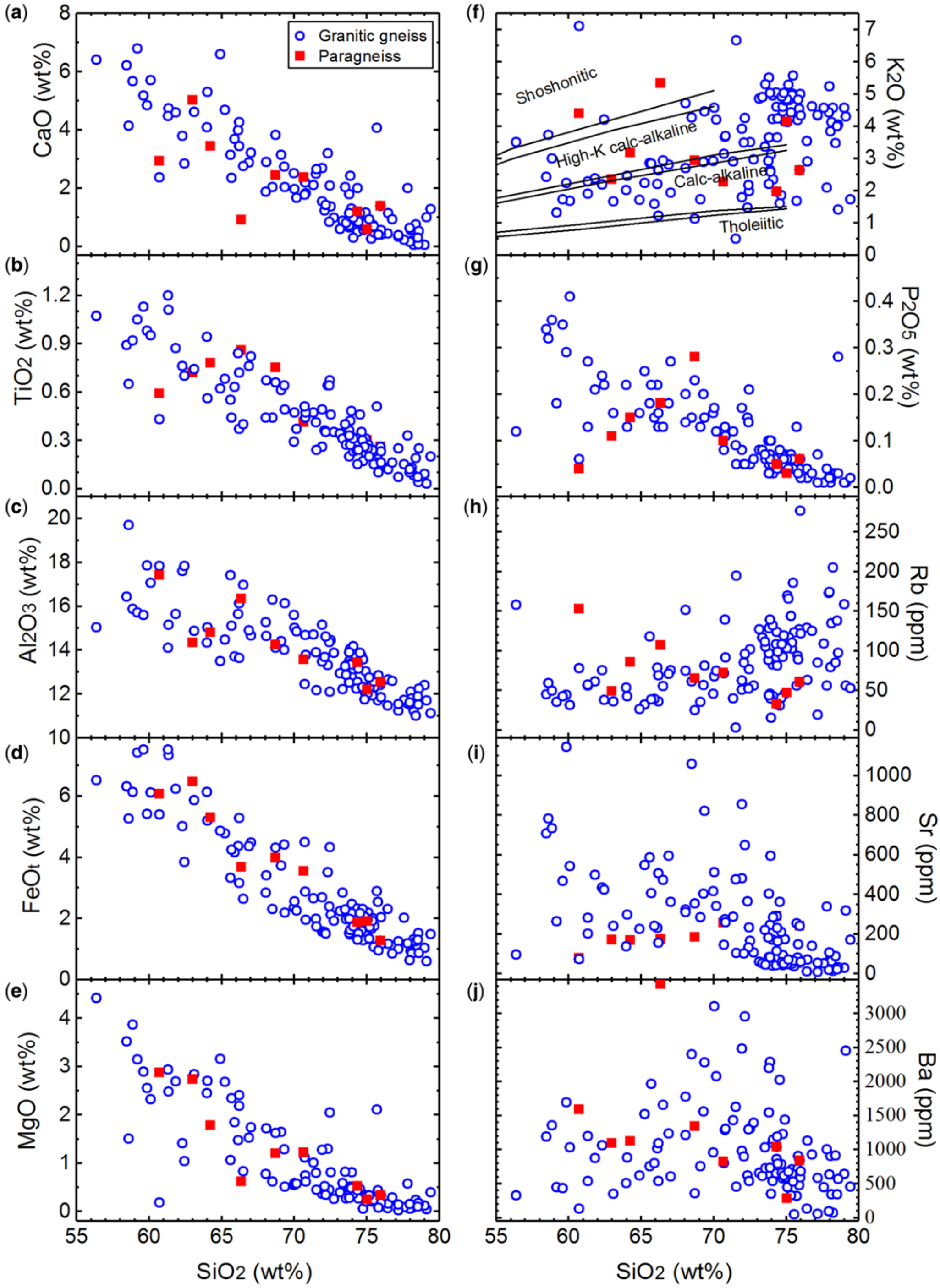

Fig. 10. Harker diagrams for UHP gneisses from the Dabie–Sulu orogenic belt. Separating lines in K_2O v. SiO_2 diagram are from Rickwood (1989). Data sources: Zheng *et al.* (1999), Li *et al.* (2000), Ma *et al.* (2000), Chen *et al.* (2002), Bryant *et al.* (2004), Liu *et al.* (2004), Zhang Z.M. *et al.* (2005, 2006*a*, *b*, 2009), Xue *et al.* (2007), Zhao *et al.* (2007*a*), Tang *et al.* (2008*b*) and Xia *et al.* (2008).

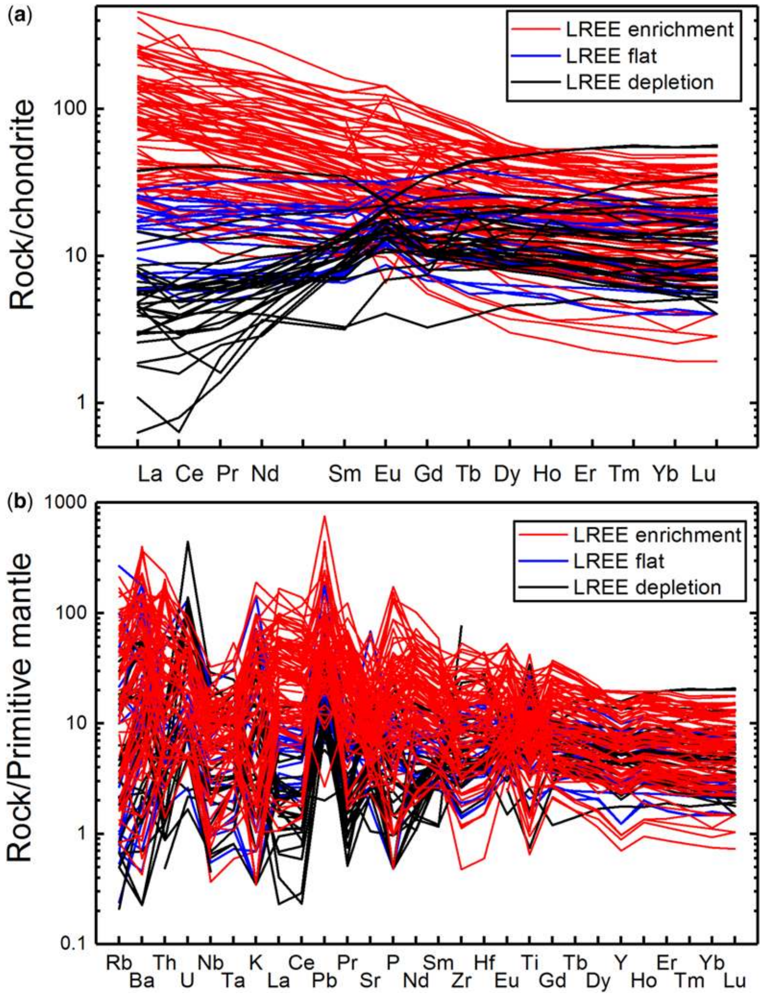

Fig. 11. (**a**) Chondrite-normalized REE patterns and (**b**) primitive mantle-normalized spidergrams for UHP eclogites from the Dabie–Sulu orogenic belt. The chondrite REE contents and primitive mantle trace element contents are from McDonough & Sun (1995). Data sources are the same as those in Figure 8.

enrichment; (2) LREE flat; and (3) LREE depletion. While the LREE enrichment is inherited from their protoliths of the continental crust (Jahn 1998), the LREE depletion is caused by extraction of felsic melts during exhumation of the deeply subducted continental crust (Zhao *et al.* 2007*a*). Although both granitic gneiss and paragneiss have large variations in their REE contents, they exhibit consistently LREE enrichment relative to HREE with $(La/Yb)_N$ ratios of 1.42–139.85 (Fig. 12a). In addition, most of the gneisses show significant Eu negative anomalies, different from the eclogites.

On the primitive mantle-normalized spidergram (Fig. 11b), the eclogites show distinct features in trace element distribution. While the majority of eclogites exhibit significant enrichment in LILE, Pb and LREE relative to high field strength elements (HFSE) and HREEs, few eclogites are considerably depleted in LILE (e.g. Rb, Ba and K) and LREE. The LILE depletion is more prominent for the samples with LREE flat and depletion. As a whole, nevertheless, the majority of eclogites exhibit concomitant depletions in Nb, Ta and Ti but enrichment in Pb, typical of mafic arc volcanics and continental crust (Kelemen *et al.* 2014; Rudnick & Gao 2014). In addition, the eclogites with LREE enrichment generally show differentially higher contents of most trace elements than those with LREE flat and depletion. In trace element geochemistry, the enrichment in LILE, Pb and LREE, but the depletion in Nb and

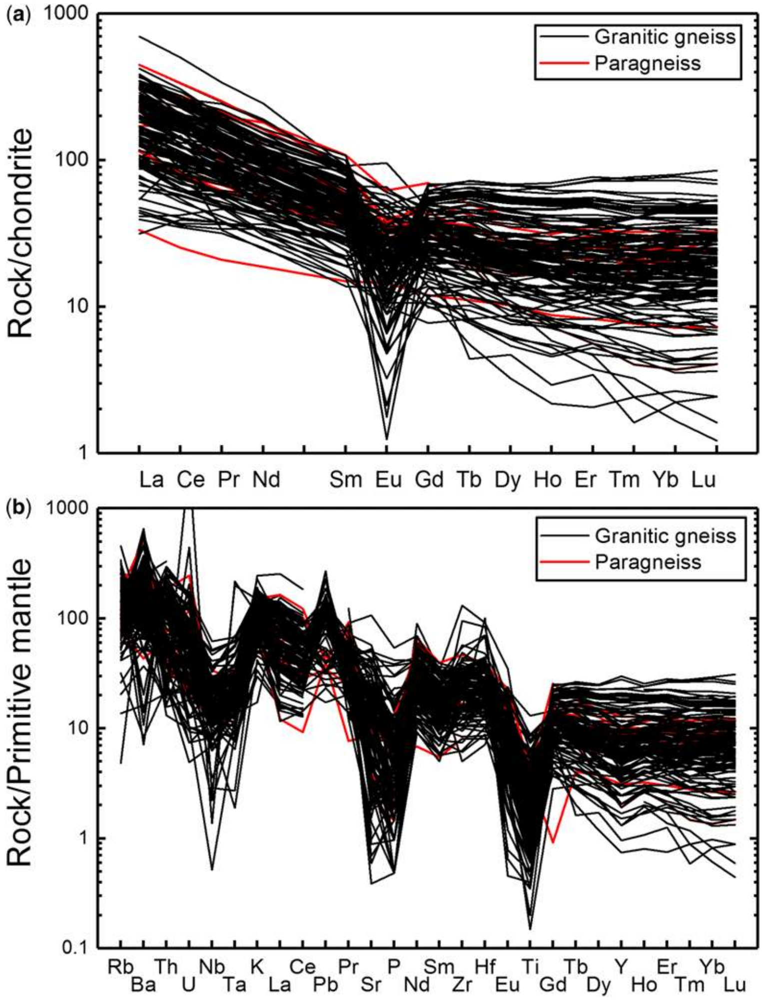

Fig. 12. (**a**) Chondrite-normalized REE patterns and (**b**) primitive mantle-normalized spidergrams for UHP gneisses from the Dabie–Sulu orogenic belt. The chondrite REE contents and primitive mantle trace element contents are from McDonough & Sun (1995). Data sources are the same as those in Figure 9.

Ta relative to HREE, are referred to as arc-like distribution patterns. Such patterns are also prominent for both granitic gneiss and paragneiss from the Dabie–Sulu orogenic belt (Fig. 12b).

Whole-rock $^{87}Rb/^{86}Sr$ ratios for the eclogites are relatively low, but have a large variation from 0.005 to 1.98. Calculated $(^{87}Sr/^{86}Sr)_i$ ratios are 0.7038 to 0.7142 at $t_2 = 230$ Ma for the UHP metamorphic age, but some samples exhibit unreasonably low ratios down to 0.6919 when calculated at $t_1 = 750$ Ma for the protolith age (Fig. 13). This indicates that their Rb–Sr isotopic system suffered secondary disturbance (Zheng 1989), which may occur during subduction zone metamorphism in the Triassic. The gneisses have variable, but high, whole-rock $^{87}Rb/^{86}Sr$ ratios of 0.31–81.75, most of the samples have $(^{87}Sr/^{86}Sr)_i$ ratios of 0.7068–0.7145 at $t_2 =$ 230 Ma, but a few samples have high $(^{87}Sr/^{86}Sr)_i$ ratios up to 0.8830 at $t_2 = 230$ Ma. In addition, when calculated at $t_1 = 750$ Ma, a few samples have much lower $(^{87}Sr/^{86}Sr)_i$ ratios of down to 0.6941, which also indicates the disturbance of Rb–Sr isotope systems by the Triassic UHP metamorphism.

While there is no systematic difference in $^{87}Rb/^{86}Sr$ ratios between the three groups of eclogites, their $^{147}Sm/^{144}Nd$ ratios are significantly different, increasing from 0.1042–0.2147 for the samples of LREE enrichment, to 0.1650–0.3138 for the samples of LREE flat to 0.3364–0.5969 for the samples of LREE depletion. The eclogites with

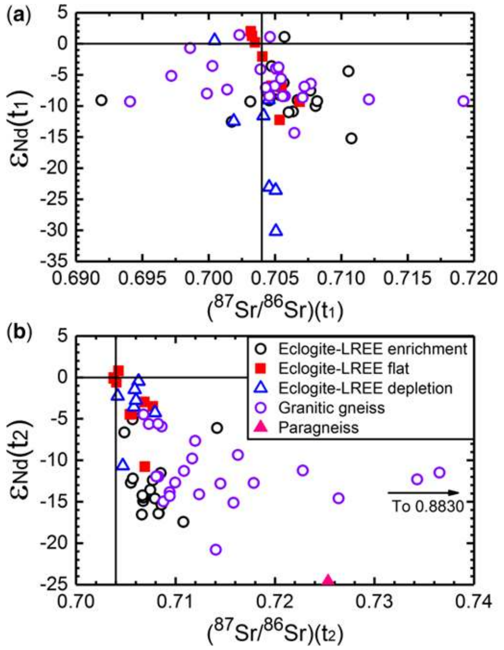

Fig. 13. Plots of initial Sr and Nd isotope ratios at (**a**) $t_1 = 750$ Ma and (**b**) $t_2 = 230$ Ma for UHP eclogites and gneisses from the Dabie–Sulu orogenic belt. Data sources: Chavagnac & Jahn (1996), Jahn (1998), Li *et al.* (2000), Ma *et al.* (2000), Chen *et al.* (2002), Liu F.L. *et al.* (2007), Zhao *et al.* (2007*a*), Tang *et al.* (2008*b*), Xia *et al.* (2008), Xie *et al.* (2010) and Chen Y.-X. *et al.* (2016).

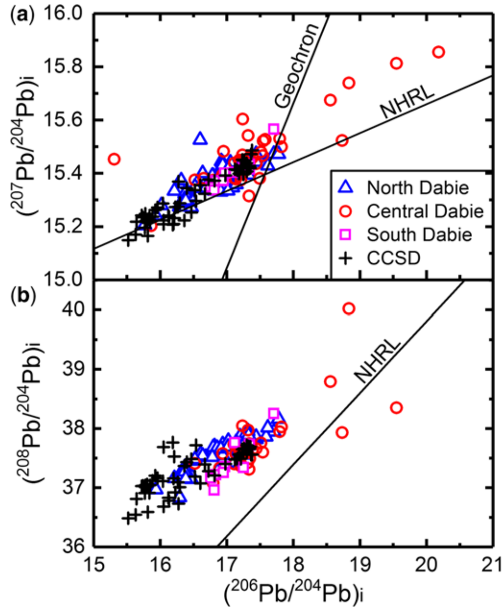

Fig. 14. Whole-rock and mineral (omphacite and feldspar) Pb isotopic ratios for the eclogites and gneisses from the Dabie–Sulu orogenic belt. Whole-rock initial Pb isotopic ratios are calculated back to $t = 230$ Ma. The Pb isotope ratio for the northern hemisphere reference line (NHRL) is defined as: $(^{207}Pb/^{204}Pb)_{NHRL} = 0.1084\ (^{206}Pb/^{204}Pb)_i + 13.491$; $(^{208}Pb/^{204}Pb)_{NHRL} = 1.209\ (^{206}Pb/^{204}Pb)_i + 15.627$ (Hart 1984). Data sources: Zhang H.F. *et al.* (2002), Zhang R.Y. *et al.* (2002), Li S.G. *et al.* (2003, 2009) and Shen *et al.* (2014).

LREE depletion have very high $^{147}Sm/^{144}Nd$ ratios of 0.3364–0.5969, resulting in unreasonably low $\varepsilon_{Nd(t)}$ values of −30.3 to −11.6 when calculated at $t_1 = 750$ Ma but reasonable $\varepsilon_{Nd(t)}$ values of −10.6 to −0.5 when calculated at $t_2 = 230$ Ma in comparison to the other eclogites (Fig. 13). In addition, there is a roughly negative correlation between $\varepsilon_{Nd(t_1)}$ and $^{147}Sm/^{144}Nd$ ratios for the eclogites (not shown), suggesting the overcorrection to initial $^{143}Nd/^{144}Nd$ ratios for the samples with high $^{147}Sm/^{144}Nd$ ratios. This indicates that the protolith of the eclogites should be enriched in LREEs, and the depletion in LREEs would have been caused by extraction of felsic melts in the Triassic (Zhao *et al.* 2007*a*). Therefore, the depletion of both LILEs and LREEs in those eclogites (Fig. 11) is likely to have resulted from the Triassic metamorphism, but the HFSE and HREE were not significantly modified by the metamorphism (Jahn 1998; Li *et al.* 2000; Zhao *et al.* 2007*a*). Compared to the eclogites, the gneisses have restricted and lower $^{147}Sm/^{144}Nd$ ratios of 0.0905–0.1625 with calculated $\varepsilon_{Nd(t_1)}$ values of −14.3 to 1.4 and $\varepsilon_{Nd(t_2)}$ values of −24.6 to −1.4 (Fig. 13).

The Dabie–Sulu UHP metamorphic rocks (including eclogite, granitic gneiss and paragneiss) have variable whole-rock and mineral (omphacite and feldspar) Pb isotope compositions, with $^{206}Pb/^{204}Pb$ ratios of 15.309–20.182, $^{207}Pb/^{204}Pb$ ratios of 15.453–15.855 and $^{208}Pb/^{204}Pb$ ratios of 36.484–40.020 (Fig. 14). Although there are some overlaps, the UHP metamorphic rocks from the Central Dabie zone exhibit much higher Pb isotope ratios than those from the North Dabie and South Dabie zones. Moreover, the CCSD main hole (CCSD-MH) UHP metamorphic rocks have relatively low Pb isotope ratios, suggesting that these rocks would have evolved at low U/Pb ratios for considerable durations.

A series of zircon U–Pb dating and O isotope analysis has been made on metamorphic rocks from the Dabie–Sulu orogenic belt (Rumble *et al.* 2002; Zheng *et al.* 2003, 2004, 2006, 2007*b*, 2008*a*, 2009; Wu *et al.* 2007*a*; Tang *et al.* 2008*a*, *b*; Chen Y.-X. *et al.* 2011; Fu *et al.* 2013; He *et al.* 2016). The results show that igneous protoliths of these metamorphic rocks mostly have

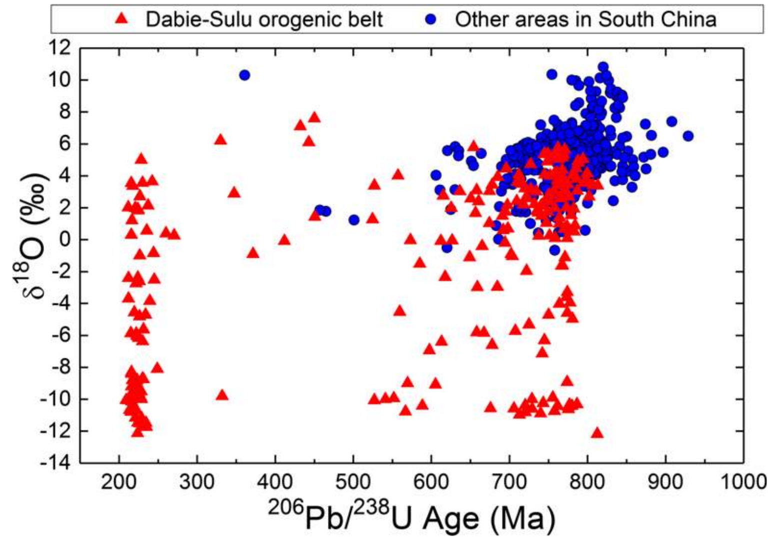

Fig. 15. SIMS zircon U–Pb age and O isotope data for metaigneous rocks from the Dabie–Sulu orogenic belt and elsewhere in South China. Data for the Dabie–Sulu orogenic belt are from Chen Y.-X. *et al.* (2011) and He *et al.* (2016), and those for other areas in South China are from Wang X.-C. *et al.* (2011), Fu *et al.* (2013) and Liu & Zhang (2013).

zircon U–Pb ages of 740–780 Ma and are variably depleted in ^{18}O relative to normal mantle (Fig. 15). Negative $\delta^{18}O$ zircon of magmatic origin only locally occurs in an UHP metagranite at Zaobuzhen in the NE Sulu zone (Tang *et al.* 2008*a*; He *et al.* 2016). The O isotope analysis of metamorphic minerals from outcrop samples indicates regional ^{18}O depletion along the Dabie–Sulu orogenic belt (Zheng *et al.* 2003, 2004; Tang *et al.* 2008*a*, *b*). Together with the O isotope analysis of CCSD-MH cores, the regional ^{18}O depletion is estimated to have a volume of >100 000 km^3 in the northern margin of the South China Block (Zheng *et al.* 2009; Zhang *et al.* 2011). Such a regional O isotope anomaly is unique in collisional orogens, providing us with an excellent opportunity to decipher crust–mantle interactions in continental subduction zones. Zircon Lu–Hf isotope analyses yield a range of $\varepsilon_{Hf(t)}$ values that mainly fall into two groups: one from 1.1 ± 0.6 to 10.1 ± 0.6 and the other from -9.1 ± 1.1 to -2.7 ± 0.6 (Zheng *et al.* 2009; Zhang *et al.* 2014). They correspond to two periods of juvenile crustal growth at 1.13 ± 0.14 and 1.98 ± 0.22 Ga, respectively.

Metamorphic modification during collisional orogeny

Multidisciplinary studies have been devoted in the past three decades to UHP metamorphic rocks and their adjacent lithotectonic units in the Dabie–Sulu orogenc belt (see reviews by Liou *et al.* 2000, 2009, 2012; Zheng *et al.* 2003, 2009, 2012; Ernst *et al.* 2007; Zheng 2008, 2009, 2012; Zhang R.Y. *et al.* 2009; Liu & Liou 2011). The results demonstrate that the two UHP metamorphic terranes were created by collisional orogeny due to northwards subduction of the South China Block beneath the North China Block in the Triassic (Fig. 16a). The exhumed UHP slices are now present in the upper continental crust chiefly as thin subhorizontal slices, bounded by normal faults on the top and reverse faults on the bottom, and sandwiched in HP or lower-grade metamorphic units. The foreland of the Dabie–Sulu orogenic belt constitutes the lower Yangtze fold-thrust belt, which were structurally deformed by north–south contraction in the Middle–Late Triassic (Hacker *et al.* 2000; Xu *et al.* 2006). This indicates the exhumation effect on the deformation of supracrustal rocks in the foreland region. Although syn-exhumation igneous rocks only occur sporadically in the Sulu orogen (Chen *et al.* 2003; Yang *et al.* 2005; Zhao *et al.* 2012, 2017*b*), post-collisional granitoids are common along the bulk Dabie–Sulu orogenic belt (Zhao *et al.* 2017*a*).

Petrological modification of the continental crust in the Triassic is significant in Dabie–Sulu UHP metamorphic rocks (e.g. Wang *et al.* 1995; Cong 1996; Liou *et al.* 2000; Xu *et al.* 2006; Zhang R.Y. *et al.* 2008, 2009; Zhang Z.M. *et al.* 2009; Zheng *et al.* 2009; Liu & Liou 2011; Chen *et al.* 2017).

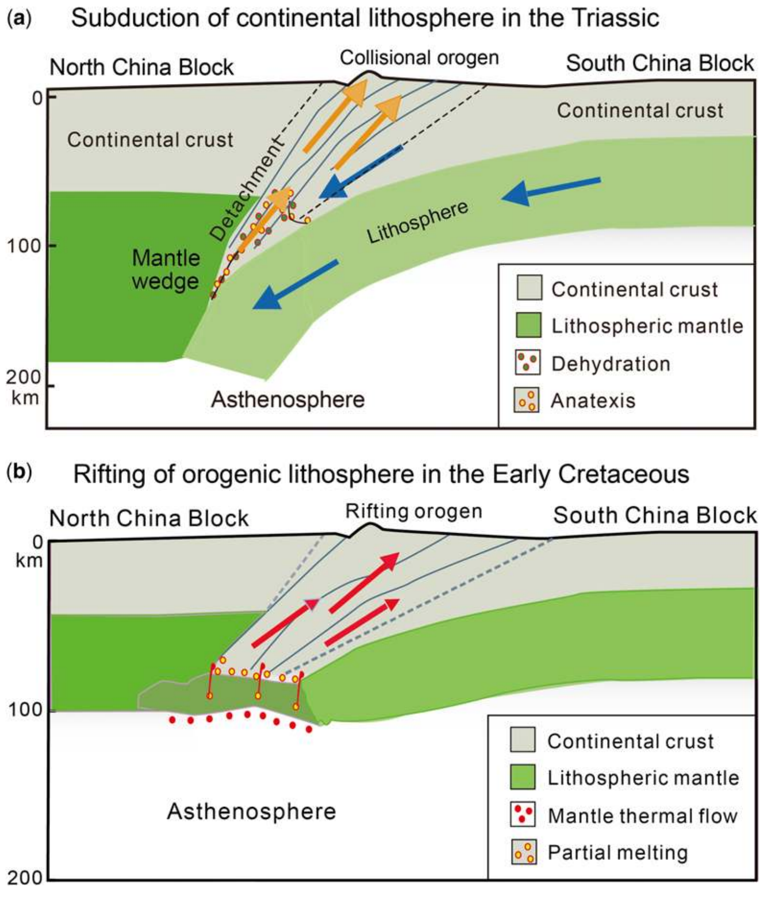

Fig. 16. Schematic diagrams showing the evolution of lithotectonic units in the Dabie–Sulu orogenic belt, from continental subduction in the Triassic to the orogenic collapse in the Early Cretaceous. (**a**) Collisional orogeny due to northwards subduction of the South China Block beneath the North China Block in the Triassic, with differential exhumation of crustal slices from different depths. (**b**) Rifting orogeny subsequent to the foundering of the collision-thickened orogenic lithosphere in the Early Cretaceous due to asthenospheric erosion, resulting in migmatitization, granulite-facies metamorphism, bimodal magmatism and emplacement of metamorphic core complexes.

Its extent is primarily associated with subduction depths. In the continental subduction zone, the maximum subduction depth is indicated by the following mineralogical characteristics: (1) coesite widely occurs as inclusions in nominally anhydrous minerals such as garnet, omphacite, zircon, kyanite and dolomite; (2) coesite occurs as inclusions in hydrous minerals such as phengite, zoisite/epidote and talc in UHP eclogites; (3) tiny inclusions of microdiamond are hosted in garnet and rare zircon from eclogite and garnet peridotite; (4) mineral records of UHP metamorphic conditions are mainly preserved in eclogite, peridotite, marble, jadeite quartzite, schist and paragneiss, with tiny inclusions of microcoesite only in zircon from the granitic gneiss; (5) abundant exsolution textures occur in UHP minerals from P-type eclogite and garnet peridotite, with the possible existence of majoritic garnet.

Nevertheless, the link of exsolution textures to subduction depths has been challenged. Ye *et al.* (2000) found high concentrations of clinopyroxene, rutile and apatite exsolutions in garnet from UHP P-type eclogite at Yangkou in the Sulu orogen, and interpreted them as resulting from the formation of pyroxene solid solutions at *c.* 7 GPa in the deeply subducted continental crust. This suggests that the Yangkou eclogite could originate from a greater depth of *c.* 200 km, implying a possible depth of crustal subduction to *c.* 200 km. Liu X.W. *et al.* (2007) found clinoenstatite exsolution lamellae in clinopyroxene grains of garnet peridotite at Bixiling in the Dabie orogen, suggesting a possible pressure of *c.* 9 GPa for precipitation and thus extending the possible depth of continental subduction to *c.* 300 km. Zhang & Liou (2003) found the exsolution of majoritic garnet in coarse clinopyroxene grains from garnet clinopyroxenite at Rizhao in the Sulu orogen, suggesting its source as being from the mantle transition zone (>450 km). It is noted that all the exsolution microtextures occur in P-type UHP eclogites in association with C-type orogenic peridotites, making their origin enigmatic. In fact, it is still controversial with regard to the interpretation of exsolution microtextures with respect to tectonic processes (Green *et al.* 2000; Hwang *et al.* 2007). They certainly indicate possible depths of over 200 km for the peridotite formation. However, it is uncertain whether they can be regarded as evidence for the subduction of continental crust to post-arc depths of >200 km (Chopin 2003; Spengler *et al.* 2006). This is because it still remains to be determined whether they did, in fact, experience crustal processes. Perhaps they have nothing to do with the deep subduction of continental crust, but instead record mineralogical changes during ascent of the primary peridotite from deeper to shallower in the mantle. Thus, caution has to be taken when interpreting the exsolution microtextures as an indicator of subduction depths, with a critical distinction in peridotite source between the overlying subcontinental lithospheric mantle (type M) and the deep-subducted mafic–ultramafic complex (type C). In particular, it is likely that the exsolution microtextures could have been produced by rapid ascent of the primary peridotite due to the mantle upwelling in response to supercontinental break-up in the Middle Neoproterozoic, which predates the continental subduction in the Triassic. In other words, it corresponds to the peridotite ultradeep source rather than the continental ultradeep subduction.

Zircons in the Dabie–Sulu UHP eclogites and gneisses consist of two parts (Chen & Zheng 2017). One is the residual magmatic cores that experienced varying degrees of metamorphic recrystallization. The other is the newly grown domains that were produced through either metamorphic reaction at temperatures below the solidus of crustal rocks or peritectic reaction at temperatures above the solidus of crustal rocks. The two types of mineralogical reaction are associated with dehydration or anataxis of the previously altered magmatic rocks, yielding mixtures of old residual and newly grown zircon domains in samples. The utilization of microbeam *in situ* microanalysis enables discrimination of newly grown domains from relict domains. For instance, zircons from the UHP eclogite and gneiss at Qinglongshan in the SW Sulu zone exhibit the lowest $\delta^{18}O$ values, as negative as −10‰ (Chen Y.-X. *et al.* 2011). Their magmatic cores with U–Pb ages of 769 ± 9 Ma generally have positive $\delta^{18}O$ values of 0.1–10.1‰, and high Th/U and $^{176}Lu/^{177}Hf$ ratios. In contrast, newly grown domains with Triassic U–Pb ages have negative $\delta^{18}O$ values of −10.0 to −2.2‰, and low Th/U and $^{176}Lu/^{177}Hf$ ratios. Therefore, the negative $\delta^{18}O$ zircon domains were grown from negative $\delta^{18}O$ metamorphic fluids that were generated by metamorphic dehydration of the negative $\delta^{18}O$ hydrothermally altered rocks. The average $\delta^{18}O$ values for the Neoproterozoic magmatic zircon cores vary from −0.9 to 6.9‰, significantly higher than the values of −9.9 to 6.8‰ for the Triassic metamorphic rims. These results indicate that although the igneous cores have higher $\delta^{18}O$ values than the metamorphic rims, the widespread existence of low $\delta^{18}O$ magmatism and negative $\delta^{18}O$ hydrothermal alteration in the northern margin of the South China Block is still evident.

In addition to the Dabie–Sulu orogenic belt, a number of studies of zircon U–Pb ages and O isotopes have been devoted to rocks elsewhere in South China (Wu R.-X. *et al.* 2006; Zheng *et al.* 2007*c*, 2008*b*; Wang X.-C. *et al.* 2011, 2013; Zhang *et al.* 2012; Fu *et al.* 2013; Liu & Zhang 2013). The results indicate that both low $\delta^{18}O$ magmatism and negative $\delta^{18}O$ hydrothermal alteration are prominent in the NE margin of the South China Block, but only the low $\delta^{18}O$ hydrothermal alteration sporadically occurred elsewhere in South China. In either case, the time of high-temperature water–rock interaction are constrained in the period of 780–740 Ma. The most plausible tectonic setting for the Middle Neoproterozoic low $\delta^{18}O$ magmatism is continental rifting in the South China Block (Zheng *et al.* 2004, 2007*b*), which took place in response to the Rodinia break-up. Because of the continental subduction zone metamorphism in the Triassic, the low to negative $\delta^{18}O$ rocks underwent dehydration, liberating negative to low $\delta^{18}O$ fluids for the growth of metamorphic and peritectic minerals. In this regard, there are generally two-stage water–rock interactions for the UHP metaigneous rocks in the Dabie–Sulu orogenic belt. The first stage is recorded by the old zircon cores of magmatic origin and their host rocks which underwent high-temperature meteoric hydrothermal alteration and even local low $\delta^{18}O$ magmatism in the Middle Neoproterozoic (780–740 Ma). The second stage is recorded by the young zircon domains of metamorphic and peritectic origin; and their negative to low $\delta^{18}O$ values were acquired during their growth through metamorphic dehydration of low to negative $\delta^{18}O$ hydrous minerals in the Triassic.

It is conventional wisdom that UHP metamorphism was evolved under nominally anhydrous conditions and is thus examined mainly in terms of petrological phase relationships between crystalline mineral. This was primarily based on petrographical observations that there are much smaller amounts of hydrous minerals in eclogite-facies UHP rocks than in blueschist- to eclogite-facies HP rocks. More and more studies have indicated the existence of water in the forms of molecular water (H_2O) and hydroxyl groups (OH^-), which are usually considered stoichiometrically anhydrous in nominally anhydrous minerals at the subarc depths (Su *et al.* 2002; Xia *et al.* 2005; Chen R.-X. *et al.* 2007*a*, 2011; Gong *et al.* 2007, 2013; Sheng *et al.* 2007; Zheng 2009). Nevertheless, the activity of water is different in metamorphic minerals in UHP and non-UHP regimes. The lack of fluids was suggested during UHP metamorphism according to the occurrence of intergranular coesite in eclogite at Yangkou in the Sulu orogen (Liou & Zhang 1996), and the preservation of relict igneous minerals and textures in coesite-bearing metagabbro (Zhang & Liou 1997). This even led to the conclusion that the lack of aqueous solutions during the subduction of continental crust to the subarc depths results in the absence of arc volcanism above continental subduction zones (Rumble *et al.* 2003; Zheng *et al.* 2003). However, polycrystalline quartz pseudomorph after coesite as inclusions is also present in allanite of allanite–quartz veins within UHP eclogite at Chizhuang in the SW part of the Sulu orogen (Zhang *et al.* 2008). This only indicates the low activity of water in UHP minerals and thus cryptic fluid action during the subduction of continental crust to subarc depths. In fact, metamorphic dehydration from HP blueschist facies through to HP eclogite facies to UHP eclogite facies is profound in view of the progressive disappearance of hydrous minerals with depth (Schmidt & Poli 2014), indicating that considerable amounts of water were indeed released from subducting crustal rocks. In this regard, there was also significant liberation of aqueous solutions from continental crust during its subduction from forearc to subarc depths and low geothermal gradients are the key to the lack of arc magmatism above continental subduction zones (Zheng *et al.* 2016).

In contrast to the cryptic fluid action during the subduction, there is the modal fluid action during exhumation of the deeply subducted continental crust, giving rise to retrograde fluids of internal origin in the Dabie–Sulu UHP metamorphic rocks (Zheng *et al.* 1999, 2003, 2009; Chen *et al.* 2007*a*, 2012; Guo *et al.* 2015). The retrograde fluids were derived from the breakdown of hydrous minerals and the exsolution of structural hydroxyl and molecular water within HP and UHP metamorphic slices during decompressional exhumation (Zheng 2009). Inspection of the relationship between the distance, petrography and $\delta^{18}O$ values of adjacent samples from the CCSD-MH reveals O isotope heterogeneities between the different and same lithologies on the scale of 20–50 cm (Chen *et al.* 2007*b*; Zheng *et al.* 2009), corresponding to the maximum scales

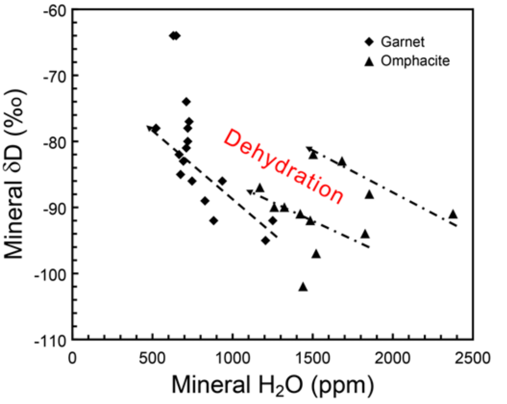

Fig. 17. The correlation between water concentration and hydrogen isotope composition of omphacite and garnet from UHP eclogites in the CCSD-MH (revised after Zheng *et al.* 2009).

of fluid mobility during the continental collision. The presence of mineral dehydration during the exhumation is further demonstrated by negative correlations between water concentration and hydrogen isotope composition of omphacite and garnet from eclogites in the CCSD-MH (Fig. 17).

Eclogite-facies veins and segregations in HP–UHP metamorphic rocks are the direct records of fluid flow in continental subduction zones. Zhang *et al.* (2008) found allanite–quartz, omphacite–quartz, zoisite–quartz, kyanite–quartz and quartz veins in Sulu UHP eclogites. The all vein minerals show chemical compositions similar to those of the host eclogites. The all veins contain a large amount of allanite, zoisite, rutile and minor apatite, which are repositories of LILEs, LREEs and HFSEs in metabasites. Most of the vein minerals form very large euhedral to subhedral crystals (or megacrysts) which contain abundant primary fluid inclusions with multiple solids, indicating their growth from silicate-rich fluids. Vein allanite and garnet contain inclusions of polycrystalline quartz pseudomorphs after coesite, and vein zircon contains coesite inclusions. These petrographical results indicate that the veins, together with the host eclogites, were subjected to synchronous UHP metamorphism. Guo *et al.* (2015) found HP omphacite–epidote, epidote-quartz and kyanite–epidote–quartz veins in Dabie UHP eclogites. The interfaces between the veins and eclogites are typically sharp, and both eclogite and vein exhibit weak deformation. The HP veins show large variations in the mineral association at different spatial locations. A prominent difference between the eclogite and vein is that the former contains >30 vol % garnet, whereas the latter contains no garnet. From the vein–eclogite boundary to the vein interior, there are roughly three types of veins: (1) omphacite–epidote veins in immediate contact with the host eclogite – near the vein–eclogite boundary, some needle-like vein epidote crystals occur nearly perpendicular to the vein; (2) epidote–quartz veins that are not in direct contact with the eclogite but generally occur between the omphacite-epidote and kyanite–epidote–quartz veins; and (3) kyanite–epidote–quartz veins that always occur in the interior of vein systems.

The flow of metamorphic fluids in Dabie–Sulu HP–UHP rocks would be in a pervasive and focused manner (Li *et al.* 2001*a*, *b*; Li X.-P. *et al.* 2004; Zheng *et al.* 2007*a*; Zhang *et al.* 2008; Chen *et al.* 2012; Sheng *et al.* 2012, 2013; Guo *et al.* 2015, 2016; Wang *et al.* 2017). The pervasive flow proceeds along grain boundaries or fine crack systems by means of the pores in the rocks. It is independent of structural control and favours the homogenization of geochemical compositions. In contrast, the focused flow proceeds along certain fractures and often leads to local geochemical heterogeneities, enabling the infiltrated regions in the rocks to be geochemically modified while others remain almost unaffected. Silica is highly soluble in metamorphic fluids at forearc–subarc depths, so that the occurrence of quartz veins in UHP eclogites can be used to indicate the focused flow of aqueous solutions during the collisional orogeny. In some cases, silica-rich fluids may pervasively infiltrate the overlying UHP rocks to result in hydrous metasomatism of the UHP metamorphic rocks. This is recorded by the kyanite quartzite in the Sulu orogen (Wang W *et al.* 2011) and the jadeite quartzite in the Dabie orogen (Gao *et al.* 2015).

Most UHP metamorphic terranes appear to have undergone little or no partial melting in the stage of subduction (Chen *et al.* 2017). This is primarily dictated by low geothermal gradients of 5–10°C km^{-1} during subduction to subarc depths (Zheng & Chen 2016). In contrast, many UHP terranes show a considerable degree of partial melting in the exhumation stage (Zheng *et al.* 2011*b*; Chen *et al.* 2017; Gao *et al.* 2017*a*; Xia & Zhou 2017), suggesting that elevated temperatures occurred. Although the initial exhumation of UHP slices may proceed through either isothermal or temperature-increased decompression (Carswell & Zhang 1999; Zheng & Chen 2017), considerable amounts of water are always released by the breakdown of hydrous UHP minerals and the exsolution of structural hydroxyl and molecular water in nominally anhydrous UHP minerals. If water was locally present in felsic UHP lithologies approaching saturation at temperatures at and above their wet solidus, partial melting would take place in deeply subducting crustal rocks (Zheng *et al.* 2011*b*). Nevertheless, partial melting of UHP rocks commonly takes place during hot exhumation if sufficient water becomes available from the UHP rocks themselves (Zheng & Hermann 2014). If the UHP rocks do melt, then they have transformed water bound in hydrous minerals and nominally anhydrous minerals bound to aqueous solutions and hydrous melts. Therefore, partial melting in UHP rocks, if present, has an important implication for tectonic exhumation and element transport in deep subduction zones (Zheng *et al.* 2011*b*).

The possibility of generating supercritical fluids in UHP rocks has received much attention recently (Ferrando *et al.* 2005; Zhang *et al.* 2008; Xia *et al.* 2010; Zheng *et al.* 2011*b*; Gao *et al.* 2012; Zheng & Hermann 2014; Huang & Xiao 2015; Wang *et al.* 2017). Although supercritical fluids could have been created in the UHP regime (Hermann *et al.* 2006; Zheng *et al.* 2011*b*; Ni *et al.* 2017), it does not mean that such fluids would indeed occur during continental collision. Ferrando *et al.* (2005) observed the occurrence of primary crystal inclusions in garnet and kyanite in the UHP eclogite, and kyanite quartzite from the Sulu orogen. Some of the crystal inclusions contain very large amounts of the elements Si, Al and Ti (of the order of tens of wt%), suggesting the possible existence of a supercritical fluid with transitional character between a aqueous solution and a hydrous melt. Zhang *et al.* (2008) suggested that the supercritical fluid attending the UHP conditions is mainly composed of $SiO_2 + Al_2O_3 + CaO + MgO + FeO + Na_2O + H_2O$, and is enriched in LREEs, HFSEs, and P, V, Sr, Ba and Pb. Xia *et al.* (2010) presented the trace element composition of zircon domains modified by a supercritical fluid showing a significant enrichment in incompatible trace elements such as not only LREE and HREE but also HFSE (Fig. 18). The action of supercritical fluids was also suggested from geochemical studies of crystal inclusions in the peritectic garnet of UHP eclogite (Gao *et al.* 2012), samples along a profile across the boundary between amphibolite retrogressed from UHP eclogite and its adjacent granitic orthogneiss (Huang & Xiao 2015), and composite granite–quartz veins in retrogressed UHP eclogite (Wang *et al.* 2017). It remains to be resolved which composition can be used as geochemical evidence for the former existence of supercritical fluids in continental subduction zones.

Since the finding of extremely negative $\delta^{18}O$ values in the minerals of UHP eclogites, granitic gneisses and quartz schists from the Dabie–Sulu orogenic belt (Yui *et al.* 1995; Zheng *et al.* 1996), a number of studies have been devoted to the origin of the unusual O isotope signature in Dabie–Sulu metamorphic rocks (Rumble & Yui 1998; Zheng *et al.* 1998, 1999, 2003, 2004; Fu *et al.* 1999; Rumble *et al.* 2002, 2003; Tang *et al.* 2008*a*; He *et al.* 2016). The combined studies of zircon U–Pb dating and O isotope analysis reveal that these negative $\delta^{18}O$ minerals were grown through metamorphic and peritectic

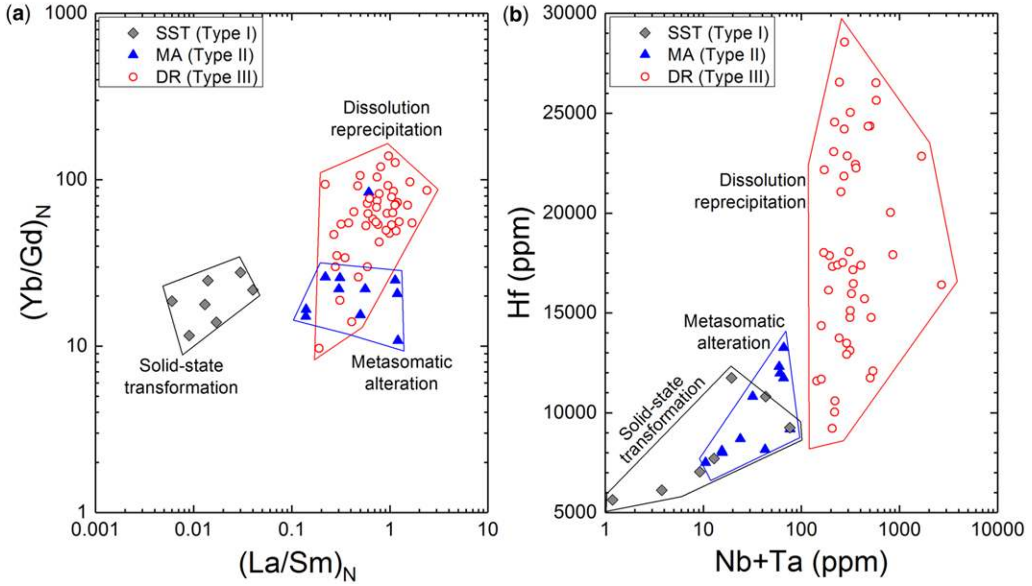

Fig. 18. Trace element diagrams for the distinction between different types of metamorphosed zircon domains that experienced different properties of metamorphic recrystallization in association with different compositions of subduction zone fluids. Data from the UHP metagranite in the Dabie orogen (Xia *et al.* 2010). The metamorphic recrystallization proceeds via the mechanisms of solid-state transformation (SST), metasomatic alteration (MA) and dissolution reprecipitation (DR), respectively. (**a**) Plot of $(Yb/Gd)_N$ v. $(La/Sm)_N$, where subscript N denotes the normalization relative to the chondrite element values. (**b**) Plot of Hf v. Nb + Ta.

reactions during the dehydration of the hydrothermally altered, negative $\delta^{18}O$ rocks in the Triassic. Preservation of the negative O isotope anomalies in the UHP minerals indicates limited crust–mantle interaction during the UHP metamorphism at subarc depths (Zheng *et al.* 1998, 2003). A quantitative estimate was made for the timescale of UHP

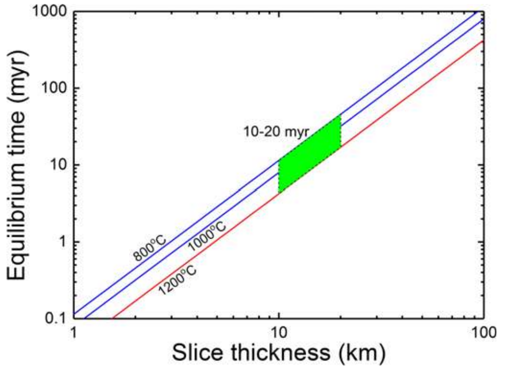

Fig. 19. Estimate of the timescale for oxygen isotope equilibration between the continental crust and the mantle wedge at subarc depths via the diffusion transport of oxygen-bearing species across the UHP slice in the Dabie–Sulu orogenic belt (revised after Zheng 2012).

metamorphism, yielding a duration of 10–20 myr at subarc depths (Fig. 19). The short timescale has been verified by SHRIMP (Sensitive High-Resolution Ion Microprobe) U–Pb dating of metamorphic zircon (Liu *et al.* 2006; Wu Y.-B. *et al.* 2006). Parageneses of mineral inclusions in zoned zircon domains combined with U–Pb ages delineate a well-constrained clockwise pressure–temperature–time (*P–T–t*) path (Liu & Liou 2011). Therefore, the Dabie–Sulu UHP rocks are typical products of subduction zone metamorphism. Nevertheless, the continental crust there was subducted at a faster rate than the oceanic crust and experienced rapid exhumation from subarc depths (Zheng *et al.* 2003, 2009).

Insights into subduction zone metamorphism

Subduction of continental lithosphere is a first-order geodynamic process of plate tectonics, and thus has a significant influence on the evolution of convergent plate margins and their role in geochemical cycles. The switch from oceanic to continental subduction is often associated with the development from accretionary orogeny to collisional orogeny, with a collage of arc terranes to continental margins. This is typical between the Indian and Asian continents, where the Cenozoic Himalayan orogen was accreted to the Mesozoic Gangdise orogen (e.g. Yin & Harrison 2000; Guillot *et al.* 2008). It also occurred in the western part of the Central Orogenic Belt of China, where the continental collision in the Mesozoic would have been superimposed on Early Paleozoic accretionary orogens to result in the composite Qinling–Tongbai–Hong'an orogenic belt between the North and South China blocks in central China (Wu & Zheng 2013). This leads to different extents of the tectonic inheritance from accretionary to collisional orogens (Zheng *et al.* 2013*a*, 2015). However, no relict of arc terranes has been found in the Dabie–Sulu orogenic belt, indicating the absence of arc–continent collision between the South and North China blocks in east-central China. This unique feature of continent–continent collision in the Dabie–Sulu orogenic belt makes it an excellent target for investigating the collisional orogeny with no inheritance from the accretionary orogeny. The difference in the two types of orogenic processes would have exerted different impacts on the structure and composition of convergent plate margins (Zheng & Chen 2016; Zheng & Zhao 2017).

The composition of the UHP metamorphic rocks is a key to identifying the nature of their protolith, which may be of oceanic or continental origin (Zheng & Chen 2016). The oceanic crust is predominated by mid-ocean-ridge basalts (MORBs) and their underlying gabbros, with a thin layer of seafloor sediments. These mafic igneous rocks are geochemically characterized by their depletion in melt-mobile incompatible trace elements such as LILEs, Pb and LREEs, and their enrichment in HFSEs such as Nb and Ta relative to HREEs; their radiogenic Sr and Nd isotopes are also depleted relative to the primitive mantle, exhibiting low $(^{87}Sr/^{86}Sr)_i$ and positive $\varepsilon_{Nd(t)}$ values (White & Klein 2014). The seafloor sediments are generally enriched in these incompatible trace elements and their pertinent radiogenic isotopes if they are of anciently terrigenous origin, but their radiogenic isotopes can be depleted if they are produced by the weathering of juvenile crust. In contrast, the continental crust is predominated by crystalline basement that is generally composed of granitoids, gneisses, amphibolite and granulites, with variable thicknesses of sedimentary cover. These crystalline rocks are usually characterized by an enrichment in melt-mobile incompatible trace elements such as LILEs, Pb and LREE, but a depletion in HFSEs such as Nb and Ta relative to HREE; their radiogenic Sr and Nd isotopes are also enriched relative to the primitive mantle, exhibiting high $(^{87}Sr/^{86}Sr)_i$ and negative $\varepsilon_{Nd(t)}$ values (Rudnick & Gao 2014). The sedimentary cover is generally enriched in these incompatible trace elements and their pertinent radiogenic isotopes if it was produced by the weathering of ancient crust. The exception is the weathering of juvenile arc crust, which gives rise to isotopically depleted sediments with positive $\varepsilon_{Nd(t)}$ values.

The present study found that the composition of UHP metamorphic rocks in the Dabie–Sulu orogenic belt is nearly bimodal in lithochemistry, being mainly felsic and minorly mafic (Fig. 8). In trace element composition, these rocks primarily show considerable enrichment in LILEs, Pb and LREEs, but depletion in Nb and Ta relative to HREE (Figs 11 & 12). In Sr–Nd isotope compositions, they are ancient crust-like, exhibiting high $(^{87}Sr/^{86}Sr)_i$ and negative $\varepsilon_{Nd(t)}$ values (Fig. 13). These geochemical observations indicate that their protoliths are ancient continental crust rather than juvenile oceanic crust, lending support to the previous conclusion that the deeply subducted slab is continental rather than oceanic (Jahn 1998; Zheng *et al.* 2003). Furthermore, it is determined that the deeply subducted continental crust was the northern edge of the South China Block, which split from the Rodinia supercontinent in the Middle Neoproterozoic (Zheng *et al.* 2003, 2004). The crustal rocks experienced variable extents of metamorphic dehydration during their subduction to and exhumation from subarc depths (Zheng 2009; Zheng *et al.* 2009). In addition, the UHP rocks experienced partial melting to different degrees during their exhumation from subarc depths towards forearc depths (Zheng *et al.* 2011*b*; Zheng & Hermann 2014; Chen *et al.* 2017). Although aqueous solutions are expected to be released from the deeply subducting continental crust (Zheng *et al.* 2016), considerable loss of fluid-mobile incompatible trace elements has not been found, except for a few UHP eclogites that suffered very local loss of felsic melts during their initial exhumation (Zhao *et al.* 2007*a*; Chen *et al.* 2016). Therefore, the composition of UHP metamorphic rocks was subjected to little change in geochemistry despite big changes in lithology. For this reason, they can be compared with the composition of syn- and post-collisional granitoids in order to determine their inheritance (Zhao *et al.* 2012, 2017*a*, *b*).

The arc-like trace element distribution patterns are prominent for the UHP gneisses and eclogites in the Dabie–Sulu orogenic belt, which are characterized by an enrichment in LILEs, Pb and LREEs, but a depletion in Nb and Ta relative to HREE in the primitive mantle-normalized diagram (Figs 11 & 12). Such patterns are primarily dictated by the mobility of fluid-mobile incompatible trace elements in deeply subducting crustal rocks (Saunders *et al.* 1991; Tatsumi & Kogiso 1997; Hermann *et al.* 2006; Zheng *et al.* 2011*b*). In general, LILEs, Pb and LREEs are preferentially partitioned into crustally derived fluids at subarc depths, whereas HFSEs and HREEs are retain in residual UHP rocks due to the stability of both rutile and garnet (Brenan *et al.* 1994, 1995*a*, *b*; Kogiso *et al.* 1997;

Kessel *et al.* 2005). This leads to specific trace element characteristics such as high LILE/HFSE and LREE/HREE ratios in the crustal fluids, with low Nb/U and Ce/Pb ratios. It is also the reason why continental arc andesites and oceanic arc basalts show low ratios of Nb/U (5.1 to 6.8) and Ce/Pb (4.4 to 6.3) on average (Kelemen *et al.* 2014). However, there is no significant Nb/U and Ce/Pb fractionation during mantle melting; thus MORBs and oceanic island basalts (OIBs) are characterized by consistently high Nb/U ratios of 47 ± 10 and Ce/Pb ratios of 25 ± 5 (Hofmann *et al.* 1986). Because island arc basalts (IABs) are generally depleted in Nb but enriched in Pb (e.g. Pearce 1982; Hawkesworth *et al.* 1991; McCulloch & Gamble 1991), they show significantly low Nb/U and Ce/Pb ratios. In this regard, the significantly low Nb/U and Ce/Pb ratios are also indicative of arc-like geochemical signatures. As illustrated in Figure 20a, the Dabie–Sulu UHP gneisses and eclogites show significantly lower Nb/U and Ce/Pb ratios than both MORBs and OIBs. Such signatures are inherited from their protoliths of Precambrian age rather than being produced by the continental subduction zone metamorphism in the Triassic. Previous zircon Hf isotope studies suggest that these protoliths were primarily produced by magmatism in the Late Mesoproterozoic and Middle Paleoproterozoic, respectively, in the northern margin of the South China Block (Zheng *et al.* 2009; Zhang *et al.* 2014). In this regard, the arc-like geochemical signatures were generated by the two episodes of oceanic subduction during the assembly of the Rodinia and Columbia supercontinents, respectively. As such, the modern plate tectonics can be traced back to the Early Paleoproterozoic when the oceanic subduction was operating during the Columbia assembly. However, further studies are required to determine when the change in thermal structure of subduction zones occurred from cold oceanic subduction to hot arc magmatism.

As noticed by Zheng *et al.* (2009), Ernst (2010) and Kylander-Clark *et al.* (2012), the exposure area of UHP eclogite-facies rocks (UHP terrane size) is correlated with the metamorphic duration in the coesite stability field (Fig. 21). As one of the largest UHP terranes on Earth, the Dabie–Sulu UHP terrane has a metamorphic duration of 15 ± 2 myr at subarc depths in terms of the mineral O isotope exchange kinetics (Zheng *et al.* 1998, 2003) and the integrated studies of petrochronology (Hacker *et al.* 2006; Liu *et al.* 2006; Wu Y.-B. *et al.* 2006). A similar timescale was obtained for the UHP terrane in the Western Gneiss Region of Norway (Kylander-Clark *et al.* 2008, 2012). In contrast, petrochronological studies indicate short durations of a few millions of years for small UHP terranes such as Dora Maira in the Western Alps, the Kaghan Valley in the Himalaya and the Woodlark in Papua New Guinea (Zheng *et al.* 2009; Kylander-Clark *et al.* 2012). Furthermore, the two groups of UHP metamorphic duration and terrane size are correlated with their protolith nature regardless of their UHP metamorphic ages (Zheng 2012). Whereas the large UHP terranes are generally of ancient crustal protoliths and suffer UHP metamorphism over long timescales with slow rates of exhumation, the small UHP terranes are commonly of juvenile crustal protoliths and experience UHP metamorphsm over short timescales with rapid rates of exhumation. As highlighted by Zheng *et al.* (2013*b*), these two types of correlations can be explained well by the subduction channel processes during continental collision: the small UHP terranes are much more susceptible to motion than the large UHP terranes in subduction channels. Therefore, the nature of pre-metamorphic protoliths dictates the type of collisional orogens, the size of the UHP metamorphic terranes and the duration of UHP metamorphism (Zheng 2012).

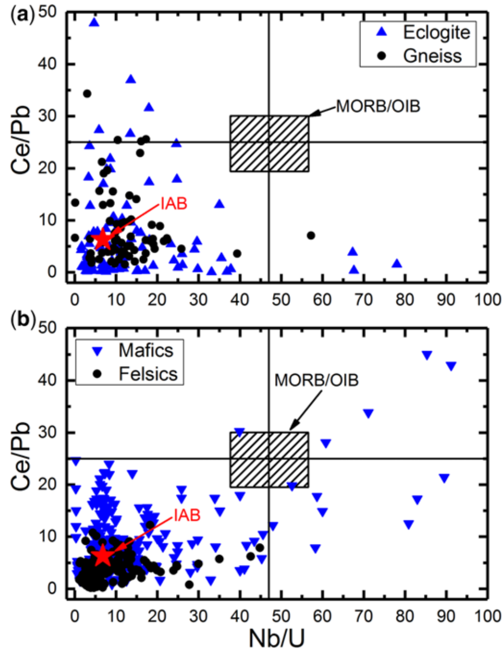

Fig. 20. Plot of Nb/U v. Ce/Pb ratios for UHP metamorphic and post-collisional magmatic rocks from the Dabie–Sulu orogenic belt: (**a**) UHP eclogites and gneisses, where data are from this compilation; and (**b**) post-collisional mafic and felsic magmatic rocks, where data for mafic rocks are from Zhao *et al.* (2013) and those for felsic rocks are from Zhao *et al.* (2017*a*). Also shown for comparison are average ratios for mid-ocean ridge basalts (MORBs), oceanic island basalts (OIBs) and island arc basalts (IABs). Data for both MORB and OIB are from Hofmann *et al.* (1986), and those for IAB are from Kelemen *et al.* (2014).

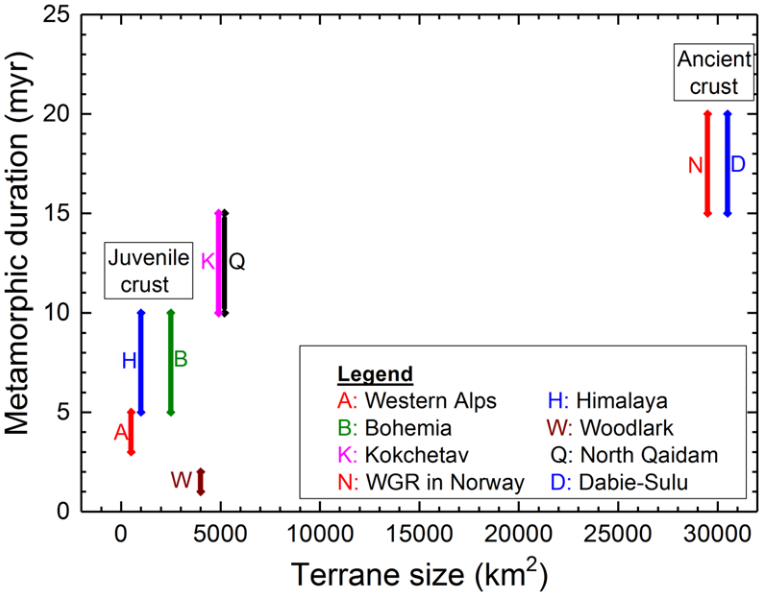

Fig. 21. The relationship between UHP terrane size and metamorphic duration (revised after Zheng *et al.* 2013*b*). Small UHP terranes contain fragments of juvenile crust and exhibit short residence times at subarc depths, whereas large UHP terranes contain no fragments of juvenile crust and exhibit long residence times at subarc depths.

The reconstruction of *P–T–t* paths for UHP metamorphic rocks is of most importance in the study of subduction zone metamorphism. A number of combined petrological and geochronological studies have been devoted to the Dabie–Sulu UHP rocks. The results have led to the recognition of three lithotectonic units with differential paths of subduction and exhumation in the Dabie orogen (Figs 3 & 16a). The depth of crustal subduction becomes shallower southwards, with the occurrence of HP blueschist- and eclogite-facies rocks in the southernmost part of the collisional orogen (Fig. 2). In contrast, greenschist-facies low-grade metamorphic rocks occur in the northernmost part of the collisional orogen, close to the North China Block (Figs 1 & 2), representing an accretionary wedge that was offscrapped from the subducting continental crust during its subduction to shallow depths of <10 km (Zheng *et al.* 2005). A similar configuration also occurs in the Himalayan orogen, where the metamorphic grade decreases southwards from Higher Himalaya to Lesser Himalaya, with low-grade metamorphic rocks in the Tethyan Himalaya which is close to the Gangdise orogen in the north (Yin & Harrison 2000; Guillot *et al.* 2008). The occurrence of metamorphic slices in the two collisional orogens can be explained by a continental subduction channel model (Zheng *et al.* 2013*b*) in which the subducting continental crust was tectonically sliced at different depths and then afterwards accreted to the overlying continental margin, building up metamorphic complexes composed of different lithotectonic units (Fig. 2). In other words, the subducting continental crust was detached at different depths, leading to the loss of its coherence and with substantial mixing in the space between the subducting slab and the mantle wedge, and thus to diverse and complex *P–T* paths for different lithotectonic units (Fig. 3). Although the tectonic evolution of UHP metamorphic slices may vary from orogen to orogen, the petrochronological studies of UHP slices generally indicate two-stage processes for their exhumation. The first stage is rapid from mantle depths to lower crustal levels, which is then followed by a marked decrease in the rate of exhumation in the second phase.

The behaviour of continental crust subducted to subarc depths for UHP metamorphism is reasonably understood as is illustrated by the comprehensive studies of various rocks from the Dabie–Sulu orogenic belt. The deeply subducted continental crust was exhumed in the form of UHP slices, allowing direct access for various investigations. Nevertheless, the UHP metamorphic rocks may be exhumed at different rates with different temperatures. It is common for UHP metamorphic rocks to be heated during their decompressional exhumation, resulting in maximum temperatures at reduced pressures (Fig. 3). This indicates an increase in the geothermal gradient of subduction zones, which may be caused by decoupling between the subducting slab and the overlying SCLM wedge, allowing heat to be transported from the underlying asthenospheric mantle (Zheng & Chen 2017). The increased magnitude of temperatures is primarily dictated by the kinetic competition between the rate of thermal conduction and the slice ascent in continental subduction channels (Zheng *et al.* 2011*a*). A fundamental question is how much of the exhumation history is recorded in the studied UHP samples, and what triggered the growth and recrystallization of metamorphic minerals during their exhumation? There may be a link between metamorphic dehydration, partial melting and mineralogical reactions at different depths. In order to unravel the peak UHP metamorphic signature, it is critical to know when peritectic reactions occurred during exhumation, especially if they happened in the post-collisional stage. To answer this question it is important to make field-based studies to acquire reasonable *P–T–t* data for the product of peritectic reactions. A key point in this approach is to remove the superimposition of eclogite-facies rocks by granulite-facies metamorphism. Afterwards, we are in a position to establish reliable links between isotopic dates (*t*) and the *P–T* conditions of mineral formation.

Constraints on continental subduction tectonics

Continental subduction has been one of the hot topics in the past three decades. The occurrence of UHP metamorphic rocks in collisional orogens is characteristic of crustal subduction to mantle depths. Many studies have been focused on the deepest, highest-grade sections of the deeply subducted continental crust, where UHP index mineral relicts such as coesite and diamond can be found for investigation (Carswell & Compagnoni 2003; Chopin 2003; Liou *et al.* 2009; Zheng *et al.* 2012). In geological studies, UHP terranes are generally assumed to have been subducted to mantle depths and exhumed back to crustal levels under the influence of their own buoyancy aided by the extension or transtension of collisional orogens (Ernst *et al.* 1997). Within this framework, various hypotheses were presented to explain the occurrence and nature of exhumed UHP terranes (e.g. Warren 2013; Burov *et al.* 2014; Li 2014). However, these hypotheses have been tested rarely with reference to known geological structures in the field and petrological sequences identified by microbeam analyses. While tectonic hypotheses are important in understanding the evolution of subduction zones, it is essential to have robust constraints on the transport of crustal slices and the change in geological processes that occur in convergent settings and their modification during and after collisional orogeny. In doing so, it is critical to test these hypotheses by inspection of available observations and interpretations. This requires the multidisciplinary research of collisional orogens by petrology, geochemistry, geochronology, structural geology and geodynamic modelling. The Dabie–Sulu orogenic belt provides a unique opportunity to advance this research because it is one of the largest and best-preserved UHP terranes on Earth. In the following subsections we highlight three aspects of controversy concerning both subduction and exhumation of continental crust in the Dabie–Sulu orogenic belt.

Monodirectional v. bidirectional subduction

There is a general consensus that UHP metamorphic rocks in the Dabie–Sulu orogenic belt were generated by monodirectional subduction of the South China Block beneath the North China Block (Cong 1996; Hacker *et al.* 1998; Liou *et al.* 2000; Zheng *et al.* 2005; Ernst *et al.* 2007). The deeply subducted continental crust of the South China Block is characterized by the occurrence of Middle Neoproterozoic magmatic rocks with low $\delta^{18}O$ values (Zheng *et al.* 2003, 2009). In contrast, the North China Block is characterized by the widespread occurrence of Paleoproterozoic–Archean rocks (Tang J. *et al.* 2007; Zheng *et al.* 2013*a*). Nevertheless, there are a few outcrops in the Dabie–Sulu orogenic belt where zircon U–Pb dating of UHP metamorphic rocks yields Paleoproterozoic–Archean ages for their protoliths (Chavagnac *et al.* 2001; Yang *et al.* 2003; Li X.-P. *et al.* 2004; Tang *et al.* 2008*b*). In view of this observation, it was hypothesized by Xu (2007) that these ancient protoliths would have had a tectonic affinity to the North China Block and thus were eroded in the Triassic by the subducting continental slab of the South China Block, leading to bidirectional subduction during the continental collision between the North and South China blocks (Fig. 22). The SCLM of the North China Block did undergo subduction erosion by the subducting continental lithosphere of the South China Block, resulting in the occurrence of M-type orogenic peridotites in the Dabie–Sulu orogenic belt (Zhang R.Y. *et al.* 2009; Chen Y. *et al.* 2015; Li H.-Y. *et al.* 2016). However, the occurrence of Paleoproterozoic–Archean crustal rocks is not unique to the North China Block. These ancient rocks also occur in the South China Block (Zhang & Zheng 2013; Zhang *et al.* 2014), making bidirectional subduction problematic. This hypothesis can be tested by examining whether the protoliths of target UHP rocks primarily originated from juvenile middle Paleoproterozoic crust or not.

The North China Block is generally characterized by arc–continent collision and crustal reworking in the middle Paleoproterozoic, without any contemporaneous growth of juvenile crust (Tang J *et al.* 2007;

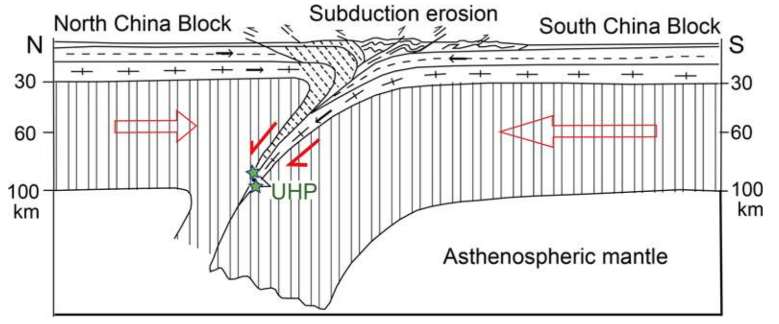

Fig. 22. The double subduction model during continental collision in the Sulu orogen (revised after Xu 2007). The continental margin of the North China Block was eroded by the subducting continental lithosphere of the South China Block leading to the occurrence of Paleoproterozoic protoliths in the UHP metamorphic zone.

Zhang *et al.* 2014). In contrast, the growth of juvenile crust is prominent during the middle Paleoproterozoic in the South China Block (Zheng *et al.* 2006, 2007*c*, 2008*b*, 2009; Zhang & Zheng 2013). Whole-rock Sm–Nd isotope studies indicate that Paleoproterozoic–Archean protoliths of Sulu UHP metamorphic rocks have similar Nd isotope compositions to contemporaneously juvenile crust, pointing to their tectonic affinity with the South China Block (Tang *et al.* 2008*b*; Zhang *et al.* 2014). In this regard, the sporadic occurrences of Paleoproterozoic–Archean protolith for UHP metamorphic rocks cannot be used as a diagnostic index to determine their origination from the North China Block. As such, the hypothesis of bidirectional subduction does not stand up to close scrutiny.

The occurrence of UHP eclogites with zircon U–Pb ages of 2.0–1.8 Ga for their protoliths in the Sulu orogen is really intriguing (Yang *et al.* 2003; Tang *et al.* 2008*b*). If these rocks with a Paleoproterozoic protolith age did have a tectonic affinity to the North China Block, they would be a type of mélange produced by subduction erosion during the continental collision in the Triassic. It is likely that the subduction erosion would lead to occurrences of different lithotectonic units inside the suture zone along the continental margins that underwent collision (Zheng *et al.* 2005, 2013*b*). Because basal subduction erosion occurred during the subduction of the South China Block beneath the North China Block to forearc depths, the Paleoproterozoic protolith of UHP metamorphic rocks in the Sulu orogen could have been offscrapped from the basement of the North China Block and then carried into subarc depths to undergo UHP metamorphism. Afterwards, they could have been tectonically emplaced into the collisional orogen, such as those presently observed. However, the O isotope analysis of whole rock and zircon for the UHP eclogites of Paleoproterozoic protolith age yields similar ^{18}O depletion to that of the hosting UHP gneiss (Tang *et al.* 2008*b*). This indicates that the protolith has a tectonic affinity to the South China Block rather than the North China Block because the ^{18}O depletion is caused by the continental deglacial water–rock interaction at high temperatures in the Middle Neoproterozoic, which would only occur in the northern margin of the South China Block (Zheng *et al.* 2004, 2007*b*; He *et al.* 2016). In this regard, the Paleoproterozoic protolith would occur as a Paleoproterozoic mafic complex in the northern margin of the South China Block. As such, the occurrence of Paleoproterozoic protoliths in the UHP metamorphic zone does not mean that these lithotectonic slices originated from the southern margin of the North China Block.

However, there might be exceptions for the granulites, gneisses and amphibolites of Paleoproterozoic–Archean age at Haiyangsuo in the Sulu orogen (Liou *et al.* 2006; Zhang *et al.* 2006; Liu *et al.* 2017). These rocks are surrounded by eclogite-facies UHP metamorphic rocks but no eclogite-facies mineral has been found within them, making their petrogenesis enigmatic. As documented by Liu *et al.* (2017), they have petrographical, geochronological and *P–T* evolution affinities to those in the Jiaobei Terrane, part of the Jiao-Liao-Ji Belt in the SE edge of the North China Block (Tang J *et al.* 2007), which experienced granulite-facies metamorphism at 1.87–1.86 Ga. However, they are distinct from the UHP metamorphic rocks in the Jiaodong Terrane in the Sulu orogen (Tang *et al.* 2008*b*), which have an igneous protolith of Middle Neoproterozoic age. In this regard, Liu *et al.* (2017) concluded that these rocks are exotic to the Sulu orogen and thus originated from the Jiao-Liao-Ji Belt. These authors have identified for the first time the Triassic metamorphic event in the Haiyangsuo unit, indicating its involvement in the continental subduction channel for metamorphism. A similar lithotectonic unit also occurs at Huangtuling in the Dabie orogen, where Late Archean rocks experienced granulite-facies metamorphism at 2.04–1.99 Ga (Sun *et al.* 2008;

Wu *et al.* 2008; Jian *et al.* 2012). Although no Triassic metamorphic age was obtained from these granulites, their involvement in the Triassic continental deep subduction was not precluded. This can be explained by the absence of hydrous minerals during their subduction in the Triassic. In addition, a metagabbro at Huilanshan, adjacent to Huangtuling, was identified as having experienced granulite-facies metamorphism at 794 ± 10 Ma during continental rifting prior to rupture from the Rodinia supercontinent (Liu *et al.* 2007*b*). It is possible that the lower crust rocks at Huangtuling suffered the two episodes of metamorphic dehydration at granulite facies in the Precambrian, leaving no hydrous minerals for breakdown to produce metamorphic and peritectic zircons in the Triassic. Whereas the granulite-facies metamorphism in the Middle Paleoproterozoic may have a bearing on the cratonization of continental crust in both North China and South China, the granulite-facies metamorphism in the Middle Neoproterozoic has nothing to do with the cratonization of South China because it was caused by continental rifting along the northern and western margins of the South China Block.

Northwards v. southwards subduction

There is a general consensus that the Dabie–Sulu UHP metamorphic rocks were generated by northwards subduction of the South China Block beneath the North China Block (Cong 1996; Hacker *et al.* 1998; Faure *et al.* 1999; Liou *et al.* 2000; Zheng *et al.* 2005; Ernst *et al.* 2007). Regional metamorphic rocks in the Dabie–Sulu orogenic belt show a northwards variation from HP blueschist through HP eclogite to UHP eclogite (Fig. 2), with greenschist-facies low-grade metamorphic rocks in the zone close to the North China Block (Zheng *et al.* 2005). According to the similarity of the Sr–Nd–Pb isotopes in Early Cretaceous felsic and mafic igneous rocks between the Dabie–Sulu orogenic belt and the North China Block, on the other hand, it was inferred that the subducted lithosphere has little resemblance to the South China Block and, thus, suggests an opposite polarity for the Triassic subduction: that is, the North China Block was subducted southwards beneath the South China Block (Jahn *et al.* 2003; Jahn & Chen 2007). Based on their structural observations and microtectonic analysis of the Shima–Wumiao area in the Central Dabie zone, Yamamoto *et al.* (2013) argued for southwards subduction of the North China Block beneath the South China Block. Furthermore, Li *et al.* (2017) further argued that the Dabie–Sulu orogenic belt could have been produced by southeastwards subduction of the North China Block to the South China Block in the Triassic. However, these arguments do not stand up under scrutiny. They were built on an insufficient understanding of the geochemical and geological observations from the continental subduction zone, and on serious confusion between exhumation and subduction structures. There were also both spatial and temporal mistakes in interpreting the eastwards and westwards extrusion of UHP metamorphic rocks along the continental margins that underwent collision. The exhumed rocks often show both structural and compositional inheritances from the subduction-modified rocks, leading to much confusion in previous studies between compressional and extensional tectonics. Therefore, the hypothesis of southwards subduction cannot explain the tectonic development of convergent continental margins from the Early Paleozoic to the Early Mesozoic, and the exhumation processes of different grades of regional metamorphism during the collisional orogeny in the Triassic.

In fact, the similarities in radiogenic Sr–Nd–Pb isotope compositions are common for continental igneous rocks, which does not make them a characteristic feature for distinguishing between different parental rocks. Instead, the U–Pb ages and O isotopes of relict zircon domains in igneous rocks are diagnostic for given parental rocks. Zircon U–Pb dating indicates the presence of Middle Neoproterozoic magmatic cores in Late Triassic felsic dykes (Wallis *et al.* 2005) and K-rich granites (Zhao *et al.* 2017*b*), consistent with similar U–Pb ages for relict zircons in the Dabie–Sulu UHP metabasites and metagranites (Chen Y.-X. *et al.* 2011; Liu & Liou 2011; He *et al.* 2016; Chen & Zheng 2017). This demonstrates that the Late Triassic intrusives and the Middle Triassic UHP meta-igneous rocks share the same ages for their parental rocks, with the UHP slices themselves as the source of syn-exhumation magmatism. As envisaged by Zheng *et al.* (2011*b*, 2015), the Late Triassic alkaline magmatism was triggered by dehydration melting of the UHP slices themselves during the initial exhumation. With respect to the Early Cretaceous granitoids in the Dabie–Sulu orogenic belt, zircon U–Pb dating and O isotope analysis indicate the presence of relict magmatic cores with not only Middle Neoproterozoic ages but also low $\delta^{18}O$ values (Zhao & Zheng 2009), demonstrating their derivation from the partial melting of the South China Block (Zhao *et al.* 2017*a*). In this regard, the general similarities in the geochemical composition of continental igneous rocks cannot be used as a diagnostic index to distinguish between different parental rocks. As such, the hypothesis of southwards subduction does not stand up under close scrutiny.

So far, no arc volcanics of either Late Paleozoic or Triassic age have been found in the SE margin of the North China Block (Cong 1996; Zheng *et al.* 2005; Xu *et al.* 2006; Ernst *et al.* 2007). This points to the absence of arc magmatism in the active continental margin during subduction of not only the former Palaeo-Tethyan oceanic slab in the Late Paleozoic but also the continental lithosphere of the South China Block in the Triassic. However, the absence of arc magmatism does not mean the presence of a passive continental margin there, and thus no northwards subduction of the South China Block beneath the North China Block. Traditionally, such an absence was ascribed to the lack of free water released from the subducting continental crust at subarc depths (Rumble *et al.* 2003; Zheng *et al.* 2003). After examining the stability of hydrous minerals at different *P–T* conditions in both continental and oceanic subduction zones, it was found that crustal rocks in both subducting continental and oceanic slabs show the same dehydration behaviour after they were buried to depths of >10 km (Zheng *et al.* 2016). Because the thermal structure of subduction zones exerts a first-order control on the dehydration of crustal rocks at forearc–subarc depths (van Keken *et al.* 2011; Zheng & Chen 2016), similar amounts of water are expected to be released from the subducting crustal rocks at subarc depths in the same geothermal gradients for metasomatism of the mantle wedge in active continental margins (Zheng *et al.* 2016). Although fertile and enriched metasomatites are generated in the mantle wedge, they are not able to partially melt immediately because of the temperature difference of 300–400°C between crustal metasomatism and arc magmatism. It takes time to heat the mantle wedge for partial melting. For this reason, arc volcanism variably occurs later than subduction zone metasomatism. In the present case, the North China Block was a craton in the Paleozoic (Menzies *et al.* 2007) and it had a thickness of >200 km in the Triassic (Zheng *et al.* 2018), so that the metasomatites in the SCLM wedge were not heated for partial melting in the Triassic because of their low temperatures during the coupled subduction between the SCLM wedge and its underlying oceanic and continental slab (Zheng *et al.* 2016). Instead, they underwent partial melting in the Early Cretaceous due to rollback of the subducting palaeo-Pacific slab (Zhao Z.-F. *et al.* 2013, 2015). Therefore, the absence of arc magmatism in the SE margin of the North China Block does not mean a lack of metamorphic fluids in the former oceanic and subsequent continental subduction channel. Thus, this observation cannot be used to argue against the northwards subduction of the South China Block beneath the North China Block.

Differential v. bulk exhumation

According to their study of numerical geodynamics, Davies & von Blanckenburg (1995) suggested a slab breakoff model for exhumation of UHP metamorphic rocks in the Western Alps. This model hypothesizes that the deeply subducting continental slab could be broken off from the descending oceanic slab as soon as buoyancy of the continental crust overcomes gravity of the oceanic crust at subarc depths and then the UHP slab is then exhumed as a whole from subarc depths to crustal levels. However, a study of seismic tomography reveals that the deep continental slab is still present in the Western Alps (Zhao L *et al.* 2015), which rejects the slab breakoff model. On the other hand, Chemenda *et al.* (1995) carried out a series of analogue experiments, which suggested that large, coherent slices of crust could be exhumed in one piece. In other words, a coherent slice of continental crust was detached from the subducting lithosphere and uplifted to crustal levels from subarc depths by slip along two faults that were bounded by a thrust below and a normal fault above (Fig. 23). Since this work, the exhumation of a crustal slice has been a popular model for the exhumation of UHP terranes.

Based on geological observations and geochronological data available for each time, various scenarios were suggested for the exhumation of UHP metamorphic rocks in the Dabie–Sulu orogenic belt. These include: (1) wedge extrusion (Maruyama *et al.* 1994); (2) orogen-parallel eastwards extrusion (Hacker *et al.* 2000, 2004); (3) a dome-extrusion nappe (Xu *et al.* 2009); (4) multiple layers of channel flow (Yang *et al.* 2009); and (5) two-stage extrusion (Li S.Z. *et al.* 2009, 2010). However, a number of petrological studies on Dabie–Sulu metamorphic rocks indicate that continental crust underwent layered detachment during its subduction to different depths (Li X.-P. *et al.* 2004; Zheng *et al.* 2005; Tang *et al.* 2006; Liu & Li 2008). The exhumed UHP slices in the collisional orogen encompass not only the subducted sedimentary cover but also the subducted crystalline basement, with the latter being composed of both upper and lower continental crust. As a consequence, different grades of metamorphic rocks were exhumed in different slices with a given sequence across the collisional orogen (Figs 1 & 2).

The slab breakoff model was also suggested for syn-collisional magmatism in association with continental subduction zone UHP metamorphism (von Blanckenburg & Davies 1995). This involves an influx of heat or melt from the underlying asthenospheric mantle. Chen *et al.* (2003) applied this model to explain the occurrence of Late Triassic K-rich granites at Shidao in the NE part of the Sulu orogen, assuming its formation to be in an extensional setting by partial melting of the lithosphere of the overriding plate due to asthenospheric upwelling following the slab breakoff. It took the North China Block to be the source of the alkaline magmas. However, zircon U–Pb dating indicates the presence of Middle Neoproterozoic magmatic cores in Late Triassic K-rich granites (Zhao *et al.* 2017*b*),

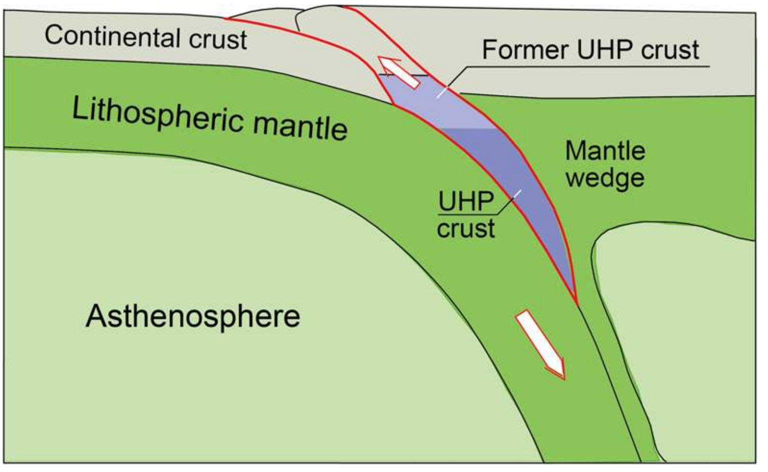

Fig. 23. The traditional model for exhumation of UHP terranes in a relatively coherent sheet during continental collision (revised after Chemenda *et al.* 1995).

indicating that their parental rocks were the South China Block rather than the North China Block. Therefore, the slab breakoff model cannot be applied to the syn-exhumation magmatism in the Sulu orogen. Instead, it can explain the contemporaneous generation of UHP and ultrahigh-temperature (UHT) metamorphic rocks in collisional orogens (Zheng & Chen 2016, 2017). Because the slab breakoff takes place during, rather than after, continental collision, this process cannot be invoked to account for the changes in the nature and composition of post-collisional magmas.

According to all the available observations and interpretation, Zheng *et al.* (2013*b*) unified these scenarios and their pertinent observations into a continental subduction channel model, in which different crustal slices were sequentially detached from the subducting continental lithosphere at different depths and exhumed along the same subduction channel towards the surface; the exhumation of UHP slices proceeds in two stages: the first is rapid from subarc depths to Moho depth and the second is slow from Moho depth to the middle crust level. In this regard, the subduction channel model can account for the differential exhumation of metamorphic slices during continental collision (Fig. 16a). Although the operation of the subduction channel processes may vary from orogen to orogen, there is a general sequence in collisional orogens (Zheng *et al.* 2013*b*). While the metamorphic grade increases from HP blueschist facies through HP eclogite facies to the UHP eclogite facies with subduction direction, greenschist-facies rocks occur primarily as the accretionary wedge along the margin of the overriding plate (Figs 1 & 2).

In summary, continental collision can be generalized as two stages in terms of their tectonic regime. The early stage is associated with coupling between the subducting slab and the overlying SCLM wedge. The compressional regime dominates the slab–mantle interface, and low geothermal gradients prevail in subduction channels. Although crustal slices can be detached from the subducting lithosphere, their buoyancy in the subduction channels is not large enough to overcome the resistance at the interface. As a consequence, almost no UHP slices can be exhumed from the subarc–forearc depths. Although fluids released from the subducting crust would have metasomatized the overlying SCLM, no syn-subduction arc magmatism can emerge because of the low temperatures in this stage. In contrast, the late stage is associated with decoupling between the subducting slab and the overlying SCLM wedge. This is generally caused by rollback of the subducting slab, giving rise to the extension regime at the slab–mantle interface and thus allowing for buoyant exhumation of the UHP slices along the subduction channels towards the surface. Furthermore, there would be heat transfer from the asthenospheric mantle into both wedge base and slab surface, leading to high geothermal gradients in the subduction channels, and thus to partial melting of metasomatic mantle domains and UHP metamorphic rocks in the late stage.

Post-collisional reworking of the UHP metamorphic rocks

The UHP metamorphic rocks in the Dabie–Sulu orogenic belt underwent variable extents of reworking in the post-collisional stage. This is recorded by migmatites, granulites and magmatic rocks of Early Cretaceous age in the high-temperature (HT)/UHP zones (Hacker *et al.* 1998; Bryant *et al.* 2004; Wu *et al.* 2007*b*; Zhao & Zheng 2009; Jian *et al.* 2012; Chen R.-X. *et al.* 2015; Gao *et al.* 2017*b*; Ji *et al.* 2017). It is particularly evident in the North Dabie zone, where the Triassic metamorphosed rocks were significantly superimposed by partial melting of Early Cretaceous age (Wu *et al.* 2007*b*; Jian *et al.* 2012; Chen R.-X. *et al.* 2015; Chen Y. *et al.* 2015; Zhao *et al.* 2017*a*). The North Dabie zone is mainly composed of tonalitic–granitic orthogneisses and magmatic rocks, with minor amounts of metaperidotites, metabasites (garnet pyroxenite, garnet amphibolite and mafic granulite), felsic granulite and granulite-facies calc-silicate. These minor volumes of metamorphic rocks occur as lenses in the regional orthogneisses. As one of the three UHP metamorphic zones in the Dabie orogen, the North Dabie zone experienced the maximum depth of continental subduction in the Triassic. However, no coesite was found in garnet of granulite retrograded from eclogite, like that in the Weihai zone of the Sulu orogen (Wang *et al.* 1993). Although microdiamond and coesite inclusions in zircon were reported for HT metamorphic rocks from the North Dabie zone (Liu *et al.* 2007*b*, 2011*a*, *b*), their Raman spectra are too weak to allow positive identification.

Furthermore, no eclogites have been found so far in the North Dabie zone. Previous studies simply took clinopyroxene as omphacite and named garnet pyroxenites as eclogites (e.g. Li *et al.* 1993; Xu *et al.* 2000; Liu *et al.* 2005), which was not confirmed in later studies (e.g. Xie *et al.* 2004; Malaspina *et al.* 2006). Relict omphacites were indeed found as inclusions in garnet from some garnet pyroxenites (Tsai & Liou 2000; Liu *et al.* 2007*a*, 2011*a*), demonstrating that these garnet pyroxenites were transformed from eclogites. This also led, again, to the naming of garnet pyroxenites as eclogites in some studies. Nevertheless, the presence of omphacite inclusions means that the garnet pyroxenites cannot be named as eclogites according to the regulations of petrological nomenclature. A geochemical study suggested a three-layer structure in the Dabie orogen (Zhao *et al.* 2008, 2011), in which the mid-temperature (MT)/UHP metamorphic rocks in the Central Dabie zone were located in the upper part, the HT metamorphic rocks in the North Dabie zone was located in the intermediate part and the source rock of the post-collisional granitoids was located in the lower part. Because of the geochemical inheritance in those migmatitic and magmatic rocks from the deeply subducted crust of the South China Block, the Early Cretaceous reworking can be regarded as post-collisional tectonism. This is also the reason why the Early Cretaceous magmatic rocks in the Dabie–Sulu orogenic belt can be named as the product of post-collisional magmatism (Zhao *et al.* 2005, 2007*b*, 2011, 2013). Although the time interval between continental collision and post-collisional foundering is about 100 myr (He & Zheng 2018), it is common for post-collisional magmatic rocks to show both structural and compositional inheritances from the collisional tectonics.

Because the HT metamorphic rocks in the North Dabie zone were retrograded from their UHP counterparts (Tsai & Liou 2000; Liu *et al.* 2005, 2007*a*, *b*, 2011*a*, *b*), their subduction to subarc depths for the Triassic UHP metamorphism is evident. However, the disappearance of not only eclogites but also UHP index minerals in these rocks requires superimposition by a specific tectonothermal event. This event should be not only intensive but also extensive throughout the North Dabie zone (Hacker *et al.* 1998; Bryant *et al.* 2004; Jian *et al.* 2012; Chen R.-X. *et al.* 2015), resulting in the contemporaneous production of migmatites (Wu *et al.* 2007*b*; Chen R.-X. *et al.* 2015), granulite (Gao *et al.* 2017*a*, *b*) and magmatic rocks (Xie *et al.* 2006; Zhao *et al.* 2017*a*). In this regard, the UHP metamorphic rocks underwent dehydration and hydration, partial melting, and melt extraction in the Early Cretaceous, leading to not only granulite- to amphibolite-facies metamorphism but also to magmatism and migmatitization. This episode of thermal tectonism can be attributed to the rifting orogeny (Zheng & Chen 2017), which was superimposed on the Triassic collision orogen (Gao *et al.* 2017*a*, *b*; Zhao *et al.* 2017*a*).

A large amount of magmatic rocks were emplaced in the Early Cretaceous into the Dabie–Sulu UHP metamorphic rocks (Zhao & Zheng 2009). The magmatic rocks in the Dabie orogen can be subdivided into two episodes with respect to their emplacement time (Xu & Zhang 2017; Zhao *et al.* 2017*a*): the early episode of rocks was emplaced principally at 145–130 Ma (Bryant *et al.* 2004; Xie *et al.* 2006; Wang *et al.* 2007; Xu *et al.* 2007; Huang *et al.* 2008), with varying degrees of structural deformation (locally gneissic foliation) and the occurrence of adakitic intrusives; and the later episode of rocks was emplaced at 130–120 Ma (Hacker *et al.* 1998; Jahn *et al.* 1999; Bryant *et al.* 2004; Zhao *et al.* 2004, 2005, 2007*b*; Xie *et al.* 2006; Huang *et al.* 2007), without considerable deformation and significant occurrence of adakitic intrusives. Zircon SHRIMP U–Pb dating also indicates two episodes of migmatization during the Early Cretaceous in the Dabie orogen (Wu *et al.* 2007*b*). Despite the systematic differences between the two episodes of magmatism and migmatization, geochemical studies indicate that they all result from partial melting of the deeply subducted continental crust of the South China Block (Zhao *et al.* 2017*a*).

The magmatic rocks of adakitic composition also occur in the Dabie orogen (Wang *et al.* 2007; Huang *et al.* 2008), suggesting partial melting of the collision-thickened lower crust. These adakitic magmas were emplaced at 145–130 Ma, and their production requires heating of the lower crust in the garnet stability field. This may be caused by lateral flow of the asthenospheric mantle in response to eastwards rollback of the palaeo-Pacific slab (Zheng *et al.* 2018). Buoyant rise of the adakitic melts would lead to a density increase in the mafic residue of partial melting, making the orogenic root susceptible to foundering into the asthenospheric mantle. In this regard, the early magmatism was terminated by thinning of the collision-thickened orogenic lithosphere (Zheng & Chen 2017). As such, the time of removing the orogenic root is contemporaneous with the time of adakitic magmatism. Consequently, the transition in the tectonic regime from orogenic thinning to lithospheric stretching may occur at about 130 Ma (Zhao *et al.* 2017*b*).

Whereas heating of the collision-thickened lower crust is associated with foundering of the orogenic root, heating of the thinned orogenic lithosphere is associated with active rifting in response to asthenospheric upwelling (Zheng & Chen 2016, 2017). Therefore, there are two-stage processes for post-collisional magmatism in the Dabie–Sulu orogenic belt: the first is thinning of the collision-thickened orogenic lithosphere by foundering of the orogenic root through the asthenospheric erosion; and the second is upwelling of the asthenospheric mantle along the thinned orogen for rifting orogeny (Fig. 16b). The second episode of magmatism is generally bimodal in composition. This rifting orogeny contributes not only to Buchan-type HT–UHT granulite-facies metamorphism along former accretionary and collisional orogens (Zheng & Chen 2017) but also to the final unroofing of UHP metamorphic rocks and the emplacement of metamorphic core complexes (Faure *et al.* 2003; Ji *et al.* 2017). Despite the inheritance in both structure and composition, the rifting orogeny is independent of the collisional orogeny in the tectonic regime (Zheng & Chen 2017).

Post-collisional mafic igneous rocks in the Dabie–Sulu orogenic belt were primarily emplaced at 130–120 Ma (Zhao Z.-F. *et al.* 2013, 2015; Dai F.-Q. *et al.* 2016). They show arc-like trace element distribution patterns and enriched Sr–Nd isotope compositions. They contain relict zircons with Triassic and Neoproterozoic U–Pb ages, indicating that crustal components in their mantle sources were derived from the recycling of deeply subducted continental crust of the South China Block. Recycling of noble gases is registered by He, Ne and Ar isotope compositions of pyroxene from post-collisional mafic igneous rocks in the Dabie orogen (Dai L.-Q. *et al.* 2016). The sources were generated through metasomatic reaction of the SCLM wedge peridotite with hydrous felsic melts derived from partial melting of the deeply subducted continental crust. This corresponds to the crust–mantle interaction in the continental subduction channel (Zheng 2012). The SCLM is predominated by peridotite in lithology, and its major elements dictate the lithochemistry of mafic–ultramafic metasomatites. In contrast, the deeply subducted continental crust is predominated by felsic rocks, whose dehydration melting yields hydrous felsic melts with significant enrichment in melt-mobile-incompatible trace elements and their pertinent radiogenic isotopes (Zheng *et al.* 2018). As a consequence, the crustal melts exert a major control on the geochemistry of metasomatites. Although the metasomatites were generated in the Triassic, they underwent partial melting for mafic magmatism in the Early Cretaceous. While the ultramafic metasomatite is responsible for the intrusives of basaltic composition (Zhao *et al.* 2013), the mafic metasomatite is responsible for the volcanics of andesitic composition (Dai F.-Q. *et al.* 2016). In either case, these metasomatites were stored in the orogenic lithospheric mantle since the Triassic and were not partially molten until the collision-thickened lithosphere was thinned for the rifting orogeny in the Early Cretaceous.

As highlighted by Zhao *et al.* (2013, 2017*a*), the post-collisional mafic and felsic magmatic rocks in the Dabie–Sulu orogenic belt are characterized by arc-like trace element distribution patterns in the primitive mantle-normalized diagram. The arc-like geochemical signatures are also evident in the diagram of Nb/U v. Ce/Pb ratios (Fig. 20b), where almost all of the post-collisional magmatic rocks show significantly lower values than both MORBs and OIBs, except hornblendites which exhibit unusually high Nb/U and Ce/Pb ratios (Dai *et al.* 2012). The arc-like signatures were not imparted in the Triassic by continental subduction at all. Instead, they are inherited from their parental rocks which contained the arc-like geochemical signature of crustal components. These crustal components originated from the deeply subducted continental crust in the northern margin of the South China Block, which was primarily produced by two episodes of oceanic subduction for arc magmatism during the Rodinia assembly in the Late Mesoproterozoic and during the Columbia assembly in the Middle Paleoproterozoic (Zheng *et al.* 2009; Zhang *et al.* 2014). In this regard, there are temporal intervals of more than 0.8–1.8 gyr between the arc magmatism and the reworking of its products in the ancient suture zones. As such, it is critical to distinguish the primary products of arc magmatism from its reworked products in accretionary and collisional orogens. Therefore, caution must be exercised when linking arc-like magmatism to oceanic subduction at ancient convergent plate margins that have been developed into modern intracontinental regions.

Implications for the Wilson cycle

Wilson (1966) was the first to recognize that dissimilar marine palaeo-faunas on both sides of the present-day Atlantic Ocean were best explained by an earlier proto-Atlantic ocean. He proposed that the Appalachian–Caledonide mountain belt of western Europe and eastern North America was formed by the destruction of a Paleozoic ocean that predated the Atlantic Ocean. He argued that the Iapetus – a precursor of the Atlantic Ocean – opened in the Early Paleozoic, closed in the Late Paleozoic and then opened again in the Late Mesozoic. This led to the concept that oceans may close and then reopen, which became known as the Wilson cycle, and its acceptance marks the application of plate tectonics principles to ancient orogenic belts (Burke & Dewey 1974). As a fundamental concept in plate tectonics, a Wilson cycle generally comprises three phases for the history of a particular ocean from its birth to its death: (1) opening and spreading; (2) development of an oceanic subduction zone; and (3) consumption and closure of the oceanic basin. In this regard, a Wilson cycle starts with the break-up of a continent and growth of an ocean with the formation of a new mid-ocean rift system (the first phase), and collisional orogeny that has terminated such a cycle at a later time (the third phase). While it is certain that the second phase is responsible for accretionary orogeny in oceanic subduction zones, it is uncertain whether there is the fourth phase responsible for the destruction of the compressional orogens prior to the opening of new oceans.

In terms of orogenesis along convergent plate boundaries, on the other hand, a Wilson cycle is generally described in the following three stages: (1) continental break-up along a pre-existing suture, leading to the opening of a new oceanic basin (Fig. 24a). The asthenospheric mantle underwent decompressional melting at seafloor spreading centres to produce mid-ocean ridges, which are generally composed of basaltic lavas and gabbroic intrusions with abyssal peridotite below and seafloor sediments above – this creates the petrological sequence of an ophiolite at constructive plate margins. (2) Subduction of an oceanic lithosphere beneath another oceanic lithosphere or a continental lithosphere (Fig. 24b). This process may initiate along a mid-ocean ridge, a back-arc rift or a transform fault. It is often associated with obduction of fragments of the oceanic lithosphere onto the continental margin, resulting in tectonic emplacement of the ophiolite at shallow depths. Further subduction of the oceanic slab to forearc depths produces HP blueschist- to eclogite-facies metamorphic rocks. Dehydration of the subducting oceanic crust at subarc depths leads to metasomatism of its overlying mantle wedge, generating the hydrous, enriched mantle domains in the mantle wedge. Partial melting of

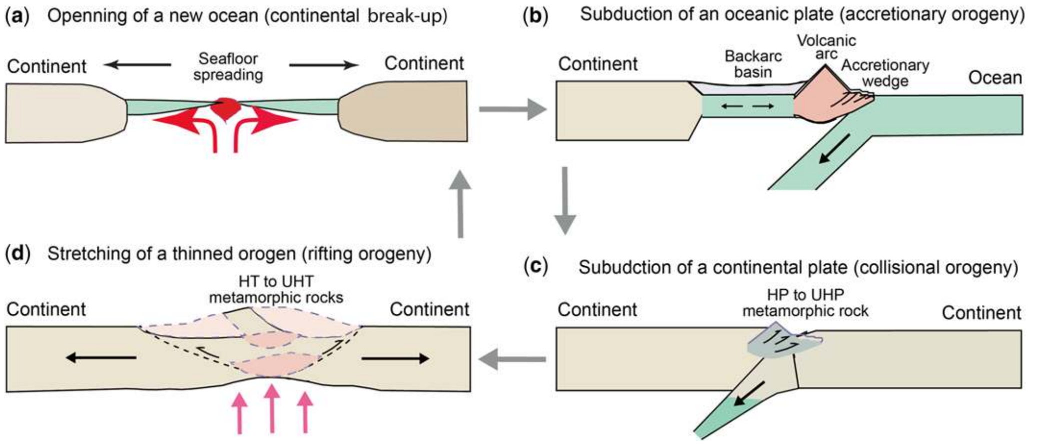

Fig. 24. Schematic cartoons showing the tectonic evolution of a Wilson cycle. (**a**) Continental break-up for the opening of a new oceanic basin along a former suture. (**b**) Accretionary orogeny due to the subduction of oceanic crust, accompanied by arc volcanism, blueschist- to eclogite-facies metamorphism and emplacement of accretionary wedge. (**c**) Collisional orogeny due to the subduction of continental crust, accompanied by HP–UHP eclogite-facies metamorphism. (**d**) Rifting orogeny due to the stretching of a thinned orogen in response to asthenospheric upwelling at plate boundaries. Whereas HT–UHT granulite-facies metamorphism and bimodal magmatism take place at convergent plate margins, mid-ocean ridges or back-arc basin mafic magmatism occurs at divergent plate margins.

such domains at a later time gives rise to arc magmatism on the overriding plate, resulting in accretionary orogeny along destructive plate margins; (3) Subduction of a continental lithosphere beneath another continental lithosphere or an arc terrane (Fig. 24c). This happens when the continental margin at the other side of the previous oceanic basin arrives at the subduction zone, leading to a collisional orogeny along convergent continental margins to produce HP–UHP eclogite-facies metamorphic rocks. While ongoing shortening induces deformation and metamorphism, as well as thickening of the continental crust, there is a lack of arc volcanism on the overlying plate.

Although all Wilson cycles lead to the formation of bigger continents, it remains to be resolved how intracontinental orogens develop from rifting to break-up prior to the opening of a new oceanic basin. Originally, Wilson (1966) envisaged that mid-ocean ridges represent places where lithosphere is being pulled apart and where new crust is being created, whereas island arcs and mountains represent places where lithosphere is being compressed. However, more and more studies indicate that island arcs are generally generated in transitional settings from compression to extension, whereas mountains can be created in both compressional and extensional settings (Dewey 1988; Andersen 1998). In particular, accretionary and collisional orogens may localize extensional tectonism hundreds of millions of years after the compressional tectonism has waned (e.g. Holdsworth *et al.* 1997; Vauchez *et al.* 1997; Tommasi & Vauchez 2001; Chenin *et al.* 2015; Zheng & Chen 2017). In addition to mountain building by subduction along destructive plate margins to create accretionary and collisional orogens (Zheng & Chen 2016), mountain building is also evident along mid-ocean ridges– which are mountain ranges on the floor of the world's oceans. The mid-ocean ridges often reach 1000–3000 m above the seafloor, where basaltic magma emerges onto the seafloor and into the crust at and near rifts along the ridge axes (Sandwell & Smith 1997; Keary *et al.* 2009). They have a continuous mountain system that is about 65 000 km long, making it the longest mountain range on Earth. Rift valleys in the centre of mountain ranges run down their spines. Therefore, the generation of mid-ocean ridges is attributable to active rifting in an intraplate setting, falling into the category of rifting orogens along constructive plate margins (Zheng & Chen 2017). Such orogens are characterized by (1) high geothermal gradients for high-temperature–low-pressure (HT/LP) metamorphism; (2) regional extension for emplacement of metamorphic core complexes; and (3) fractured fluid flow for high-temperature water–rock reaction. They have a bearing on the initiation of intraplate rifting in the former accretionary and collisional orogens (Fig. 24d), which may undergo lithospheric thinning by removing their roots at first and then destruction by active rifting for mountain building (Zheng & Chen 2016, 2017). This leads to the continental rifting that generally fails to run into rupture, making the orogenic lithosphere a normal thickness due to gravitational balance. If it runs into the break-up, a new Wilson cycle begins (Fig. 24a). In either case, rifted continental margins are characterized by such processes as lithospheric extension, orogenic collapse, partial melting of the thinned lithosphere, granulite-facies metamorphism, volcanic eruption, rift basin development, and the emplacement of metamorphic core complexes and large magmatic bodies (Zheng & Chen 2017; Zheng & Zhao 2017). Nevertheless, failed continental rifts are more common than successful ones.

It has been known for a while that the South China Block separated from the Rodinia supercontinent during its break-up in the Middle Neoproterozoic (Li Z.X. *et al.* 2003, 2008). The present northern margin of the South China Block split from Rodinia (Zheng *et al.* 2013*a*), so that this continental block was rotated relative to its original position (Li Z.X. *et al.* 2004). Continental rifting was evident during the splitting of the South China Block from Rodinia, which is recorded by the following observations in the northern margin of the South China Block: (1) bimodal magmatism at 780–740 Ma (Zheng *et al.* 2003, 2009); (2) low to negative $\delta^{18}O$ granitic magmatism and high-temperature deglacial water–rock interaction at 780–740 Ma (Zheng *et al.* 2004, 2007*b*, 2008*a*); and (3) granulite-facies metamorphism at 794 ± 10 Ma (Liu *et al.* 2007*a*). The separation of the South China Block from Rodinia would have proceeded along the Grenvillian orogen that marks the supercontinental assembly in the Late Mesoproterozoic (Zheng *et al.* 2008*a*). Afterwards, a new oceanic basin was opened between the South China Block and Rodinia following the continental rifting in the Middle Neoproterozoic. Therefore, the Wilson cycle started the first stage of its tectonic evolution along the northern margin of the South China Block in the Middle Neoproterozoic (Fig. 25a).

In general, one of the following three rock associations can be used to indicate the existence of oceanic subduction zones (Zheng & Chen 2016): (1) blueschist- to eclogite-facies metamorphic rocks; (2) mafic–ultramafic ophiolites; and (3) mafic arc volcanics. The eclogites and arc volcanics of Paleozoic age occur in the Qinling–Tongbai–Hong'an orogens (Wu & Zheng 2013; Zhou *et al.* 2015), indicating the disappearance of the Palaeo-Tethyan oceanic slab between the South and North China blocks. In this regard, the second stage is the subduction of oceanic lithosphere for the accretionary orogeny during the Paleozoic (Fig. 25b). However, continental

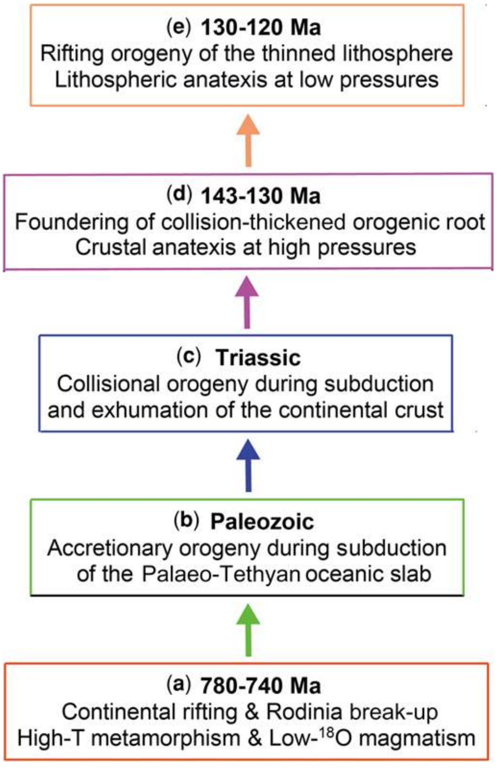

Fig. 25. A schematic flowchart illustrating an incomplete Wilson cycle recorded by metamorphic rocks in the Dabie–Sulu orogenic belt. (**a**) A new ocean was opened due to break-up of the Rodinia supercontinent in the Middle Neoproterozoic. (**b**) Northwards subduction of the Palaeo-Tethyan oceanic slab beneath the North China Block for an accretionary orogeny in the Paleozoic. (**c**) Northwards subduction of the South China Block beneath the North China Block for a collisional orogeny in the Triassic. (**d**) Thinning of the collision-thickened orogenic lithosphere due to the foundering of the orogenic root at 143–130 Ma. (**e**) Partial melting of the thinned lithosphere for a rifting orogeny at 130–120 Ma.

subduction zones are indicated by the occurrence of eclogite-facies metamorphic rocks and orogenic peridotites, but they contain neither ophiolites nor arc volcanics (Zheng & Chen 2016). Thus, the third stage is the subduction of the South China Block beneath the North China Block for the collisional orogeny in the Triassic (Fig. 25c), giving rise to the UHP metamorphic rocks in the Dabie–Sulu orogenic belt (Cong 1996; Liou *et al.* 2000; Zheng *et al.* 2003; Xu *et al.* 2006). Both accretionary and collisional orogenies are associated with tectonic compression for the formation of thickened lithosphere along convergent plate margins (Zheng & Zhao 2017). Such thickened orogens may be thinned at a later time via mechanisms such as lithospheric delamination, slab breakoff and asthenospheric erosion (Zheng & Chen 2016, 2017). Afterwards, the thinned orogens may be heated by the underlying asthenospheric mantle, resulting in tectonic extension for the rifting orogeny (Zheng & Chen 2017). Therefore, the thinning and destruction of thickened orogens are the two-stage processes at ancient convergent plate margins.

Petrological studies indicate that the Dabie–Sulu orogenic belt was reactivated for the rifting orogeny at 130–120 Ma, subsequent to the thinning of the collision-thickened orogenic lithosphere at 143–130 Ma (Zhao *et al.* 2017*a*). Such two-stage processes are evident in the Dabie orogen (Fig. 25d, e), where stretching of the collisional orogen for the rifting orogeny is recorded by the granulite-facies superimposition of UHP eclogite-facies rocks (Gao *et al.* 2017*a*, *b*), the emplacement of metamorphic core complexes (Faure *et al.* 2003; Ji *et al.* 2017) and coeval magmatism (Zhao *et al.* 2017*a*). Because the rifting orogen generally shows both structural and compositional inheritances from the former collisional orogen, it had led to some confusion in previous studies between compressional and extensional tectonics. At present, there is no relict of the subducted continental slab at lithospheric depths beneath these collisional orogens (Dong *et al.* 2008; Luo *et al.* 2012; He *et al.* 2014), indicating that the orogenic roots would have been foundered in the Early Cretaceous (Gao *et al.* 2017*b*; Zhao *et al.* 2017*a*; He & Zheng 2018). Although foundering may be realized by one of the following mechanisms such as thermal erosion, delamination and convective removal (Zheng & Chen 2016, 2017), thinning of the collision-thickened orogenic lithosphere is the premise of lithospheric destruction for continental rifting.

No matter whether the continental rifting at this stage fails to develop into break-up, it results in HT/LP metamorphism and the production of bimodal igneous rocks with dominance of granites in these thinned orogens (Fig. 24d). If the continental rifting at this stage could develop into rupture, it would have evolved to the opening of a new oceanic basin, returning to the first stage of the Wilson cycle for its tectonic evolution (Fig. 24a). In this regard, the rifting orogeny serves as an early phase of the first stage in a Wilson cycle (Fig. 24d), whereas the opening of a new ocean is a late phase of the first stage. As such, a Wilson cycle is composed of the three common stages of an orogeny from the rifting stage through the accretionary stage to the collisional stage along convergent plate boundaries (Fig. 24), with short timescales for individual orogenies. This results in a refined pattern of cyclicity in the creation and destruction of subduction-related orogens in the theory of plate tectonics.

Concluding remarks

A collisional orogeny along continental subduction zones comprises such two fundamental processes as subduction and exhumation, which correspond, respectively, to passive and active motion of crustal tracts in continental subduction channels. On the one hand, the continental lithosphere becomes subducted due to gravitational traction of high-density oceanic lithosphere, finally reaching subarc depths for coesite- and diamond-phase UHP metamorphism. On the other hand, UHP metamorphic slices were detached from the subducting continental lithosphere and exhumed along subduction channels to crustal levels due to the relative buoyancy of low-density continental crust. While continental deep subduction is generally characterized by low geothermal gradients, the exhumation of UHP slices commonly proceeds in elevated geothermal gradients. Recognition and understanding of metamorphic processes during the subduction and exhumation of continental crust are of considerable importance in the build-up of temporal and spatial links to changes in lithospheric thickness, metamorphic P–T conditions and the stability of hydrous minerals in continental subduction zones. The last issue may exert a primary control on both the thermodynamics and the kinetics of dehydration and hydration in UHP metamorphic minerals, which have a great bearing on fluid action and partial melting in UHP slices and, thus, on the preservability of UHP index signatures.

Significant progress has been made on understanding UHP metamorphic rocks from the Dabie–Sulu orogenic belt. The results demonstrate that these spectacular rocks were produced by subduction of the South China Block beneath the North China Block in the Triassic. Although there is a sporadic occurrence of Paleoproterozoic–Archean rocks in the Sulu orogen, it does not mean that bidirectional subduction from both the South and North China blocks occurred along the collided continental boundary. The post-collisonal magmatic rocks from the Dabie–Sulu orogenic belt share their Sr–Nd isotope compositions with those from both the South and North China blocks, so this cannot be used as a valid parameter to identify the subduction polarity. Instead, mineral O isotopes and parental rock ages are characteristic of those in the northern margin of the South China Block, so that the subducted-crust-derived materials are characterized by negative $\delta^{18}O$ values and Middle Neoproterozoic zircon U–Pb ages. The two geochemical signatures are unique and, thus, unambiguously indicate the northwards subduction of the South China Block beneath the North China Block.

The subducting continental lithosphere was detached at different depths and then sequentially exhumed towards the surface. This gives rise to a sequence of metamorphic slices with different metamorphic grades at the passive continental margin. In the Dabie–Sulu orogenic belt, for instance, the UHP metamorphic slices were detached at subarc depths from the subducting continental crust of the South China Block and then exhumed sequentially southwards along the continental subduction channel. They are bracketed by the HP blueschist- to eclogite-facies complexes in the south and the low-pressure greenschist-facies complexes in the north. A similar configuration also occurs in the Himalayan orogen, demonstrating that the sequence of exhumed HP–UHP metamorphic slices can be used to indicate the subduction polarity. After the continental collision, the two continental blocks are unified as a whole – resembling a supercontinental assembly in geological history. This initiates a supercontinental cycle, and its break-up is the first stage of a Wilson cycle. Nevertheless, the supercontinental break-up would start with the thinning of the subduction-thickened orogenic lithosphere and subsequent rifting orogeny in its early phase, followed by the supercontinental break-up in its late phase for the opening of a new ocean.

Acknowledgements This study was supported by funds from the Chinese Ministry of Science and Technology (2015CB856100) and the National Science Foundation of China (41590620). Thanks are due to Lulu Fu, Xiao-Ying Gao, Qiang He and Qiong-Xia Xia for their assistance during preparation of this manuscript. We are grateful to two anonymous reviewers for their comments, which greatly helped the improvement of the presentation.

Funding This was supported by funding from National Natural Science Foundation of China (grant No.: 41590620) and Ministry of Science and Technology of the People's Republic of China (grant No.: 2015CB856100) to Y.-F. Zheng.

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