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Dating of prograde metamorphic events deciphered from episodic zircon growth in rocks of the Dabie–Sulu UHP complex, China

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Abstract

The timing of ultra-high pressure (UHP) metamorphism has been difficult to determine because of a lack of age constraints on crucial events, especially those occurring on the prograde path. New Sensitive High-Resolution Ion Microprobe (SHRIMP) U–Pb age and rare-earth element (REE) data of zircon are presented for UHP metamorphic rocks (eclogite, garnet peridotite, garnet pyroxenite, jadeite quartzite and garnet gneiss) along the Dabie–Sulu UHP complex of China. With multiphase metamorphic textures and index mineral inclusions within zircon, the Dabie data define three episodes of eclogite-facies metamorphism, best estimated at 242.1±0.4 Ma, 227.2±0.8 Ma and 219.8±0.8 Ma. Eclogite-facies zircons of the Sulu UHP complex grew during two major episodes at 242.7±1.2 and 227.5±1.3 Ma, which are indistinguishable from corresponding events in the Dabie UHP complex. A pre-eclogite metamorphic phase at 244.0±2.6 Ma was obtained from two Sulu zircon samples which contain low pressure–temperature (plagioclase, stable below the quartz/Ab transformation) and hydrous (e.g., amphibole, stable below ~ 2.5 Gpa) mineral inclusions. In terms of Fe–Mg exchange of trapped garnet–clinopyroxene pairs within zircon domains, we are able to determine the Pressure–Temperature (*PT*) conditions for a specific episode of metamorphic zircon growth. We suggest that mineral phase transformations and associated dehydration led to episodic eclogite-facies zircon growth during UHP metamorphism (~ 2.7 Gpa) began at 242.2±0.4 Ma ($n=74$, pooling the Dabie–Sulu data), followed by peak UHP metamorphism (>~ 4 Gpa) at 227.3±0.7 Ma ($n=72$), before exhumation (<~ 220 Ma) to quartz stability (~ 1.8 Gpa). The Dabie–Sulu UHP metamorphism lasted for about 15 Ma, equivalent to a minimum subduction rate of 6 mm/year for the descending continental crust.

Keywords: Dabie–Sulu; SHRIMP; Eclogite and peridotite; Zircon; UHP metamorphism

1. Introduction

Despite numerous geochronological studies on UHP (>2.7 Gpa) rocks, the kinetics and timing of prograde metamorphic events associated with ultra-deep continental subduction remain largely unconstrained. One of the most spectacular cases of deep continental subduction [1–3] is the Dabie–Sulu belt of China where the South China continental crust was brought to mantle depths exceeding 120 km (3 to 4 Gpa) in the Triassic. UHP rocks generally evolve along a clockwise *PTt* path, where prograde metamorphism with increasing pressure and temperature conditions reflects progressive

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continental subduction to great depth, followed by fast exhumation to lower crustal levels [4]. However, dating of prograde metamorphism is a considerable challenge because: (a) inherited prograde metamorphic minerals mainly occur as inclusions or inclusion assemblages in garnet and, rarely, in zircon and are not suitable for isotopic dating; (b) many isotopic systems (Sm–Nd, Rb–Sr and Ar–Ar) in different minerals have blocking temperatures below the crystallization temperature and, therefore, intrinsically record cooling ages; and (c) the main metamorphic minerals, namely garnet and clinopyroxene, and their isotopic systems tend to become reset when metamorphic *PT* conditions dramatically change and mineral phase transformations occur as continental crust continually descends into the subduction zone. Zircon, a chronometer resistant to resetting up to high temperatures (possibly greater than 1000 °C, Ref. [5]) can grow over a wide range of *PT* conditions (amphibolite-, granulite- and eclogite-facies) [6] and thus potentially records the timing of physical and chemical changes during UHP metamorphism. Furthermore, zircon in UHP rocks frequently contains mineral inclusions which allow us to directly estimate metamorphic conditions of zircon formation during a specific evolutionary phase. We performed 239 SHRIMP U–Pb analyses on metamorphic zircons that episodically grew in the Dabie–Sulu UHP complex. The SHRIMP II ion microprobe (for analytical procedures see supplementary text) was applied to measure zircon domains (ca. 25–30 μm spot diameter, ca. 2–3 μm deep pits) for U–Th–Pb isotopes [7–9] and rare earth elements (REE) [10–12]. The *PT* conditions of metamorphic zircon formation were estimated in terms of Fe–Mg exchange of trapped garnet–clinopyroxene pairs. A general time frame for prograde UHP metamorphism could thus be established.

2. In-situ UHP metamorphism and overview of previous geochronology

The Dabie (Fig. 1-A)–Sulu UHP (Fig. 1-B) complex constitutes the largest known UHP metamorphic belt on Earth. It consists of felsic gneiss, marble, metapelite, jadeite quartzite, eclogite, garnet pyroxenite and garnet peridotite, produced during northward-subduction of the South China crust beneath the North China Craton [13]. Coesite [14] has been found in eclogite, jadeite quartzite, marble and metapelite. Even felsic gneiss, that mainly reflects amphibolite-facies mineral assemblages, occasionally preserves coesite in zircon [15], thereby providing solid evidence for *in-situ* regional UHP metamorphism. Diamond occurs sporadically in eclogite and peridotite within the Dabie [16] and Sulu [17] UHP belts, suggesting peak metamorphic conditions above the diamond/graphite transformation in the 4–6 Gpa/900–1000 °C range of diamond-bearing terranes [3].

The Dabie–Sulu UHP complex has been subjected to several geochronological studies which yielded numerous metamorphic ages including Sm–Nd [18–22] as well as multigrain ID-TIMS [23], single crystal ID-TIMS [24–26] and ion microprobe U–Pb data [13,27–38]. These data generally reflect Triassic metamorphism though with a broad age spectrum (~ 205–250 Ma). The UHP metamorphism has been interpreted to be Middle Triassic (~ 228–245 Ma)[34,37,39], Mid- to Late Triassic (~ 220–230 Ma) [18,20] or, more precisely, at 226–227 Ma [22,36], and Late Triassic (~ 220 Ma) [33]. Controversy concerning the timing of peak UHP metamorphism stems from isotopic disequilibrium (Sm–Nd) [22] and a poor understanding of the analyzed metamorphic zircon populations which may contain multiple age components [13,27,37]. Moreover, metamorphic ages, regardless of the dating method, vary greatly between samples and localities. For instance, Sm–Nd ages of the Bixiling garnet peridotite–eclogite complex of the Dabie Mountains are 209–218 Ma [19], whereas in the adjacent Maowu complex (Fig. 1-A) they are between 221 and 236 Ma [20]. This is inconsistent with *in-situ* regional UHP metamorphism and a coherent evolution of the UHP complex.

It is noteworthy that reported metamorphic ages of UHP rocks exhibit two distinct peaks at ~ 242–238 Ma and ~ 226–228 Ma. One typical case is the geochronology of the Shuanghe UHP Slice (Fig. 1-A) where Sm–Nd mineral isochrons yielded ages of 226.3 ± 3.2 Ma (garnet + omphacite + rutile) for a coesite-bearing eclogite and 226.5 ± 2.3 Ma (garnet + two phengites) for UHP gneiss, which may correspond to the age of peak UHP metamorphism [18,22]. A Sm–Nd age of 242 ± 3 Ma was determined through a garnet + whole rock tie-line of a strongly retrograde eclogite, and was interpreted as evidence for a retrograde metamorphic influence on the Sm–Nd system [18,22]. Single zircon ID-TIMS dating to determine metamorphic ages via a lower Concordia intercept yielded ages of 238.4 ± 1.3 Ma [25], 226 ± 8 Ma and 228 ± 12 Ma for country gneiss samples [26].

Ion microprobe U–Pb ages of metamorphic zircons from eclogite, garnet peridotite, garnet pyroxenite and gneiss along the Dabie–Sulu UHP belt generally vary between 191 and 266 Ma with weighted means ranging from ~ 220 Ma to ~ 245 Ma [13,27–34,36,37]. Being aware of the large variation in apparent ages (~ 209–250 Ma) and high MSWD's (mean square of weighted derivates) up to 13, Hacker et al. [13] found more than one single age population in their Dabie samples.

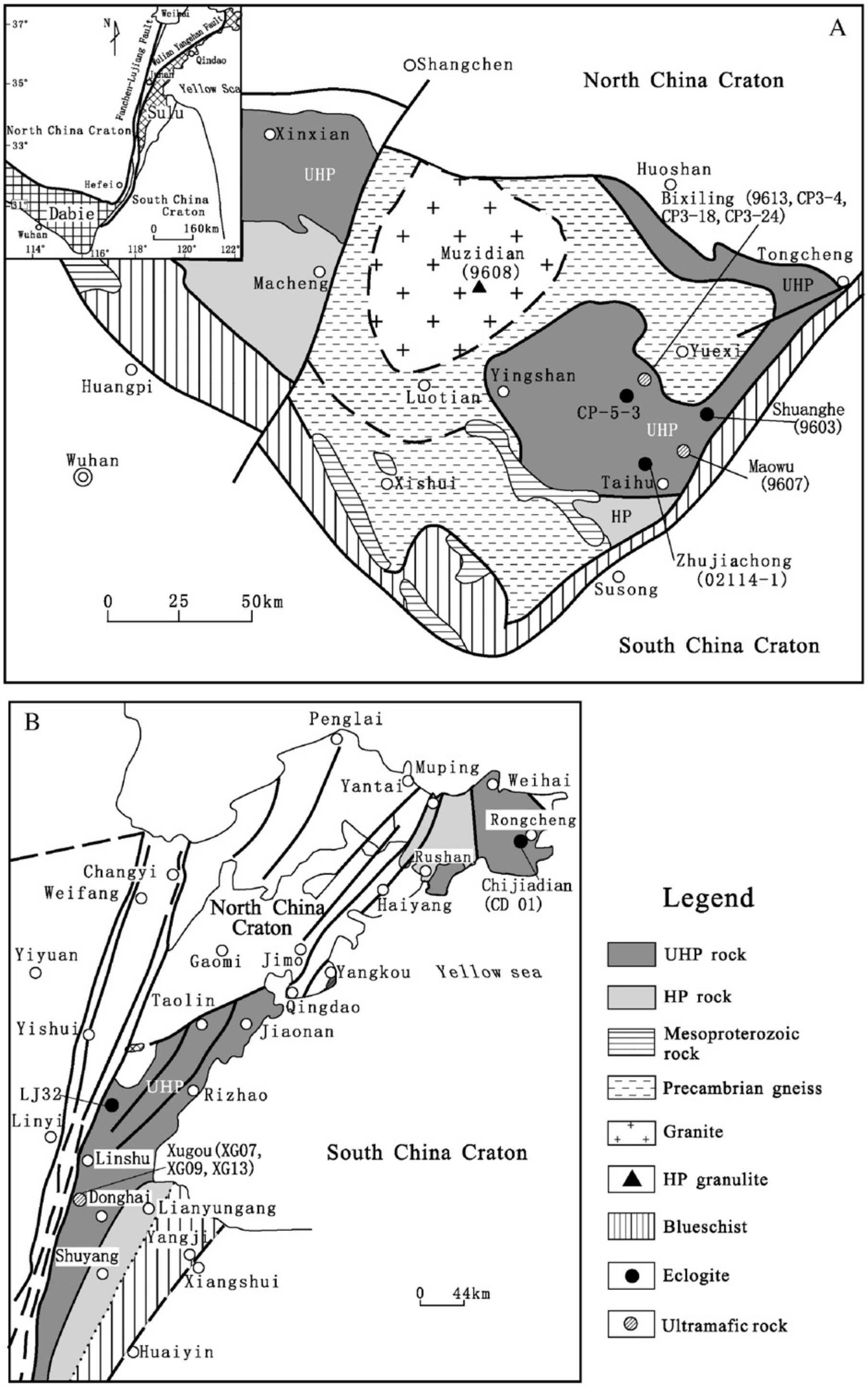

Fig. 1. Geological sketch maps of the Dabie (A) and Sulu (B) UHP complexes. The Sulu UHP Complex is considered to be the eastern extension of the Dabie UHP complex, offset about 530 km by the Tan–Lu fault (Fig. 1.-A, inset). The legend relates to both (A) and (B).

Accordingly, these authors proposed two episodes of metamorphic zircon growth at ~ 240 Ma and ~ 219 Ma respectively.

Multiple zircon growth during Triassic metamorphism has been observed in UHP gneisses from the Dabie and Sulu belts. Low Th/U overgrowths and whole zircon grains of quartzo-feldspathic gneiss from central Dabieshan yielded concordant U–Pb ages of 220–238 Ma, representing growth during UHP metamorphism, whereas thin, euhedral rims yielded concordant ages of 214–220 Ma due to retrograde metamorphism [27]. Wan et al. [34] reported U–Pb ages of 244.0 ± 4.7 Ma for coesite- and omphacite-bearing zircon mantles, and 226.1 ± 2.3 Ma for rims from a gneiss cobble in the Hefei Basin. Based on the UHP index mineral coesite within zircon in a paragneiss collected from the superdeep-drill hole in the Sulu belt, Liu et al. [30] argued that the coesite-bearing zircon phase dated UHP metamorphism at 229 ± 4 Ma; however, in a more recent paper [31], these authors also found coesite in 238–266 Ma zircon domains.

In conclusion, extensive geochronological studies of UHP rocks along the Dabie–Sulu belt in the past two decades have documented a wide spectrum of metamorphic ages which may indicate a succession of metamorphic events in the Triassic. We relate pulses of metamorphic zircon formation to dramatic changes in metamorphic *P–T* conditions through *in-situ* zircon domain dating and geochemistry, accompanied by detailed petrography.

3. Geological setting and sample description

3.1. Dabie UHP complex

The eastern Dabie Mountains are bounded by the Shangcheng–Macheng Fault to the west and the Tan–Lu Fault to the east (Fig. 1-A) and lie at the eastern end of the Qinling–Dabie belt. They comprise three principal units: (a) a gneiss unit known as the Dabie Group that mainly consists of metamorphic rocks retrograded to amphibolite-facies; Proterozoic [40] and Triassic (P. Jian et al., unpublished data) granulites and eclogites [21,35] are locally preserved; (b) a central UHP complex which contains coesite and diamond and represents the Dabie UHP complex; and (c) a southern HP metamorphic belt which possibly correlates with the HP belt of the Hong'an terrain to the west.

We investigated eight samples from several well-known localities of the Dabie UHP complex, namely Shuanghe [41], Maowu [20], Bixiling [42] and Zhujiachong [43] (Fig. 1-A), which cover the major lithologies.

Coesite-bearing jadeite quartzite (sample 9603) was collected from the Shuanghe UHP slice, which was described in detail by Zheng et al. and Liou et al. [26,41]. The rock is medium-grained and consists of jadeite (Jd = 85–90 mol%, 45–60 vol.%), quartz (35–50%), garnet (~ 5%) and accessory rutile, monazite and zircon. Polygonal quartz aggregates constitute the matrix. Coesite and quartz pseudomorphs after coesite occur in jadeite and garnet. Coronas of fine-grained smaragdite, plagioclase and magnetite surrounding garnet and jadeite relics are well developed and represent striking retrograde features. A total of 109 zircon grains were found in thin sections (~ 9000 mm^2) of the sample. Zircon occurs mostly in jadeite (21 grains, ~ 19%), symplectite after jadeite (34 grains, 32%), and quartz (32 grains, ~ 30%). Fewer grains were found interstitially in quartz (12 grains, ~ 11%) and along the boundary between quartz and symplectite (6 grains, ~ 5%). A few grains also occur in garnet (2 grains) and quartz inclusions within jadeite (1 grain). This mode of occurrence shows that zircon is mainly enclosed within, and or/associated with, jadeite and quartz and thus indicates that a Si-rich fluid and accompanying eclogite-facies metamorphism were responsible for zircon formation.

Sample (9607) is a garnet pyroxenite from the Maowu mafic–ultramafic body which measures about 250 × 50 m and occurs in a felsic gneiss. The Maowu body consists of metre- to centimetre-wide layers, and rock types include the dominant garnet pyroxenite, eclogite, websterite, harzburgite and omphacitite [20,37].

The Bixiling garnet–eclogite complex (~ 1.5 km^2) is the largest coesite-bearing mafic–ultramafic massif of the Dabie–Sulu region. Coesite-bearing eclogite at Bixiling is composed of layered mafic (dark-coloured) and banded eclogites (light-coloured), and the latter makes up about 90% of the complex. Dark-coloured eclogite is characterized by low quartz content (~ 0.1–1%), and a gabbroic–basaltic composition. Light-coloured eclogite is rich in quartz and kyanite and contains bands, several to several tens of centimetres wide, consisting of garnet + jadeitic omphacite + muscovite and/or muscovite + garnet. The studied eclogite samples CP3-4 and CP3-18 were collected from an outcrop on the eastern bank of the Qian River where the two kinds of eclogites are sharply bounded.

Sample CP3-4 is a light-coloured eclogite, consisting of quartz (~ 48%), clinopyroxene (~ 27%), kyanite (~ 20%), garnet (~ 3%), rutile (~ 1.4%), rare phengite (~ 0.2%), and accessory zircon. It is characterized by large amounts of quartz, much kyanite, and a high Na_2O content (8.19%) in clinopyroxene, which led Cheng et al. [28] to name it a kyanite jadeite quartzite. This light-coloured eclogite contains a significant number of zircons (37 grains in a 3000 mm^2 thin section), which are mainly enclosed in quartz (~ 75%), less frequently in kyanite (~ 10%) and clinopyroxene (~ 3%), but some grains also occur interstitially (~ 12%).

Sample CP3-18 is dark-coloured, layered, medium- to fine-grained eclogite, but locally slightly coarse-grained, and contains dominantly garnet (~ 52%) and omphacite (~ 38%). Garnet is usually fine-grained, but omphacite is coarser in size, therefore the rock locally exhibits an indistinct porphyroblastic texture. Rutile is unusually high (~ 7.5%). Minor quartz (~ 0.1%) occurs as veinlets or patches and must have formed from a local Si-rich fluid, probably after peak eclogite-facies metamorphism. Zircon is rare in the dark eclogite, and only ten grains were observed in 12 thin sections (totally ~ 25,000 mm^2). Most zircons occur in quartz (11 grains), and only one grain was seen in garnet.

The Bixiling garnet–peridotite is closely associated and in conformable contact with the dark-coloured eclogite, and locally the latter is found as inclusions within garnet–peridotite. Garnet peridotite occurs as folded layers enclosed within the main light-coloured eclogite, and sample no. 9613 was collected at the north end of the complex. It comprises olivine (~ 55%), clinopyroxene (~ 20%), and garnet (~ 20%), with minor ilmenite, talc, magnesite, phengite, rutile and Ti-clinohumite. Zircon was only found in coarse-grained garnet.

Sample CP3-24 is a garnet-gneiss, collected on the northern boundary of the Bixiling complex. The rock is medium- to fine-grained, heterogeneous, and is mainly composed of quartz, albite–oligoclase, K-feldspar, muscovite and chlorite after biotite, with minor relicts of garnet, secondary epidote, and trace amounts of zircon, titanite and apatite. Coarse-grained felsic aggregates (<5–8 mm) occur in the gneiss, which is probably an

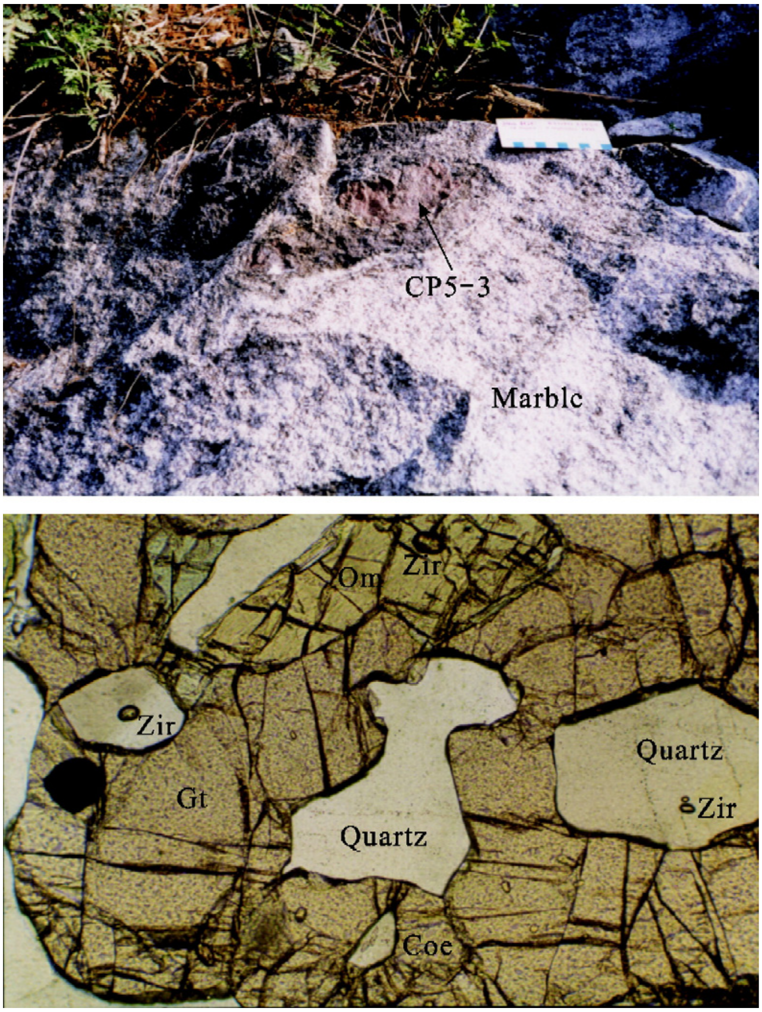

Fig. 2. Photograph showing the field occurrence of garnet-rich eclogite (CP5-3) (upper) and photomicrograph (lower) showing that zircons occur in quartz pseudomorph after coesite and omphacite within garnet.

indication of anatectic processes during metamorphism. Many zircons are found in quartz and feldspar.

Northwest of Changpu, the NNW-trending UHP metamorphic sedimentary sequence consists mainly of banded jadeite quartzite and marble with minor eclogite lenses. The studied eclogite (CP5-3) was collected ~ 4 km west of Bixiling where it occurs as a nodule (~ 60 mm–150 mm) enclosed in marble (Fig. 2, upper). From the core to the rim, omphacite decreases gradually, whereas amphibole increases. As a result, the rock becomes a garnet amphibolite at the rim. The sample is mainly composed of garnet (~ 53 vol.%), amphibole (~ 34%), quartz (~ 9%), as well as minor rutile (~ 2%) and calcite (~ 2%). Omphacite, coesite and pseudomorphs after coesite are found as inclusions in garnet. Quartz occurs as polygonal quartz aggregates or inclusions in garnet. In spite of its mafic composition this sample is rich in zircon. 58 grains were found in thin sections (total ~ 9000 mm^2), enclosed in quartz (~ 52%), amphibole (~ 19%), garnet (~ 9%), calcite (~ 3%), and locally at grain boundaries (~ 6%). One of the most important observations is that many zircons (~ 9%) occur in quartz inclusions within garnet (Fig. 2, bottom). These quartz inclusions show well-developed radial fractures and are therefore pseudomorphs after coesite. Similarly, zircon was found in omphacite inclusions (~ 2%) within garnet. These textural relationships suggest that zircon must have formed before, or at the same time as, coesite.

The Zhujiachong paragonite eclogite unit is located in the south of the UHP complex. Our sample (02114-1) consists of omphacite, garnet, minor quartz and kyanite as well as abundant hydrous minerals that include clinozoisite as well as porphyroblasts of zoisite, blue amphibole and paragonite. This type of eclogite has previously been interpreted as a cold, quartz-bearing HP rock [38,44,45], in contrast to hot, coesite-bearing eclogite in most parts of the Dabie Mountains. Recent discoveries of coesite in zircon and garnet have reassigned the paragonite eclogite to UHP metamorphism [15,38], followed by post-peak re-equilibration at about 18–24 kb and 570–700 °C [43].

3.2. Sulu UHP complex

The Sulu UHP complex is the eastern extension of the Dabie UHP complex [13] but is offset ~ 530 km to the northeast by the Tan–Lu fault (Fig. 1-A, inset; Fig. 1-B). Eclogite and garnet peridotite occur as tectonic blocks along the belt [33,46–51]. We investigated five samples from three localities in the Sulu UHP complex, namely Xugou, Junnan and Chijiadian (Fig. 1-B), which are located in the south, middle and the north of the belt.

The Xugou garnet peridotite massif [48] (~ 500–1500 m long) is located about 30 km north-west of the Chinese Continental Scientific Drilling (CCSD) site in the Donghai area, southern Sulu UHP complex. The massif consists of peridotite (mainly harzburgite with minor lherzolite), garnet clinopyroxenite and eclogite. Most eclogites occur as lenses ranging from 0.5 to 15 m in thickness, and are enclosed concordantly in peridotite. Three representative samples were selected for SHRIMP dating. Sample XG13 is a garnet peridotite mainly composed of olivine and/or serpentine (95 vol.%) with lesser amounts of enstatite, diopside, rare chromite, garnet and accessory zircon. Sample XG07 is a porphyroblastic eclogite adjacent to peridotite. The porphyroblasts are mainly coarse-grained garnet (1–10 mm) and rare omphacite, set in a fine-grained matrix of amphibole + feldspar + chlorite + epidote. Some primary minerals were replaced by surrounding aggregates of coarser intergrowths of prehnite and albite, rimmed by a thin layer of diopside; they appear to exhibit an amygdaloidal texture [48]. Sample XG09 is a banded eclogite, composed of coarse-grained (2.5–3 mm) garnet- and omphacite-rich compositional layers.

Eclogite sample LJ32 was collected from the Junnan area, the middle segment of the Sulu UHP Complex, where eclogite occurs as small lenses in the surrounding felsic gneiss. The studied eclogite mostly has a granoblastic texture, but is locally porphyroblastic. It consists of garnet (~ 45%), omphacite (~ 45%), rutile (~ 5%), glaucophane (~ 3%), phengite (~ 1%) and accessory apatite and zircon. Most porphyroblasts are coarse-grained garnet, whereas the matrix consists mainly of a fine-grained aggregate of omphacite. Cross-cutting veins containing phengite and glaucophane aggregates are common.

One eclogite associated with garnet peridotite was collected at Chijiadian (CD01), where garnet peridotite and associated eclogite have been described by several authors [51,52]. Eclogite occurs as small lenses (0.1 to 2 m in length) and is enclosed within garnet peridotite. The sample is mainly composed of garnet (~ 65%) and omphacite (~ 33%), with minor rutile and accessory zircon.

4. Results and interpretation

Table 1 summarizes the ages corresponding to the metamorphic evolution and *P*–*T* estimates. Table S1 contains SHRIMP zircon U–Pb data of the Dabie samples, whereas Table S2 lists SHRIMP U–Pb data of

Table 1
Triassic zircon ages and *PT* estimates for Dabie–Sulu UHP complexes

Sample	Lithology	Mineral constraints				*T* inclusions (°C)		*P–T* rock	
		Pre-eclogite (Ma)	Episode 1 (Ma)	Episode 2 (Ma)	Episode 3 (Ma)	2.7 (GPa)	4.0 (GPa)		References
Dabie UHP complex									
9603	Jadeite Quartzite		Inclusion-free 242.5±0.5	Gt, Om 227.4±1.1			748	800±50 °C >3.0 GPa	[44]
9607	Pyroxenite		Cpx 241.4±1.6	Gt, Chl 227.3±1.5				750±50 °C 4–6 GPa	[58]
CP5-3	Eclogite		Inclusion-free 240.8±0.9					545 °C 2.7 GPa	Present work
9613	Garnet Peridotite			Gt, Cpx, Chl 226.7±2.6			725 735	4.7–6.7 GPa 820–970 °C	[54]
CP3-4	Eclogite			Gt, Om 227.9±2.8			803	875 °C	Present work
CP3-18	Eclogite				Gt, Om 220.1±2.3		783	603 °C	Present work
CP3-24	Gneiss				219.3±1.1				
0244-1	Eclogite				220.4±1.3			570–700 °C 1.8–2.4 GPa	[43]
Weighted means			242.1±0.4 (*n*=51)	227.2±0.8 (*n*=41)	219.8±0.8 (*n*=52)				
Sulu UHP complex									
LJ32	Eclogite		Inclusion-free 243.1±1.4	Gt, Om, Ru 227.6±3.6					
XG13	Peridotite	01-bearing 244.6±7.6		Gt, Cpx 227.8±7.1				780–870 °C 5–7 GPa	[48]
XG07	Eclogite	Hb, P1, Chl, Kf 244.8±2.8		Gt, Om 224.8±2.7	Ep 217±18		885		
XG09	Eclogite		Gt, Om, Ru 242.0±2.9		Ep, Kf 192–215	607			
CD01	Eclogite	Inclusion-free 240.5±4.7	Gt, Om, Ru 227.0±2.6	Overgrowth 207±6			850	820–920 °C 4–6 GPa	[42,52]
Weighted means	244.0±2.6 (*n*=16)	242.7±1.2 (*n*=23)	227.5±1.3 (*n*=31)						

the Sulu samples. The chemical compositions of mineral inclusions are shown in Table S3 (garnet, clinopyroxene/omphacite) and Table S4 (amphibole, epidote, chlorite, olivine, plagioclase and K-feldspar). Tables S1–S4 are available as supplementary online material.

4.1. Dabie UHP complex

Episodic zircon growth corresponding to multiphase textures is best preserved in the Shuanghe jadeite quartzite (9603) and the Maowu garnet pyroxenite (9607). Metamorphic zircon of the jadeite quartzite generally consists of a core, with or without a mantle, surrounded by a thin, bright (low-U) luminescent rim (Fig. 3, 1–7). These cores and mantles have low Th/U ratios, generally <0.1, and are typically sector-zoned (Fig. 3, 5–7), a common feature of high-grade metamorphic zircon and probably generated during dehydration processes [8,53]. Seventeen analyses of cores yielded ages of 239.1 to 248.1 Ma with a weighted mean of 242.8±0.6 Ma ($\chi^2=1.31$, where χ^2 is chi-square, when $\chi^2=1$ for a large population, the error of the weighted mean is perfectly consistent with the error of individual analyses). Six mantles yielded ages between 239.6 and 245.5 Ma with a weighted mean of 242.5±0.5 Ma ($\chi^2=0.90$), identical to that of the cores. Pooling of the core and mantle data provides a weighted mean age of 242.5±0.5 Ma ($n=23$, $\chi^2=1.18$) that we interpret to reflect the first episode of metamorphic zircon growth. Three garnet- and omphacite-bearing zircon domains (Fig. 3, 2–4) have ages of 233.9 to 226.5 Ma (analyses 24-2, 22-2 and 3-2), two patched cores (analyses 12-2 and 24-1), 226.5 and 228.6 Ma, and three outermost rims (Fig. 3, 1 and 3) (analyses 24-3, 12-1 and 25-1) which are in equilibrium with the peak metamorphic assemblage and have relatively young ages (226.5–224.6 Ma). These

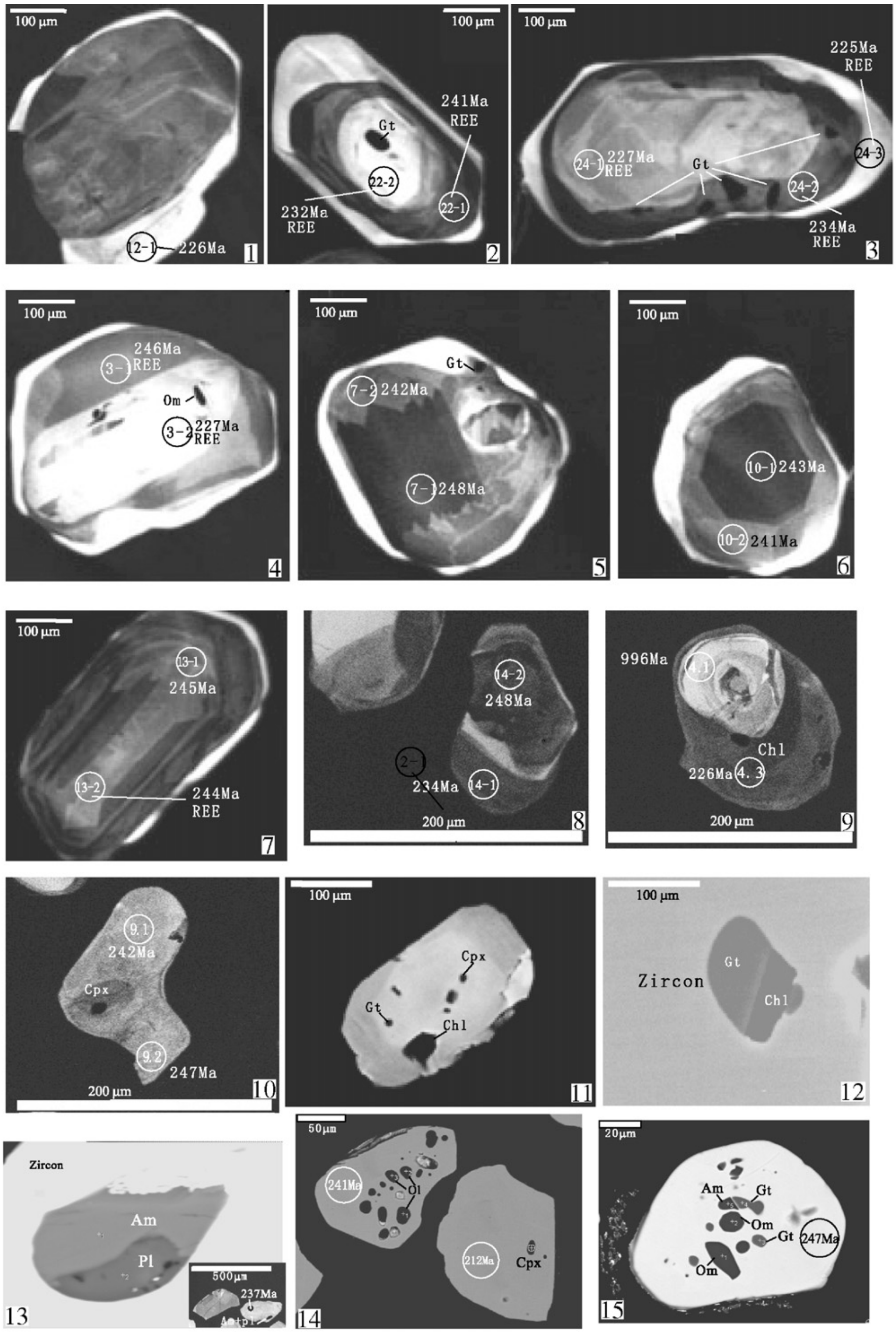

Fig. 3. Representative images of zircon: (1–7) CL images of zircons from jadeite quartzite, note sector-zoned textures (5, 7); (8–10) CL images of zircons from the Maowu garnet pyroxenite; (11 and 12) images of zircons from the Bixiling garnet peridotite. Note that chlorite (9) occurs in the overgrowth (226 Ma) adjacent to an inherited core, and clinopyroxene (10) occurs in the first episode of zircon domain (244–245 Ma). (11) CL image of zircon of the Bixiling garnet peridotite (9613) shows oscillatory zoning, suggesting that it crystallized in a fluid. (12) Back scatter electronic (BSE) image showing garnet and chlorite inclusions in zircon of the Bixiling garnet peridotite; (13–15) BSE images showing distribution of inclusions in zircon of Sulu samples. Circle and number denote spot center and age. REE denotes spot for REE measurement. Gt = garnet, Om = omphacite, Cpx = clinopyroxene, Chl = chlorite, Ol = olivine, Pl = plagioclase, Am = amphibole.

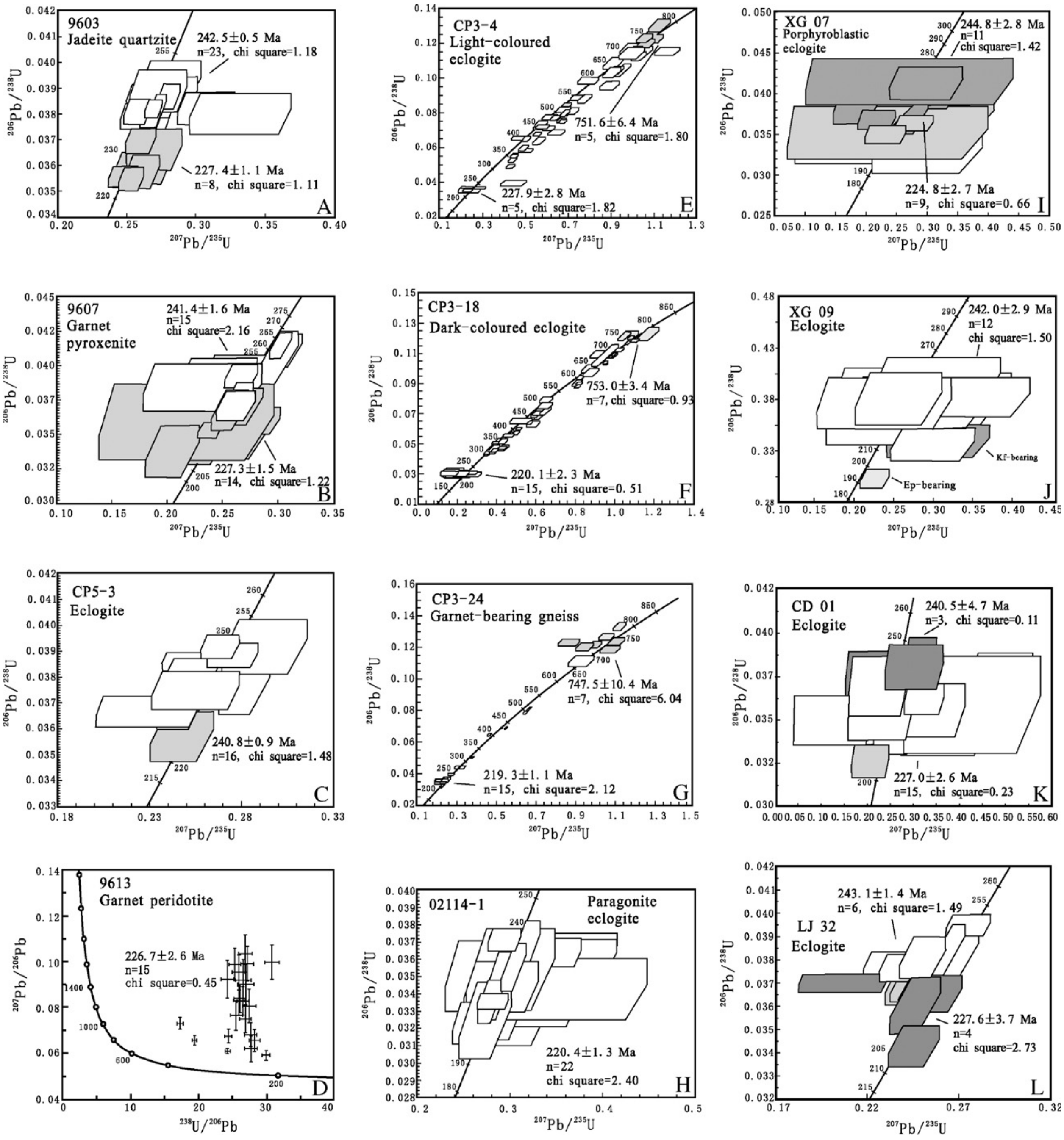

Fig. 4. U–Pb concordia diagrams. Note: Fig. 3-D is a Tera–Wasserburg plot, other plots are conventional diagrams.

are significantly younger than the first episode zircons, and on the concordia diagram (Fig. 4-A), they cluster at 227.4 ± 1.1 Ma ($n = 8$, $\chi^2 = 1.11$). This second episode of zircon growth must be related to mineral phase transformation during peak metamorphism as indicated by a striking compositional difference of omphacite inclusions within zircon (Figs. 3,4 and Table S3) from jadeite of the main constituent of the peak metamorphic assemblage.

Similarly, our garnet pyroxenite sample (9607) contains zircons showing two episodes of metamorphic growth. A thin, bright, peripheral zone usually marks the boundary between domains (Fig. 3-8). The internal domain, which locally contains clinopyroxene, represents

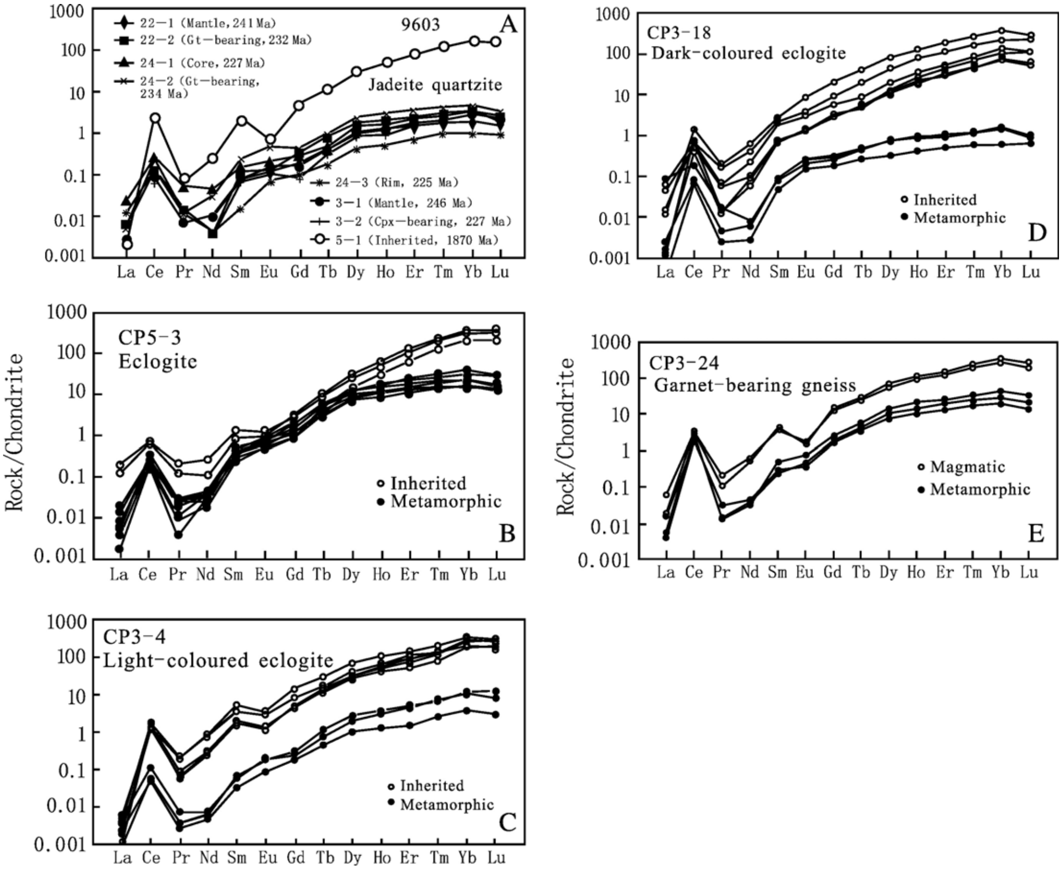

Fig. 5. Chondrite-normalized zircon REE abundances (A–E): (A) Shuanghe jadeite quartzite (9603); (B) CP5-3 in which the first episode of zircon has flat HREE patterns; (C) Bixiling light-coloured eclogite (CP3-4) in which the second episode of zircon has flat HREE patterns; (D) Bixiling dark-coloured eclogite (CP3-18) and (E) the Bixiling gneiss; in theses two samples the youngest generation of metamorphic zircons (~ 220 Ma) shows flat HREE patterns. Normalizing values are after Masuda [73].

the first episode of metamorphic zircon growth (241.4± 1.6 Ma, $n = 15$, $\chi^2 = 2.16$). Furthermore, the overgrowth reflecting the second episode of metamorphic zircon formation is dated at 227.3± 1.5 Ma ($n = 14$, $\chi^2 = 1.22$) (Fig. 4-B; Table S1), in good agreement with a previously reported U–Pb age of 227±5 Ma for the Maowu pyroxenite [37].

Metamorphic zircon of sample CP5-3 (eclogite nodule within marble) includes newly formed grains and overgrowth on small cores. Mineral inclusions are generally absent from zircon. With one younger exception (~ 225 Ma), the weighted mean age was determined at 240.8±0.9 Ma ($n = 16$, $\chi^2 = 1.48$) (Fig. 4-C), and this is consistent with the first episode of zircon growth in the previously described samples.

The Bixiling garnet peridotite–eclogite massif and adjacent garnet-gneisses have been studied in detail. Zircons of the garnet peridotite (9613) are mostly homogeneous under CL, but several grains contain small cores (>~ 740 Ma). Most zircons contain inclusions of pyrope-rich garnet ($Pyp_{47.6–62.7}$ $Alm_{24.5–38.3}$ $Grs_{11.2–14.5}$ $And_{10–16.6}$ $Sps_{0.8–2.4}$) and low-Al clinopyroxene ($Na_2O = 1.01–2.28\%$, $Al_2O_3 = 0.31–1.62\%$) (Table S3), which are comparable to the peak UHP assemblage of the whole-rock [54] (Fig. 3-11). Fifteen SHRIMP analyses yielded a weighted mean age of 226.7±2.6 Ma ($\chi^2 = 0.45$) (Fig. 4-D). Zircons from two eclogite samples contain eclogite-facies mineral inclusions (garnet, omphacite and rutile) which mostly occur in volumetrically dominant cores which, in turn, are surrounded by a thin overgrowth. Weighted mean metamorphic ages for the light-coloured eclogite (high-silica equivalent, CP3–4), the dark-coloured eclogite (gabbroic equivalent, CP3-18) and a garnet-bearing gneiss (CP3-24) are given at 227.9±2.8 Ma ($n = 5$, $\chi^2 = 1.82$, Fig. 4-E), 220.1±2.3 Ma ($n = 15$, $\chi^2 = 0.51$; Fig. 4F) and 219.3± 1.1 Ma ($n = 15$, $\chi^2 = 2.12$; Fig. 4-G) respectively. Dating of inherited cores provided indistinguishable protolith ages of 751.6±6.4 Ma (CP3-4), 753.0±3.4 Ma (CP3-18) and 747.5±10.4 Ma (CP3-24). The massif must have been well preserved as a whole prior to, during and after UHP metamorphism but nevertheless documented two episodes of metamorphic zircon growth at ~ 228–227 Ma and ~ 220–219 Ma which is indicative for *in-situ* UHP metamorphism.

Most zircons of the Zhujiachong paragonite eclogite (02114-1) consist of two distinct domains, namely a weakly luminescent core, surrounded by a narrow, bright rim that has extremely low U and Pb concentrations. Twenty-two cores were analyzed and provided a weighted mean age of 220.1±1.3 Ma (χ^2=2.40, Fig. 4-H). This is comparable to the latest phase of zircon growth in the Bixiling Massif and possibly records a post-peak re-equilibration event. According to Li et al. [38], two episodes of metamorphic zircon growth were found in a nearby paragonite eclogite where the older metamorphic zircon grew at 243±3 Ma (n=7) and the younger at 222±4 Ma (n=3).

In-situ SHRIMP REE measurements enabled us to test whether the dated zircons grew during eclogite-facies conditions. The first episode of zircon growth (episode 1, Table 1) produced grains which are often free of mineral inclusions, and their eclogite-facies affinity is shown by conspicuously flat HREE patterns and insignificant negative Eu anomalies [10–12] (Fig. 5-A,-B, samples 9603 and CP5-3). The second episode of zircon growth (episode 2) gave rise to grains which generally contain eclogite-facies mineral inclusions but otherwise show similar REE patterns as the first episode zircons (Fig. 5-A and C; samples 9603 and CP3-4) and so does the latest zircon generation (Fig. 5-D and E; samples CP3-18 and CP3-24) (episode 3). Consequently, Triassic zircons of the Dabie samples, regardless of their specific growth episode, are typical eclogite-facies zircons. Overall, the Dabie data define three episodes of eclogite-facies metamorphism. These are best estimated by coeval zircon ages at 242.1± 0.4 Ma (n=51, χ^2=1.08; samples 9603, CP5-3 and 9607, Table 1), 227.2±0.8 Ma (n=41, χ^2=0.82; samples 9603, 9607, 9613 and CP3-4) and 219.8± 0.8 Ma (n=52, χ^2=1.72; samples CP3-18, CP3-24 and 02114-1) respectively.

4.2. Sulu UHP complex

Most zircons of the Xugou garnet peridotite–eclogite samples are unzoned, round grains. Mineral inclusions (Tables S3 and S4) were used to discriminate between zircon domains in cases where the Cathodoluminescent (CL) response of different domains formed under different conditions was not distinctive. Our SHRIMP dating has determined several zircon-forming events, including a pre-eclogite phase, and two episodes of eclogite-facies metamorphism, which constrain the timing of prograde metamorphism in the massif.

The age of pre-eclogite metamorphism was obtained from two Xugou samples, a porphyroblastic eclogite (XG07) and a garnet peridotite (XG13). A variety of mineral inclusions was found in the zircons of the porphyroblastic eclogite, including low P–T (plagioclase, stable below the quartz/Ab transformation), hydrous (amphibole, stable below ~ 2.5 Gpa) and typical eclogite-facies minerals (garnet, omphacite, rutile). Ten zircons containing quartz, feldspar, and amphibole (Fig. 3-13) or chlorite were analyzed. The weighted mean age was calculated at 244.8±2.8 Ma (n=11, χ^2=1.42), which reflects a pre-eclogite metamorphic phase (Fig. 4-I). Olivine (Fig. 3-14), garnet and clinopyroxene were found in several zircon grains of the garnet peridotite (XG13). The mean age of olivine-bearing zircons is 244.6±7.6 Ma (n=5, χ^2=0.16; Table 1). We suggest that this age also reflects a zircon-forming event prior to eclogite-facies metamorphism. By pooling the above two ages, a weighted mean age for the pre-eclogite metamorphic phase is given at 244.0± 2.6 Ma (n=16, χ^2=1.04), which is close to the 244± 3 Ma U–Pb age of a pre-UHP titanite phenocryst that survived in the central Dabie UHP complex [55].

Sample XG09 is an eclogite composed of coarse-grained (2.5–3 mm) garnet- and omphacite-rich compositional layers. Garnet, omphacite, amphibole (Fig. 3-15), rutile, K-feldspar and epidotite were found as inclusions. Twelve garnet-, omphacite- and rutile-bearing zircons were analyzed, and the weighted mean age is 242.0±2.9 Ma (χ^2=1.50; Fig. 4-J) which is similar to the first episode of eclogite-facies zircon growth in the Dabie UHP complex.

Moreover, eclogite-facies inclusion-bearing zircons of the porphyroblastic eclogite (XG07) were dated at 224.8±2.7 Ma (n=9, χ^2=0.66) (Fig. 4-I), and similar grains in the garnet peridotite yielded a mean age of 227.8±7.1 Ma (n=10, χ^2=3.57). These ages are similar to 227.4±3.5 Ma in an nearby eclogite [36] which contains a single eclogite-facies metamorphic zircon population with diagnostic REE pattern and mineral inclusions. However, epidote-bearing zircons in the Xugou samples are significantly younger (<220 Ma) (Table 1) and are thus indicative of retrograde metamorphism. Accordingly, rocks of the Xugou massif have experienced a coherent metamorphic evolution but preferentially generated metamorphic zircons during the pre-eclogite phase, during different phases of eclogite-facies metamorphism and during retrograde metamorphism.

Eclogite (CD01) enclosed in the Chijiadian garnet peridotite contains abundant zircons, some of which have eclogite-facies mineral inclusions. Dating of these inclusion-bearing zircons yielded a narrow age range of 218.0–234.4 Ma with a weighted mean of 227.0± 2.6 Ma (n=15, χ^2=0.23). Three inclusion-free zircons were dated at 240.5±4.7 Ma (n=3, χ^2=0.11), and an overgrowth on a garnet-bearing zircon yielded 206.8± 5.8 Ma (Fig. 4-K).

Finally, eclogite sample (LJ32) occurring in gneisses has been studied. The zircons display core-overgrowth relationships, and the age of inclusion-free overgrowth is 243.1±1.4 Ma (n=7, χ^2=1.49), whereas the age of overgrowth containing eclogite-facies minerals is 227.6±3.7 Ma (n=4, χ^2=3.29) (Fig. 4-L).

These results demonstrate that eclogite-facies zircons of the Sulu UHP complex grew during two major episodes at 242.7±1.2 (n=23, χ^2=1.29) (episode 1, Table 1) and 227.5±1.3 Ma (n=31, χ^2=0.96) (episode 2). Most analyzed zircons from the Sulu samples are extremely low in U (~ 50 ppm to several ppm) and Pb which resulted in a relatively poor precision of individual analyses and account for the minor age difference between Dabie and Sulu samples.

4.3. Interpretation

Our new data confirm that Dabie–Sulu UHP rocks usually contain more than one zircon population [13]. It is straightforward that episodic zircon growth corresponds to multiphase textures in two Dabie samples (9603 and 9607). Furthermore, mineral inclusions identify episodes of metamorphic zircon growth in most samples.

We suggest that episode 1 eclogite-facies zircon ages (Table 1) of 242.1±0.4 Ma (Dabie) and 242.7±1.2 Ma (Sulu) provide the best estimate for the timing of a crucial mineral phase transformation from pre-eclogite metamorphism to the eclogite-facies. Pre-eclogite facies metamorphism associated with dehydration shortly before HP–UHP metamorphism was dated at 244.0± 2.6 Ma. Inclusions of olivine (XG13), feldspar, amphibole and chlorite (XG07) within zircon of the Sulu samples support this explanation. An earlier eclogite-facies metamorphic event throughout the Dabie–Sulu area was dated at 242.1±0.4–242.7± 1.2 Ma (Table 1). This conclusion is strongly supported by the occurrence of eclogite-facies mineral inclusions in this particular generation of zircons in a Dabie garnet pyroxenite (9607) (Fig. 3-10) and a Sulu eclogite (XG09) (Fig. 3-15) and by the diagnostic REE patterns (Fig. 5-A, B) of eclogite-facies zircons in two Dabie samples (9603 and CP5-3). The similarity in ages obtained from these two kinds of mineral inclusion assemblages is of particular importance. It shows that a pre-eclogite facies metamorphism and an eclogite-facies metamorphism, which both led to metamorphic zircon growth, must have occurred during a very short period of time (from 244.0±2.6 Ma to 242.7±1.2 Ma), thereby constraining the onset of eclogite-facies and/or HP–UHP metamorphism.

Metamorphic pressures during the first episode of eclogite-facies zircon growth may have varied amongst the different samples. Coesite-bearing zircons from a UHP cobble (244.0±4.7 Ma) [34] and a UHP gneiss sample (mean=245±14 Ma) [31] have similar ages of the episode 1 zircon, which may represent the beginning of UHP metamorphism. In our case, two Dabie samples (9603 and CP5-3) which contain mainly the first episode zircons, coesite, pseudomorphs after coesite, omphacite as well as zircon are well protected within garnet [41], indicating that zircon probably formed synchronously with coesite as garnet grew. The temperature estimate for the studied coesite–eclogite nodule (CP5-3) in marble is about 545 °C (at 2.7 Gpa, Table 1). Estimates of the metamorphic temperature during this episode of zircon growth are difficult to obtain because garnet and clinopyroxene inclusions are absent in most cases. Nevertheless, this zircon generation from one Xugou eclogite (XG09) contains abundant garnet and omphacite inclusions (Fig. 3-15), and the temperature could be estimated at 607–578 °C (Table 1), using the Krogh [56] calibration with assumed pressures of 2.7 Gpa for the quartz/coesite phase boundary and 1.8 Gpa as the lower limit (quartz stable). This *PT* estimate for episode 1 zircon growth is broadly consistent with the lower limit (~ 2.7 Gpa and ~ 660 °C) of coesite eclogite-facies metamorphic conditions (e.g., Liou et al., Ref. [41]).

The second episode of eclogite-facies zircon growth at 227.2±0.8 Ma (Dabie) and 227.5±1.3 Ma (Sulu) represents the peak of UHP metamorphism above the diamond/graphite transformation. Garnet, clinopyroxene and omphacite inclusions are common in this zircon generation, and these inclusions record the metamorphic *P–T* conditions before and when zircon formed. Several recent studies on UHP ultramafic rocks [46–52,54,57,58] and eclogites [59,60] estimated peak metamorphic pressures exceeding 3.6–4.2 Gpa and up to 7 Gpa. We assume a pressure of ~ 4 Gpa (~ 120 km) for the temperature calculation. Representative compositions of mineral inclusions and minerals analyzed by electronic microprobe are available in Table S3.

Garnet, clinopyroxene and/or omphacite inclusions represent a pre-existing eclogitic assemblage trapped in Dabie zircons and are compositionally different from their counterparts in the whole-rock. Namely garnet is

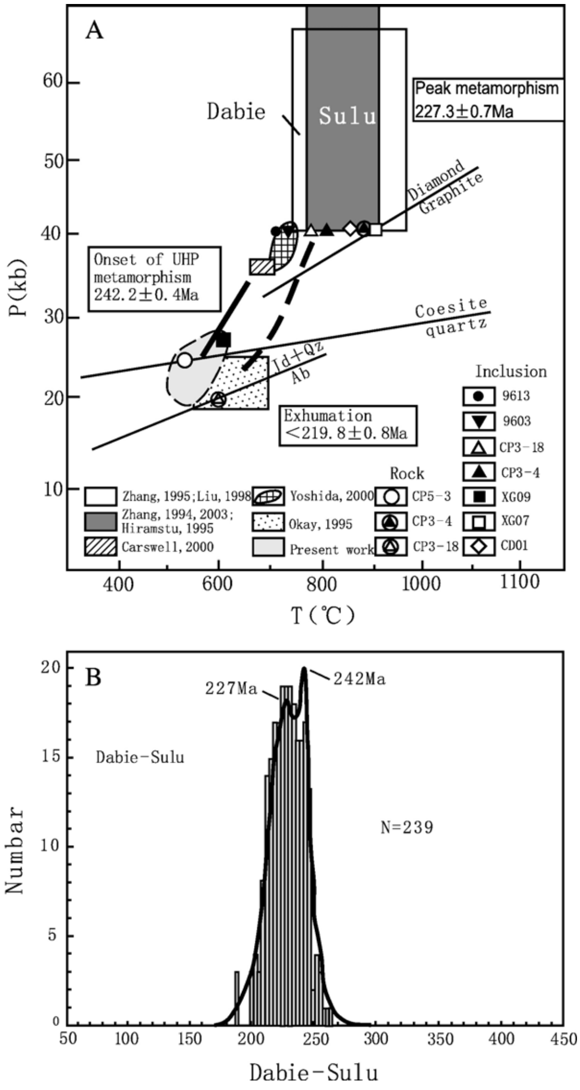

Fig. 6. Schematic *PTt* path (A) showing chronology of Dabie–Sulu UHP metamorphic rocks; and (B) Histogram exhibits double-peak age pattern of the Dabie–Sulu UHP complex. Solid line represents the cumulative probability which takes into account the uncertainties in the individual age determinations. The data source is from the present work.

lower in MgO, and clinopyroxene is lower in Na_2O. The calculated temperatures range from 725 to 803 °C that is slightly lower than peak temperatures of the rocks which are usually higher than 800 °C (Table 1). The temperatures for two Sulu samples are estimated at 850 and 885 °C, similar to, but still slightly lower than, the peak temperature of their host rocks. These relationships indicate that this episode of zircon growth occurred on the prograde metamorphic path, close to peak metamorphic conditions. We therefore conclude that a major mineral phase transformation during peak metamorphism led to new zircon growth at the expense of a pre-existing eclogitic assemblage. This mineral phase transformation may have been associated with dehydration reactions. Chlorite, a hydrous mineral phase, may be stable in subducted peridotite up to 5 Gpa [61] and was found in zircon of the Maowu garnet pyroxenite (Fig. 3-10) and the Bixiling garnet peridotite (Fig. 3-11 and 12). Furthermore, chlorite coexisting with garnet (Fig. 3-12) was found in zircon, indicating that chlorite decomposed to form garnet and released water when zircon was formed. This reaction was experimentally determined to occur at a pressure of about 4 Gpa [61].

The last episode of eclogite-facies zircon growth was at about 219.8 ± 0.8 Ma (Table 1) in three Dabie samples (CP3-24, CP3-18 and 0244-1) due to post-peak exhumation to the quartz stability field. A trapped garnet–omphacite pair in one Bixiling eclogite (CP3-18) records a temperature of 783 °C, comparable to peak metamorphic conditions of the area (Table 1). However, the temperature estimated for the whole-rock is much lower (about 603 °C, Table 1), suggesting that zircon was formed when metamorphic temperatures rapidly decreased. A few results also indicate that the youngest zircons (after 220 Ma) grew in the Sulu UHP complex. The time interval between peak metamorphism and exhumation is about 7 Ma and is equivalent to an exhumation rate of 11 mm/year, raising the UHP rocks from ~ 120 km (~ 4 Gpa) at about 227 Ma to lower crustal levels of about 50 km (~ 1.8 Gpa) at about 220 Ma or later.

5. Discussion

5.1. Regional implications

Our zircon-based chronology of the UHP rocks enhances the understanding of *in-situ* UHP metamorphism and associated large-scale continental subduction. As shown in Fig. 6-A, the Dabie and Sulu UHP complexes evolved along a general *PTt* path with timing of onset of UHP metamorphism at 242.2 ± 0.4 Ma ($n = 74$, $\chi^2 = 1.30$; pooling Dabie and Sulu data) and peak metamorphism at 227.3 ± 0.7 Ma ($n = 72$, $\chi^2 = 0.88$). This strongly suggests a coherent metamorphic evolution for the Dabie and the Sulu UHP complexes.

In-situ UHP metamorphism is also strongly supported by the observation that metamorphic zircon age patterns of UHP rocks are independent of rock types. In other words, eclogites, ultramafic rocks (garnet peridotite and pyroxenite), metasediments (jadeite quartzite) and garnet-bearing felsic gneiss all have the same multi-peak age pattern, although individual samples may differ in zircon population and, therefore, in age records. The geological significance of metamorphic zircon ages for the gneiss is particularly emphasized here. Gneiss makes up more than 90% of the Dabie–Sulu UHP complex but in most cases contains an amphibolite-facies assemblage which contrasts with undoubted UHP eclogite, garnet peridotite and jadeite quartzite. Carswell et al. [59] demonstrated that the gneisses followed a common subduction-related clockwise *PT* path together with UHP eclogite. Our new data (CP3-24), together with previous SHRIMP dating of gneiss [13,29,31], demonstrate that Dabie–Sulu garnet-bearing felsic gneisses grew metamorphic zircons at ~ 240–245 Ma, ~ 227–229 Ma, and ~ 220 Ma and, therefore, experienced the entire cycle of Triassic metamorphism. The consequential conclusion is that the South China crust (Precambrian volcanic-derived sediments) and intrusive mafic–ultramafic massifs must have been deeply subducted, UHP metamorphosed and then exhumed as a whole.

Our new SHRIMP zircon ages demonstrate that major age variations no longer exist between different localities along the Dabie and the Sulu UHP complex (Fig. 6-B). Zircon geochronology of samples from Shuanghe, Maowu, Bixiling and Zhujiachong of the Dabie UHP complex yielded identical results. Furthermore, there is no age discrepancy between samples from the southern, middle and northern segments of the Sulu belt.

Finally, high pressure granulite-facies metamorphism in the Dabie gneiss unit (sample 9608, Fig. 1-A) has been dated at 241 ± 9 Ma ($n = 6$, $\chi^2 = 1.44$) (P. Jian et al. unpublished data) and corresponds to a pressure of at least 18 kb. Several SHRIMP metamorphic zircon ages of 232 to 226 Ma [12,39,62] were also obtained for eclogites from the Hong'an HP–UHP terrane (Fig. 1-A). These ages indicate that the Dabie gneiss unit and the Hong'an terrane must have evolved concurrently with the Dabie–Sulu UHP complex during the Triassic even though *PT* conditions differed substantially between the different segments [39].

5.2. Geochronological implications

Metamorphic zircons are common in UHP rocks worldwide, even in garnet peridotite and garnet pyroxenite [33,63], and a better understanding of the processes through which these minerals form is essential to correctly interpret UHP zircon ages. Eclogite-facies zircon growth is generally attributed to peak metamorphism and associated fluid circulation [11,64], during early phases on the exhumation path [65,66], or to the exhumation path only [67]. Our determination of *PT* conditions for zircon formation indicates that eclogite-facies metamorphic zircon may grow episodically at the onset of HP–UHP metamorphism (episode 1), peak UHP metamorphism (episode 2) and exhumation (episode 3).

Episode 1 zircons, as represented by metamorphic cores in jadeite quartzite sample 9603 and entire metamorphic grains of the eclogite nodule in marble sample CP5-3, are attributed to new metamorphic growth from a Si-rich fluid released by dehydration reactions under eclogite-facies conditions. This conclusion is supported by the petrographic observation that most of the zircon occurs in quartz (see Section 3.1 for sample description), garnet, jadeite and/or omphacite. Episode 2 zircons are normally interpreted to have formed during a dehydration reaction or fluid circulation during peak UHP metamorphism [64]. The latest eclogite-facies zircon generation (episode 3) is well documented in the dark coloured eclogite (CP3-18). This sample contains minor mounts of quartz (~ 0.1%) that occurs as microveins or patches, and these host more than 90% of the newly-formed zircon grains (see Section 3.1 for sample description). Therefore, the latest metamorphic zircon formation probably resulted from local, Si-rich fluid activity. We propose that variable local chemical environments during specific phases of the metamorphic evolution were responsible for episodic zircon growth in the UHP rocks. Caution should be exercised with any arbitrary weighted mean age calculation without consideration of possible multiple metamorphic age components in UHP rocks that would yield geologically meaningless mixed ages. This is why a broad age spectrum (~ 220 Ma to ~ 245 Ma) has previously emerged from SHRIMP zircon dating of Dabie–Sulu UHP rocks.

UHP rocks from other ultra-deep continental subduction zones such as the Kokchetav massif of Kazakhstan [65,66] and the Western Gneiss Region of Norway [68–70] display broad metamorphic age spectra similar to that of the Dabie–Sulu UHP complex. The age spectrum for the Kokchetav massif incorporates multiple zircon growth consisting of a pre-UHP phase, UHP mineral-bearing domains, granulite-facies mineral-bearing domains, and idiomorphic overgrowth, which record the timing of pre-UHP evolution and subsequent exhumation [65,66]. Metamorphic ages for the Western Gneiss Region of Norway appear to show an earlier HP metamorphism (~ 425 Ma) overprinted by UHP metamorphism (~ 400 Ma, see Ref. [68]). SHRIMP dating of other HP–UHP complexes documents a prolonged metamorphic evolution such as in the Greenland Caledonides (Devonian to Carboniferous)

[71], or repeated HP–UHP metamorphism such as the Rhodope massif of northern Greece [72]. In summary, episodic zircon growth is recorded in HP–UHP rocks worldwide due to a multi-phase, complicated metamorphic evolution.

6. Conclusions

Episodic zircon growth links mineral phase transformations and associated fluid activities to ultra-deep subduction kinetics and timing of events of prograde metamorphism. Two main zircon-forming events in the Sulu–Dabie UHP belt provide chronological constraints on the prograde *PT* path from the onset of HP–UHP metamorphism (242.2±0.4 Ma, Fig. 6-A) to peak UHP conditions (227.3±0.7 Ma). A minimum subduction rate of ca. 6 mm/year can be deduced from a 30 ° dipping slab, assuming the onset of UHP metamorphism at 2.7 Gpa (~ 75 km depth) and 600 °C on the quartz/coesite phase boundary, and a peak metamorphic pressure of 4 Gpa (~ 120 km depth). The duration for the South China continental lithosphere to remain at mantle depths is more than 15 Ma. This general time frame of prograde metamorphism implies that the Dabie–Sulu UHP rocks evolved coherently, even though their *PT* conditions may differ substantially, and therefore strongly supports widespread regional *in-situ* UHP metamorphism. Our approach made it possible to decipher episodes of zircon growth which reflect dramatic changes in metamorphic *P–T* conditions in the evolving UHP rocks.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2006.07.043.

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