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Zircon SHRIMP U–Pb dating for gneisses in northern Dabie high *T*/*P* metamorphic zone, central China: Implications for decoupling within subducted continental crust

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Abstract

Zircon SHRIMP U–Pb ages and cathodoluminescence (CL) images reveal that most zircon separated from two tonalitic gneiss samples in the northern Dabie high *T*/*P* metamorphic zone (NDZ) have four different domains: (1) inherited core, with clear oscillatory zoning, low-*P* mineral inclusions and high Th/U ratios, indicating the Neoproterozoic age of the protolith; (2) inner-mantle, with homogeneous CL intensity, low Th/U ratios of ≤ 0.09 and occasionally ultrahigh pressure metamorphic (UHPM) mineral inclusions such as diamond, garnet and rutile, which defined a weighted mean $^{206}Pb/^{238}U$ age of 218 ± 3 Ma, corresponding to the age of ultrahigh-pressure metamorphism; (3) outer-mantle with lower Th/U ratio and retrograde mineral inclusions, which yields a retrogressive age of 191 ± 5 Ma; and (4) rim, which is black luminescence, with relatively high Th/U ratios of 0.12–0.40 and a weighted mean $^{206}Pb/^{238}U$ age of 126 ± 5 Ma, indicating an overprint of the Early Cretaceous migmatization. Consequently, four discrete and meaningful age groups have been identified. Remarkably, the U–Pb ages of both UHPM zircon and retrograded metamorphic zircon from the NDZ are significantly younger than the U–Pb ages of 238 ± 3 Ma–230 ± 4 Ma for UHPM zircon and U–Th–Pb ages of 218 ± 1.2 Ma–209 ± 3 Ma for rutile and monazite overgrowths (representing the cooling or retrograded metamorphic time corresponding to amphibolite-facies) from the southern Dabie UHPM zone (SDZ), respectively. Combined with reported ages for UHPM rocks from the NDZ, SDZ and Huangzhen low-*T* eclogite zone (HZ), we found that the metamorphic ages of these three UHPM units in the Dabie orogen gradually decrease from south to north. This age distribution suggests that the three UHPM units represent 3 exhumed crustal slices, which are decoupled from each other and have different subduction and exhumation histories. Firstly, the subducted Huangzhen crustal slice was detached from the underlying subducted continental lithosphere, and then exhumed because of the buoyancy. In the meantime, subduction of underlying continental plate continued. After the initiation of this process, lithologic separations or decoupling within subducted continental crust occurred repeatedly several times to form an imbricate megastructure in the Dabie UHPM belt.

Keywords: Decoupling; Continental subduction; Zircon U–Pb dating; UHPM rocks; Dabie orogen

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1. Introduction

Formation and exhumation of ultrahigh pressure metamorphic (UHPM) rocks has been a hot topic in geologic community. Subduction of continental crust into mantle depths has long been demonstrated by the discovery of UHP index minerals such as coesite and micro-diamond in supracrustal rocks in various orogenic belts (e.g., Chopin, 1984; Smith, 1984; Okay et al., 1989; Wang et al., 1989; Sobolev and Shatsky, 1990; Xu et al., 1992), the mechanism for exhumation of UHPM rocks, however, remains controversial, e.g., intracontinental thrusting and concomitant erosion (Okay and Sengör, 1992; Chemenda et al., 1996), a tectonic-wedge-extrusion model (Maruyama et al., 1994, 1996), ascent of thin tectonic slices by buoyancy-driven model (Ernst et al., 1997; Ernst, 2001), a multi-stage model involving buoyancy, wedging and thermal doming (Dong et al., 1998), coeval thrusting and normal faulting (Faure et al., 1999), a multi-stage model involving buoyancy, sub-vertical extrusion, normal uplift and lithospheric extension (Wang and Cong, 1999), and orogen-parallel extrusion accompanied by layer-parallel thinning (Hacker et al., 2000; Ratschbacher et al., 2000). Nonetheless, all these models for UHPM rock exhumation assumed that the whole subducted continental crust was detached from the underlying mantle lithosphere and then exhumed as a whole (e.g., Chemenda et al., 1995; Hacker et al., 2000; Massonne, 2005). Such models were based on a hypothesis that detachment only occurred in the lower crust, due to its more ductile behavior compared to the upper crust and the lithospheric mantle (i.e. the "jelly sandwich model"; e.g. Zuber, 1994). Modeling results of lithospheric viscosity–depth curves based on reasonable geotherms and models of lithospheric composition however, suggest that there are at least two low-viscosity zones within continental crust at different depths (Meissner and Mooney, 1998). Accordingly, several HP–UHP metamorphic crustal slices could be produced by decoupling or detachment along low-viscosity zones during subduction of continental crust, which seems more likely to be a realistic geological process for the Dabie–Su-Lu UHPM belt.

The Dabie–Su-Lu UHPM belt in east-central China can be divided into three UHPM units from north to south: the northern Dabie high *T*/*P* metamorphic zone (NDZ), the southern Dabie UHPM zone (SDZ), and the Huangzhen low-*T* eclogite zone (HZ). Recently, the Pb isotopic mapping on the Dabie UHPM belt has revealed the detachment between subducted upper continental crust (the southern Dabie UHPM zone) and felsic lower crust (or lower part of upper crust) (the northern Dabie high *T*/*P* metamorphic zone) (Li et al., 2003b). The intensive Sm–Nd and U–Pb geochronological studies consistently indicated the UHPM ages of 238−225 Ma for the rocks from the SDZ (e.g., Li et al., 1989, 1993; Ames et al., 1996; Rowley et al., 1997; Hacker et al., 1998; Li et al., 2000; Ayers et al., 2002). By contrast, the Sm–Nd age of 212±4 Ma for eclogite from the NDZ (Liu et al., 2005a) is significantly younger than the Sm–Nd age of 226±3 Ma for eclogite from the SDZ (Li et al., 2000).

In this study, we report zircon SHRIMP U–Pb age data on two samples of tonalitic gneiss from the NDZ. The purposes of this work are: (1) to precisely determine the ages of the peak and retrograde metamorphism in the NDZ; (2) to examine whether different UHP rock units in the Dabie orogen may have different peak and retrograde metamorphic ages; and (3) to present a model of within-crust lithologic decoupling and multi-slice exhumation to better interpret the age distribution pattern in the Dabie UHPM belt.

2. Geological setting and sample

The Qinling−Dabie orogen is a collision zone between the North China Block (NCB) and South China Block (SCB). The Dabie Mountains represent the eastern section of the belt, and are transected at its eastern end by the Tan–Lu fault. The Su-Lu orogen is believed to be the eastern extension of the Dabie orogen. The UHPM rocks exposed in the Dabie and Su-Lu orogen comprise the largest known UHPM belt on the Earth. The general geology of the Dabie orogenic belt has been described by many authors (e.g., Xu et al., 1994; Hacker et al., 2000; Li et al., 2001; Zheng et al., 2003; Xu et al., 2005b). It is well accepted that the Dabie orogen can be divided into five major litho-tectonic units from north to south: (1) the Beihuaiyang zone (BZ); (2) the northern Dabie high *T*/*P* metamorphic zone (NDZ); (3) the southern Dabie UHPM zone (SDZ); (4) the Huangzhen low-*T* eclogite zone (HZ); and (5) the Susong complex zone (SZ), separated by Xiaotian–Mozitan fault (XMF), Wuhe–Shuihou fault (WSF), Hualiangting–Mituo fault (HMF) and Taihu–Mamiao fault (TMF), respectively (see Fig. 1).

The BZ is mainly composed of the Paleozoic flysch formation (the Foziling group) (Xu et al., 1994; Li et al., 2001; Xu et al., 2005b) and unsubducted continental crust of the SCB (the Luzhenguan complex) (Okay and Sengör, 1993; Zheng et al., 2004). In addition, post-collisional volcanic–sedimentary rocks are developed in the Jurassic–Cretaceous basins in this zone.

The NDZ is mainly composed of Neoproterozoic banded tonalitic and granitoid gneiss and Early Cretaceous

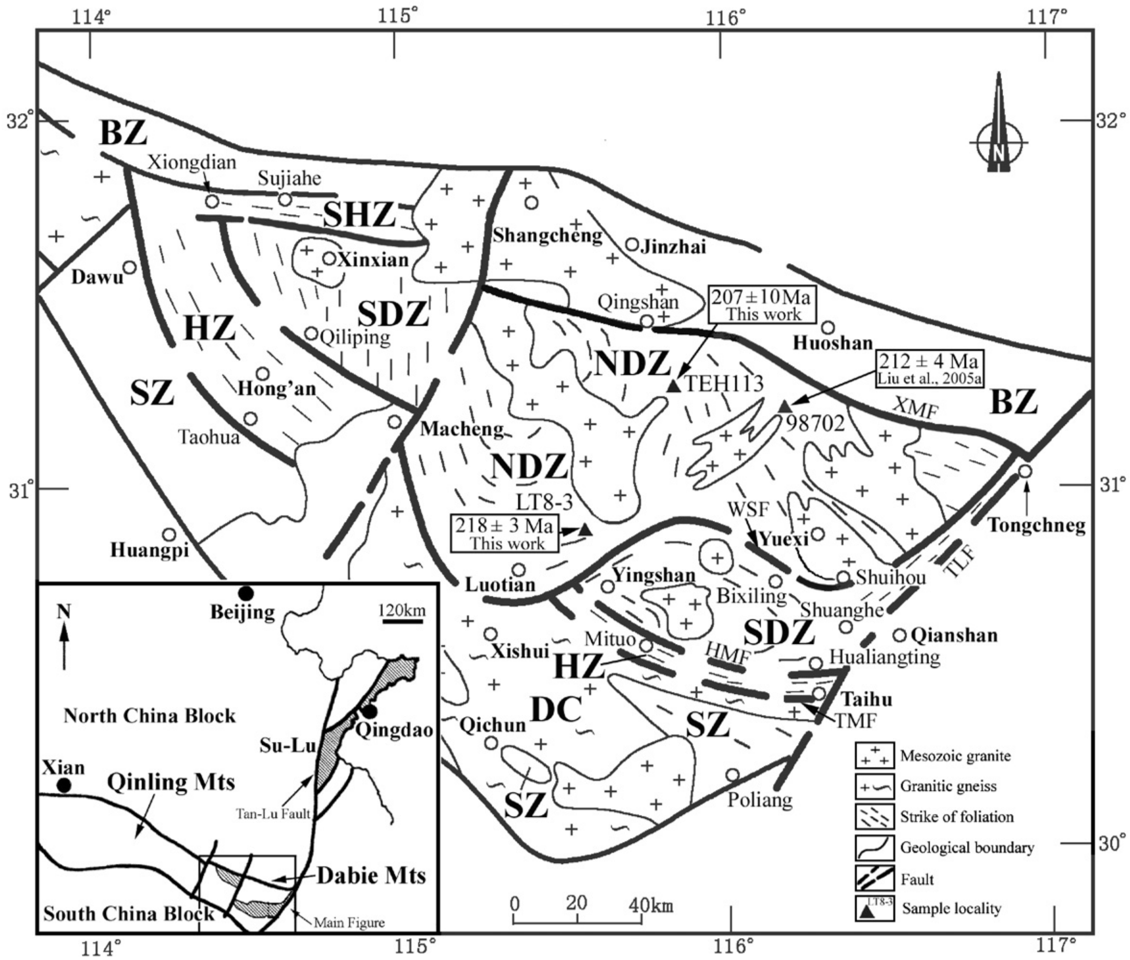

Fig. 1. Schematic geological map of the Dabie orogen, with inset showing the location of this area within the Triassic Qinling–Dabie–Su-Lu collision orogen in central China (modified after Xu et al., 2005b). The shaded area in the inset shows the UHPM belt. Sample localities with sample numbers are described in detail in the text. BZ = Beihuaiyang zone, NDZ = northern Dabie high *T*/*P* metamorphic zone, SDZ = southern Dabie UHPM zone, SZ = Susong complex zone, SHZ = Sujiahe HP metamorphic zone, DC = amphibolite-facies Dabie complex, XMF = Xiaotian–Mozitan fault, WSF = Wuhe–Shuihou fault, HMF = Hualiangting–Mituo fault, TMF = Taihu–Mamiao fault, TLF = Tan–Lu fault.

post-collisional intrusions with minor meta-peridotite (including dunite, harzburgite and lherzolite), garnet pyroxenite, garnet-bearing amphibolite, granulite, and eclogite. The Luotian dome in the western part of the NDZ is a highly uplifted and eroded area with abundant felsic and mafic granulite lenses indicating that the NDZ could be a slice of upper part of lower crust or lower part of upper crust (Fig. 1). Although most of the rocks are of amphibolite-facies and eclogite, their relics have been identified with overprinting of granulite-facies in the NDZ (Tsai and Liou, 2000; Xu et al., 2000; Liu et al., 2001; Xiao et al., 2001; Liu et al., 2005b). Recently, the occurrence of quartz exsolution in Na–clinopyroxene (Tsai and Liou, 2000; Xu et al., 2000; Liu et al., 2001), oriented inclusions of polycrystalline rods of quartz, K-feldspar and albite in clinopyroxene (Malaspina et al., 2006), and rutile, apatite and clinopyroxene exsolution in garnet (Xu et al., 2005a) have been observed in eclogites from the NDZ. The quartz exsolution in Na–clinopyroxene has been considered to be evidence of ultrahigh-pressure conditions (cf. Liou et al., 1999 for review), while silica and K-feldspar rods are considered to be segregation products from pre-existing supersilic and K-rich clinopyroxene, respectively, that contained excess SiO_2 and K_2O at peak metamorphic conditions, stable at diamond stability field (e.g., Smith, 1984; Sobolev and Shatsky, 1990; Chopin, 2003). The rutile, apatite and clinopyroxene exsolutions in garnet are similar to those from Yangkou eclogite in the Su-Lu region reported by Ye et al. (2000), indicating that the eclogites here experienced UHP metamorphism at possible pressures of 5−7 GPa. In addition, Xu et al. (2003, 2005a) found micro-diamonds from the eclogites in the NDZ. So, the needle mineral exsolutions in garnet and clinopyroxene, and micro-diamond imply that eclogites from the NDZ subducted to mantle depths and experienced UHP metamorphism. Initial zircon U–Pb (Liu et al., 2000) and Sm–Nd (Liu et al., 2005a) geochronological studies suggest that eclogites from the NDZ formed in the Triassic, which indicates that the NDZ was involved in the Triassic continental subduction of the South China Block. The peak P–T conditions were estimated to be 808−874 °C or higher and >2.5 GPa (Liu et al., 2005a) or perhaps >5−7 GPa (Xu et al., 2005a). In addition, the overspread migmatization during 110 to 130 Ma is a typical characteristics for the NDZ (e.g., Chen et al., 1991; Hacker et al., 1998, 2000; Wang et al., 2002), which may influence some isotope systems on the gneiss and eclogite (e.g., Hacker et al., 1998; Liu et al., 2000; Xie et al., 2004).

The SDZ is composed of typical UHPM rocks, including eclogite, gneiss, quartz jadeitite, marble, etc. The occurrence of diamond and coesite in the rocks reveals temperature–pressure conditions of 700 to 850 °C and >2.8 GPa or perhaps ≥4 GPa for the UHP metamorphism (e.g., Xu et al., 1992; Wang et al., 1995; Cong, 1996), whereas the oriented magnetite lamellae and $FeTiO_3$ rod exsolutions in olivine from the UHPM ultramafic rocks in the SDZ suggested the peak conditions at P>5−7 GPa or perhaps 10 GPa and T=700−800 °C (e.g., Jin et al., 1998; Zhang et al., 1999). The UHP rocks from the SDZ only experienced amphibolite- and green-schist-facies retrograde metamorphism (e.g., Xu et al., 1992; Wang et al., 1995; Cong, 1996). Therefore, overprinting of granulite-facies retrograde metamorphism is unusual for eclogites from the NDZ, suggesting that the SDZ and NDZ units had different exhumation histories.

The HZ consists of mainly eclogite and gneiss. The eclogite in this zone is characterized by relatively lower metamorphic temperature, and coesite- and diamond-free eclogite, hence the Huangzhen eclogite was previously referred as HP "cold" eclogite zone by Okay (1993). Recently, Li et al. (2004) found coesite pseudomorphs from the eclogite in the Huangzhen eclogite zone and confirmed that this "cold" or lower-T eclogite zone experienced UHP metamorphism with peak conditions of 3.3 GPa and 670 °C, and subsequent amphibolite- and green-schist-facies retrograde metamorphism.

The SZ is a green-schist−amphibolite-facies metamorphic unit with conditions of 400−500 °C and 0.5−0.6 GPa, which comprises mica–quartz schist, marble, amphibolite and meta-phosphorous series (e.g., Xu et al., 1994; Zhai et al., 1995; Xu et al., 2005b).

Therefore, there are three UHPM crustal slices in the Dabie orogen, i.e., the NDZ, the SDZ and the HZ. The Pb isotopic mapping in Dabie mountains reveals that UHPM rocks characterized by relative higher radiogenic Pb ($^{206}Pb/^{204}Pb$=17.026~20.781) in the SDZ were derived from subducted upper continental crust, while UHPM rocks characterized by relative lower radiogenic Pb ($^{206}Pb/^{204}Pb$=15.844~17.204) in the NDZ were derived from subducted lower continental crust (Li et al., 2003b). This point is supported by their different lithologic associations, hydrous mineral assemblages and metamorphic temperatures. It is well known that the NDZ is an orthogneiss unit with minor eclogite and/or granulite blocks. Recent study has demonstrated that some eclogites from the NDZ were transformed from mafic lower continental crustal rocks (Liu et al., 2005b). While the SDZ is an orthogneiss+supracrustal rocks unit, in which eclogite lens or blocks are interbedded with UHPM sediments such as paragneiss, marble and jadeite quartzite (cf., Xu et al., 1994; Zheng et al., 2003). The eclogite from the NDZ contains neither phengite nor other HP–UHP metamorphic hydrous mineral, which suggests the absence of fluid during their metamorphic process (Liu et al., 2004c, 2005a; Liu and Li, 2005). Whereas phengite–zoisite hydrous minerals are common in the eclogite from the SDZ (Cong, 1996) and lowsonite–barrositic amphibole–phengite hydrous minerals were observed in the eclogite from the HZ (Li et al., 2004), which indicates more abundant fluids in the SDZ and HZ during UHP metamorphism. Fluid inclusions in the UHPM rocks from the SDZ and NDZ are also different. The composition of metamorphic inclusions in the UHPM rocks from the SDZ is mainly aqueous fluid with various salinities, while those in the UHPM rocks from the NDZ are mainly N_2 or CO_2, suggesting more aqueous fluids in the SDZ during metamorphism (Xiao et al., 2001, 2002). In addition, the peak metamorphic temperatures of three UHP slices gradually increase from south to north, i.e. from T<700 °C (generally, 570–670 °C) for the Huangzhen eclogite in the HZ (Wang et al., 1992; Okay, 1993; Zhai et al., 1995; Li et al., 2004) to 700–800 °C for the UHP eclogites in the SDZ (Okay, 1993; Xu et al., 1994; Cong, 1996), and then to 808–874 °C for the eclogite in the NDZ (Liu et al., 2005a). The temperature variations may be related to the positions of the protoliths in subducted continental crust, indicating that protoliths come from different crustal levels (e.g., upper and lower continental crust, respectively) and originally had different temperatures. In summary, in view of more supracrustal rocks and hydrous minerals, aqueous fluid inclusions, lower peak metamorphic temperatures and higher radiogenic Pb isotopic composition of the eclogite in the HZ and SDZ, it is reasonable to propose that HZ and SDZ were from uppermost and middle parts of subducted

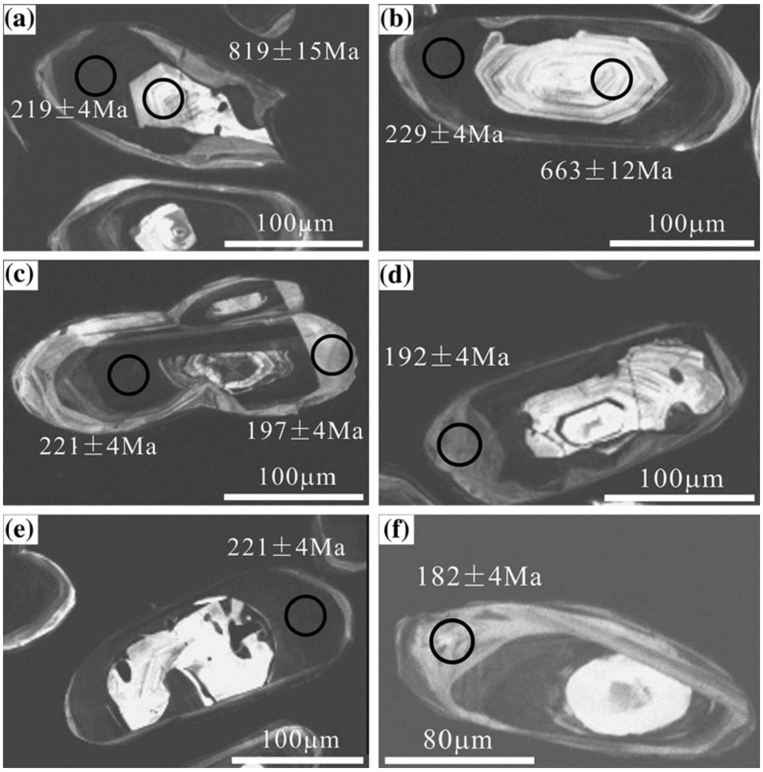

Fig. 2. CL images with $^{206}Pb/^{238}U$ ages for zircon grains from sample LT8-3 at Jinjiapu in southern part of the northern Dabie high *T*/*P* metamorphic zone.

upper continental crust in the SCB, respectively. In contrast, the NDZ is characterized by the absence of hydrous HP–UHP metamorphic mineral, N_2 or CO_2-inclusions, higher peak metamorphic temperature, minor supracrustal rocks and more abundant granulite outcrops as well as lower radiogenic Pb isotopic composition, and thus represents upper part of subducted lower continental crust or lower part of subducted upper continental crust.

Two garnet-bearing tonalitic gneiss samples (LT8-3 and TEH113) used for zircon U–Pb dating in this paper were collected from Jinjiapu and Ta'erhe, which are located in the southwest part (namely the Luotian dome) and north part of the NDZ, respectively (Fig. 1). The investigated gneisses are composed of plagioclase, quartz, amphibole, minor garnet, clinopyroxene and rutile; rare hypersthene is occasionally found (Liu and Li, 2005). In addition, micro-diamond observed in sample TEH113 suggests that the tonalitic gneiss from the NDZ experienced ultrahigh-pressure metamorphism and have similar metamorphic process to the enclosed eclogite (Liu et al., 2006).

3. Analytical method

Zircon was separated from approximately 5 kg gneiss sample by crushing and sieving, followed by magnetic and heavy liquid separation and hand-picking under binoculars. Approximately 500 zircon grains for each sample, together with a zircon U–Pb standard TEM (417 Ma), were mounted using epoxy, which was then polished until all zircon grains were approximately cut in half. The internal zoning patterns of the crystals were observed by CL image, which was analyzed at the Institute of Mineral Resources, Chinese Academy of Geological Sciences (CAGS). The representative CL images for the studied samples are presented in Figs. 2 and 3.

Mineral inclusions in zircon have been used for diagnosis of zircon origin. Mineral inclusions were identified using Raman spectroscopy at the Analytical Centre, China University of Geosciences (Wuhan) and the Continental Dynamics Laboratory, CAGS, and/or substantiated using the electron microprobe analyzer (EMPA) at the Analytical Centre, China University of Geosciences (Wuhan). The analytical conditions on the Raman and EMPA were reported by Xu et al. (2005a) and Liu et al. (2005a). Representative Raman spectra of inclusion minerals in zircon from sample TEH113 are listed in Fig. 4.

Zircon U–Pb dating was performed by using the SHRIMP II at Beijing SHRIMP Center, CAGS. Analytical procedures are similar to those described by

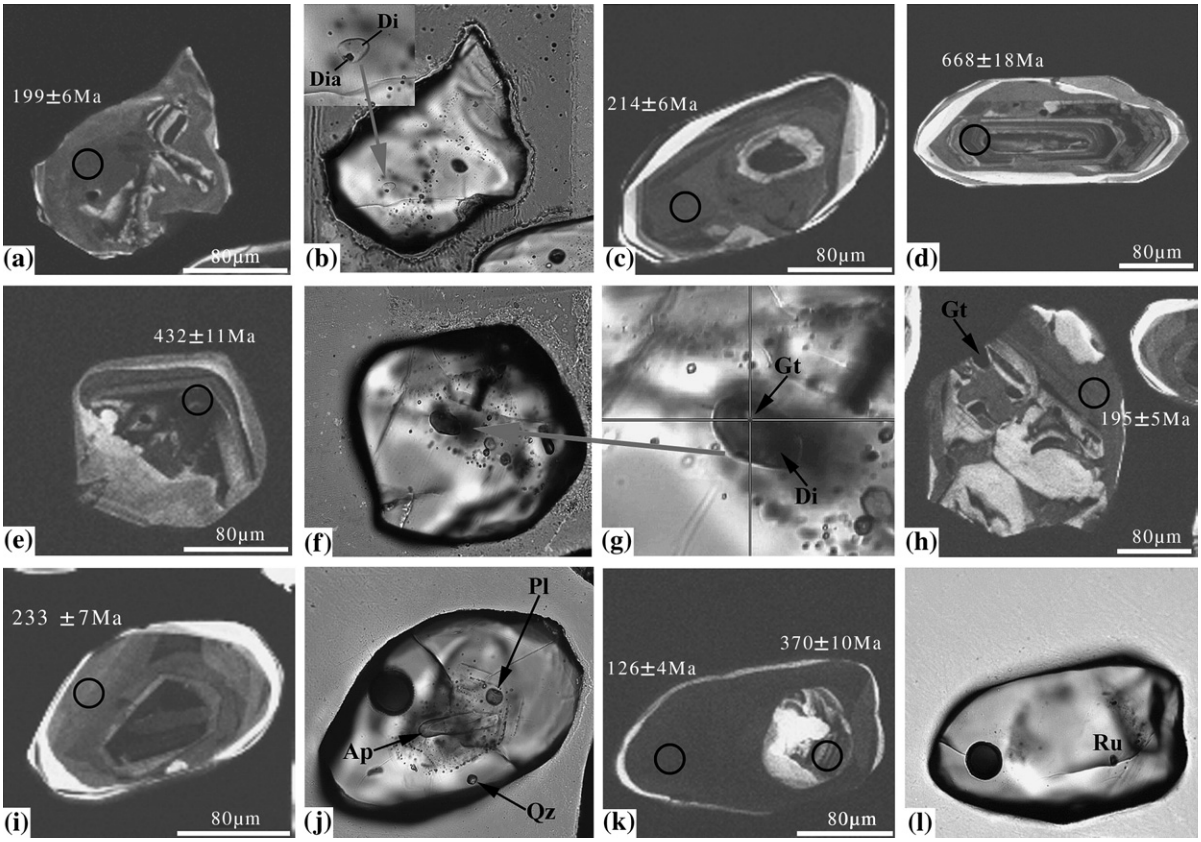

Fig. 3. Micro-photographs and the spots and ages of SHRIMP analysis of zircon grains from sample TEH113 at Ta'erhe in northern part of the northern Dabie high *T*/*P* metamorphic zone. (a), (c), (d), (f), (h), (i) and (k) are CL images with $^{206}Pb/^{238}U$ ages for zircons; (b), (f), (j) and (l) are plane-polarized light (PL) images; (g) is an enlargement part of (f) and a scanning image by Raman. Zircons (a) and (b), (e) and (f), and (i) and (j) are the same grain, respectively. Dia, Di, Pl, Ap, Qz and Ru represent diamond, diopside, plagioclase, apatite, quartz and rutile, respectively. All mineral inclusions in zircon grains were identified by Raman spectra in Fig. 4 or electron microprobe analyses (Liu et al., 2006).

Compston et al. (1992) and Williams (1998). Both optical photomicrographs and CL images were taken as a guide to selection of U–Pb dating spot. The mount was vacuum-coated with a ~500 nm layer of high-purity gold. The intensity of the primary O_2^- ion beam was 9 nA. Spot sizes were ~30 μm and each site was rastered for 150 s before analysis. Five scans through the mass stations were made for each age determination. Standards used were SL13, with an age of 572 Ma and U content of 238 ppm, and TEM, with an age of 417 Ma (Williams, 1998; Black et al., 2003). Data processing was carried out using the Squid and Isoplot programs (Ludwig, 2001), and measured ^{204}Pb was applied for the common lead correction. The SHRIMP results are presented in Tables 1 and 2, and in Fig. 5. The errors given in Tables 1, 2, Fig. 5 for individual analyses are quoted at the 1σ level, whereas the error for weighted mean ages given in Fig. 5, and in the text, are quoted at 2σ (95% confidence level).

4. Results of SHRIMP U–Pb dating

4.1. Sample LT8-3

Zircons separated from sample LT8-3 are 100−300 μm in length, subhedral to euhedral and long prismatic. Based on CL images four domains can be identified in most zircons (Fig. 2), i.e., bright-luminescent cores, low-luminescent inner-mantle (M1) (Fig. 2a, b, c and e), relatively bright-luminescent outer-mantle (M2) (Fig.2d and f) and thin low-luminescent rim (Fig. 2d). Euhedral cores preserve obvious oscillatory zonation, whereas M1, M2 and rim domains are homogeneous in CL.

The cores occasionally contain some magmatic minerals such as potassium feldspar, quartz, biotite and apatite. Data from the cores yield apparent $^{206}Pb/^{238}U$ ages ranging from 394 to 819 Ma with Th/U ratios of 0.84−1.73. A concordant age among them is 819±15 Ma and others are discordant age. Because

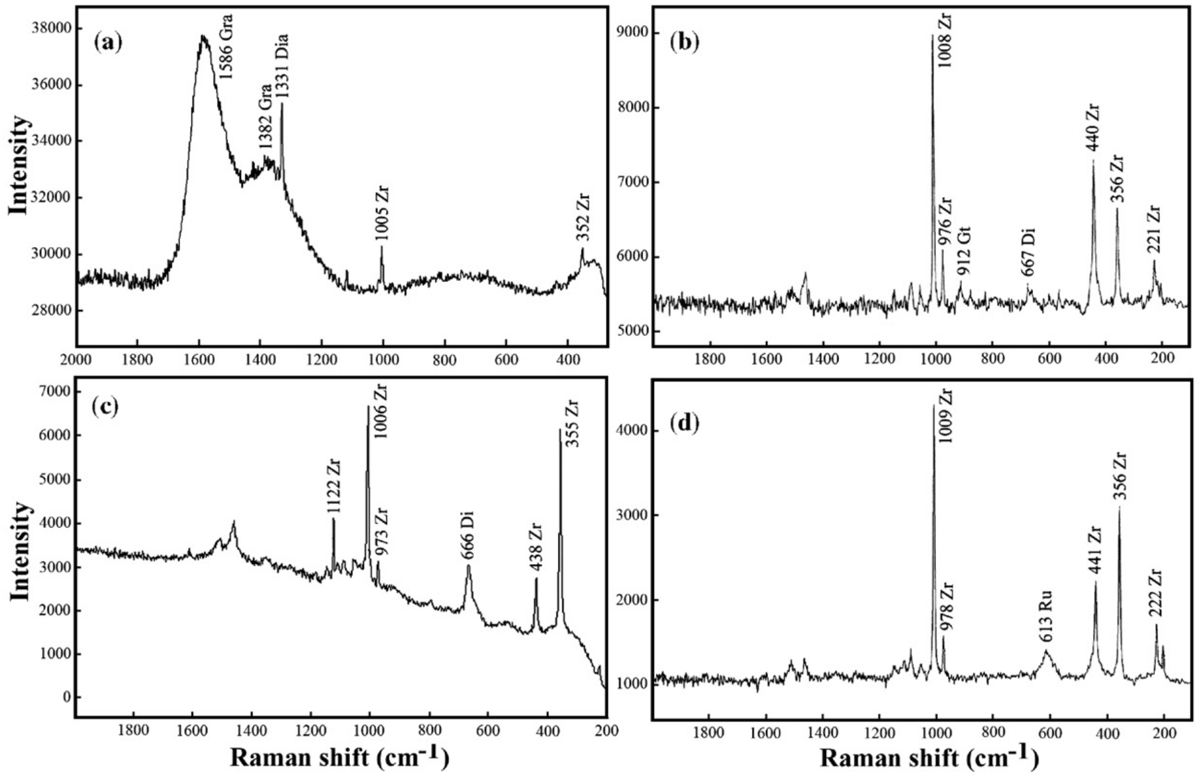

Fig. 4. Representative Raman spectra of inclusion minerals in zircon from sample TEH113. (a) Diamond (Dia) and graphite (Gra); (b) garnet (Gt) and diopside (Di); (c) diopside (Di); (d) rutile (Ru); these spectra also contain host zircon peaks at 1005−1009, 973−978, 438−441, 352−356 and 221−222 cm^{-1}.

oscillatory zonation and high Th/U ratios of the cores are indicative of a magmatic origin (Rubatto and Gebauer, 2000), the age of 819 Ma represents the protolith age of the gneiss. Fifteen analyses of the M1 domains record $^{206}Pb/^{238}U$ concordant ages ranging from 213 to 230 Ma, with a weighted mean age of 218±3 Ma (MSWD=2.7) and Th/U≤0.02. The HP metamorphic mineral inclusions such as garnet have been observed in the M1 domains, which together with the low Th/U ratios suggest that these ages are the peak metamorphic time of the gneiss.

The M2 domains are variable in shape and in sharp contact with the M1 in CL. Twelve analyses of the M2 domains give ages from 181 to 201 Ma, with a weighted mean $^{206}Pb/^{238}U$ age of 191±5 Ma (MSWD=3.8) and Th/U≤0.02. This age indicates the retrograde metamorphic time because of their lower Th/U ratios and absence of HP mineral inclusion in M2 domains. Two analyses of the M2 domains give a younger apparent age of 160±4 Ma (spot 3.13) and an older age of 206±3 Ma, respectively. The former is a discordant age which was probably affected by the later event, and the latter may record a mixing age of M1–M2 domains, because the M2 domain of this grain is thinner than the ion beam spot. The rim of zircon grains from sample LT8-3 are too thin (generally <10 μm) (e.g., Fig. 2d) to be analyzed by the SHRIMP II.

4.2. Sample TEH113

Zircon grains separated from sample TEH113 are 150−400 μm in size, and most are rounded (with length-to-width of 1:1−1:2). Similar to sample LT8-3 described above, four domains can be discerned by CL images in several zircon grains (Fig. 3c, d, i and k). Many of the cores vary in shape and are commonly embayed by metamorphic grey mantle, although clear oscillatory zoning still exists, indicating that they are of magmatic origin. Two types of mantle can be identified based on their shape and luminescent in CL: (1) most vary in shape because they embay the cores and are characterized by variable grey-luminescent (namely grey mantle or M1) (Fig. 3a, c, h and i), and (2) some with regular shape surrounding the M1 are characterized by homogeneous bright-luminescent (namely white mantle or M2) (Fig. 3c, d and i). The rim is homogenous low-luminescent (Fig. 3c, d and k). While the black

Table 1
SHRIMP zircon U–Pb data for tonalitic gneiss (sample LT8-3)from the northern Dabie high *T*/*P* metamorphic zone

Spot	D	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	Th/U	$^{206}Pb^*$ (ppm)	$^{207}Pb^*/^{206}Pb^*$	± %	$^{207}Pb^*/^{235}U$	±%	$^{206}Pb^*/^{238}U$	±%	$^{206}Pb/^{238}U$ age (Ma)	
1.1	C	0.42	179	160	0.89	16.7	0.06730	2.9	1.0060	3.5	0.10840	2.0	663	±12
2.1	M1	0.03	3372	36	0.01	101	0.05135	0.90	0.24740	1.9	0.03495	1.7	221	±4
3.1	M2	0.53	350	1	0.00	9.59	0.05280	5.9	0.23100	6.2	0.03173	1.9	201	±4
2.2	M1	0.14	2445	32	0.01	70.6	0.05149	1.3	0.23830	2.2	0.03357	1.7	213	±4
2.3	M1	0.18	2175	31	0.01	67.7	0.05097	1.9	0.25410	2.5	0.03616	1.7	229	±4
2.4	M1	0.18	2351	29	0.01	66.6	0.05029	1.5	0.22820	2.3	0.03290	1.7	209	±3
2.5	M1	0.21	3209	34	0.01	93.9	0.05128	1.5	0.24030	2.3	0.03399	1.7	215	±4
2.6	M1	0.21	2425	37	0.01	71.1	0.05135	1.6	0.24110	2.3	0.03406	1.7	216	±4
4.1	C	0.43	378	654	1.73	28.5	0.06300	2.5	0.76100	3.1	0.08750	1.9	541	±10
2.7	M1	0.18	1977	32	0.02	57.0	0.05180	1.9	0.23940	2.6	0.03352	1.7	213	±4
2.8	M1	0.12	2446	39	0.02	70.9	0.05197	1.6	0.24140	2.4	0.03368	1.7	213	±4
2.9	M1	0.14	1978	32	0.02	57.3	0.05203	1.5	0.24150	2.3	0.03366	1.7	213	±4
2.10	M1	0.11	2891	34	0.01	86.6	0.05138	1.5	0.24680	2.3	0.03484	1.7	221	±4
3.2	M2	2.24	424	3	0.01	11.5	0.05950	8.1	0.25400	8.4	0.03101	2.0	197	±4
1.2	C	0.30	187	162	0.86	19.7	0.06740	3.2	1.1360	3.7	0.12230	1.9	744	±14
2.11	M1	0.11	3263	39	0.01	102	0.05175	1.2	0.25940	2.1	0.03636	1.7	230	±4
2.12	M1	0.09	2412	22	0.01	72.5	0.05278	1.3	0.25430	2.1	0.03494	1.7	221	±4
2.13	M1	0.09	2566	35	0.01	77.4	0.05243	1.5	0.25370	2.3	0.03509	1.7	222	±4
2.14	M1	0.11	3953	35	0.01	120	0.05136	1.0	0.24930	2.0	0.03521	1.7	223	±4
2.15	M1	0.41	1772	27	0.01	52.8	0.05190	2.0	0.24700	2.7	0.03453	1.7	219	±4
3.4	M2	0.93	250	2	0.01	6.70	0.04490	20	0.19100	20	0.03091	2.2	196	±4
3.3	M2	0.77	643	4	0.01	16.8	0.05060	4.3	0.21070	4.6	0.03018	1.9	192	±3
1.3	C	0.46	174	147	0.84	20.3	0.06530	2.6	1.2190	3.2	0.13540	2.0	819	±15
3.5	M2	0.16	1538	13	0.01	43.1	0.05425	1.6	0.24340	2.3	0.03255	1.7	206	±3
1.4	M2	1.37	539	4	0.01	14.6	0.05130	8.1	0.21900	8.3	0.03101	1.9	197	±4
3.6	M2	1.94	389	2	0.01	9.94	0.04180	19	0.16800	19	0.02917	2.0	185	±4
3.7	M2	1.49	459	1	0.00	11.4	0.04660	9.4	0.18400	9.6	0.02855	2.1	181	±4
3.8	M2	1.34	694	3	0.00	18.0	0.04450	7.6	0.18200	7.8	0.02977	1.9	189	±3
3.9	M2	1.32	515	2	0.00	13.6	0.06180	5.4	0.26000	5.7	0.03047	1.9	193	±4
3.10	M2	1.93	543	5	0.01	13.7	0.04650	12	0.18500	12	0.02878	2.1	183	±4
3.11	M2	0.70	725	9	0.01	19.8	0.05050	3.8	0.21980	4.2	0.03156	1.8	200	±4
3.12	M2	1.18	537	2	0.00	13.3	0.05560	6.8	0.21900	7.0	0.02858	2.0	182	±3
3.13	M2	2.28	431	11	0.02	9.50	0.05990	13	0.20700	13	0.02507	2.5	160	±4
4.2	C	0.73	596	532	0.89	32.5	0.06140	4.7	0.53300	5.1	0.06300	1.8	394	±7

Errors are 1 − sigma; Pb_c and Pb* indicate the common and radiogenic portions, respectively; common Pb corrected using measured ^{240}Pb.
D – domain, C – core, M1 – inner-mantle, M2 – outter-mantle.

overgrowth rims are very thick in some zircon grains (Fig. 3k). UHPM mineral inclusions (such as diamond) have been identified in grey mantle (see below for details), indicating that they are UHP metamorphic domains in origin. While higher Th/U ratios of 0.12–0.40 and younger ages of 126 Ma (see below for details) suggest that the black rims were magma overgrowth in origin corresponding to the regional Early Cretaceous magmatism in the NDZ.

Magmatic mineral inclusions including potassium feldspar, quartz, biotite and apatite have been identified in the cores (Fig. 3j). The analyses of 14 spots from all the cores yield apparent $^{206}Pb/^{238}U$ ages ranging from 342 to 700 Ma with Th/U ratios of 0.18−1.47. As shown in Fig. 5b, all the core data points distributed along a discordant line, which defined upper and lower intercepts at 815±69 Ma and 210±62 Ma (MSWD=1.02), respectively, corresponding to the Neoproterozoic crystallization and the Triassic metamorphism. Seven analyses of the M1 domains record $^{206}Pb/^{238}U$ concordant ages ranging from 195 to 229 Ma, with a weighted mean age of 207±10 Ma (MSWD=3.3) and Th/U ≤ 0.09. The eclogitic mineral inclusions such as rutile (Fig. 3i) were found in M1 domains. In addition, micro-diamond (Fig. 3b), garnet (Fig. 3f, g and h) and diopside (Fig. 3b, f and g) inclusions were documented by Raman spectroscopy (Fig. 4) and/or EMPA on the zircon M1 domain (Liu et al., 2006). The Raman spectrum of the diamond inclusion contains the typical peak of 1331 cm^{-1} associated with the graphite peak (1586 cm^{-1}) (Fig. 4) because diamond was partly transformed to graphite after the UHPM stage (Liu et al., 2006). The unusual

Table 2
SHRIMP zircon U–Pb data for tonalitic gneiss (sample TEH113) from the northern Dabie high T/P metamorphic zone

Spot	D	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	Th/U	$^{206}Pb^*$ (ppm)	$^{207}Pb^*/^{206}Pb^*$	± %	$^{207}Pb^*/^{235}U$	± %	$^{206}Pb^*/^{238}U$	± %	$^{206}Pb/^{238}U$ age (Ma)	
113-2.1	R	0.00	1073	131	0.12	18.2	0.0504	3.1	0.1371	4.3	0.01975	2.9	126	±4
113-1.1	C	0.00	167	138	0.83	14.3	0.0662	2.5	0.911	4.5	0.0997	3.8	613	±22
113-2.2	C	0.51	1007	1171	1.16	60.2	0.0578	3.2	0.552	4.2	0.0693	2.7	432	±11
113-1.2	C	0.13	636	361	0.57	32.3	0.0617	2.1	0.502	3.6	0.0590	2.8	370	±10
113-1.3	C	0.00	552	362	0.66	51.7	0.0659	1.7	0.993	3.2	0.1093	2.8	668	±18
113-4.1	R	0.00	678	275	0.40	11.5	0.0488	3.7	0.1328	4.7	0.01975	2.9	126	±4
113-1.4	C	0.32	872	893	1.02	83.9	0.0639	1.8	0.984	6.6	0.1117	6.4	683	±42
113-1.5	M1	0.00	205	1	0.01	6.14	0.0686	4.2	0.334	5.8	0.0353	4.0	223	±9
113-5.1	M1	0.00	327	143	0.44	5.93	0.0666	3.7	0.1969	5.0	0.02143	3.4	137	±5
113-2.3	M1	0.00	468	3	0.01	13.5	0.0508	3.8	0.236	4.7	0.03371	2.9	214	±6
113-2.4	M1	0.00	483	6	0.01	12.6	0.0533	6.7	0.225	7.3	0.03064	2.9	195	±5
113-2.5	C	0.14	246	273	1.11	22.4	0.0655	2.3	0.955	3.7	0.1057	2.9	648	±18
113-2.6	M1	0.00	390	5	0.01	10.6	0.0578	3.0	0.253	4.2	0.03171	2.9	201	±6
113-2.7	C	0.10	758	135	0.18	35.5	0.0600	2.2	0.451	3.5	0.0545	2.8	342	±9
113-3.1	M1	0.00	317	14	0.04	10.9	0.0615	5.9	0.340	6.6	0.0401	3.0	253	±7
113-2.8	C	0.09	409	320	0.78	40.4	0.0647	1.9	1.022	3.4	0.1146	2.8	700	±19
113-2.9	C	0.18	535	785	1.47	47.0	0.0671	2.7	0.943	4.3	0.1019	3.3	626	±20
113-3.2	M1	0.44	737	108	0.15	30.6	0.0531	3.0	0.352	4.9	0.0481	3.9	303	±12
113-1.6	C	0.27	332	133	0.40	27.7	0.0639	2.2	0.854	3.6	0.0969	2.8	596	±16
113-2.10	M1	0.55	398	19	0.05	10.8	0.0504	7.2	0.218	7.8	0.03133	3.0	199	±6
113-2.11	C	0.32	985	203	0.21	48.7	0.0587	2.1	0.464	3.6	0.0573	2.9	359	±10
113-2.12	M1	0.00	410	7	0.02	12.2	0.0599	3.1	0.288	4.3	0.0349	2.9	221	±6
113-2.13	M1	0.00	719	25	0.03	19.4	0.0533	2.8	0.230	5.5	0.0314	4.8	199	±9
113-2.14	M1	0.00	808	120	0.15	24.7	0.0585	3.7	0.288	4.8	0.0357	3.0	226	±7
113-3.6	C	0.00	160	48	0.30	12.9	0.0635	2.9	0.822	4.1	0.0938	2.9	578	±16
113-4.2	M1	0.00	397	7	0.02	12.3	0.0503	3.1	0.251	4.3	0.0361	2.9	229	±7
113-2.15	M1	0.00	351	33	0.09	9.91	0.0523	3.3	0.237	4.4	0.03283	2.9	208	±6
113-2.16	C	0.03	1195	876	0.73	79.0	0.06058	1.3	0.642	3.0	0.0769	2.7	478	±13
113-3.7	M1	0.41	471	2	0.01	13.4	0.0483	5.4	0.219	6.1	0.03295	2.9	209	±6
113-3.8	M1	0.20	1246	4	0.00	31.1	0.0481	2.5	0.1921	3.7	0.02897	2.8	184	±5
113-3.9	C	0.00	206	242	1.17	13.0	0.0630	3.3	0.639	4.4	0.0736	2.9	458	±13
113-3.10	M1	1.02	382	21	0.05	12.2	0.0456	7.1	0.231	7.7	0.0368	2.9	233	±7

Errors are 1 − sigma; Pb_c and Pb^* indicate the common and radiogenic portions, respectively; common Pb corrected using measured ^{240}Pb.
D – domain, C – core, M1 – inner-mantle, R – rim.

paragneiss of UHPM minerals (e.g. diamond) and relatively low-P mineral (e.g. diopside) could be simply a consequence of the different reaction kinetics (Bruno et al., 2001). Similar cases had been found by some researchers, e.g., the peak eclogite-facies mineral assemblages associated with relic igneous minerals from the meta-granite in the Sesia zone (Compagnoni and Maffeo, 1973), and the preservation of gabbroic texture and relict igneous minerals in UHP rocks from Yangkou in the Su-Lu orogen (Liou and Zhang, 1996). These were most commonly attributed to a lack of fluid availability during metamorphism (e.g. Liou and Zhang, 1996; Mosenfelder et al., 2005). As mentioned above, the NDZ is a lower crust slice and absence of hydrous HP–UHP metamorphic mineral and aqueous fluid, hence, the clinopyroxene (diopside) may not transform into omphacite and, coevally, the alkalic plagioclase may not decompose into quartz + jadeite at the peak metamorphic conditions of the orthogneiss in the NDZ. More recently, the synthesis experiments using a sample with identical bulk composition to the natural eclogites from the NDZ documented that the peak UHPM paragneiss consists of garnet, clinopyroxene and rutile, which was stable at $P \sim 3.5$ GPa and $T \geq 750-800$ °C, whereas the clinopyroxenes are mainly diopside and augite (Malaspina et al., 2006). Therefore, the zircon M1 domains formed under UHPM conditions and the age of 207 ± 10 Ma recorded on the M1 domains with low Th/U ratios should represent the peak UHPM time of the gneiss. This age is marginally consistent with the age of 218 ± 3 Ma for sample LT8-3 within error limits. The M2 domains are thinner than the ion beam spot and contain lower U contents, thus cannot be analyzed. Most of the zircon rims were too thin to be measured, and only two thick rims can be dated and give identical age of 126 ± 4 Ma with a weighted mean $^{206}Pb/^{238}U$ age of 126 ± 5 Ma.

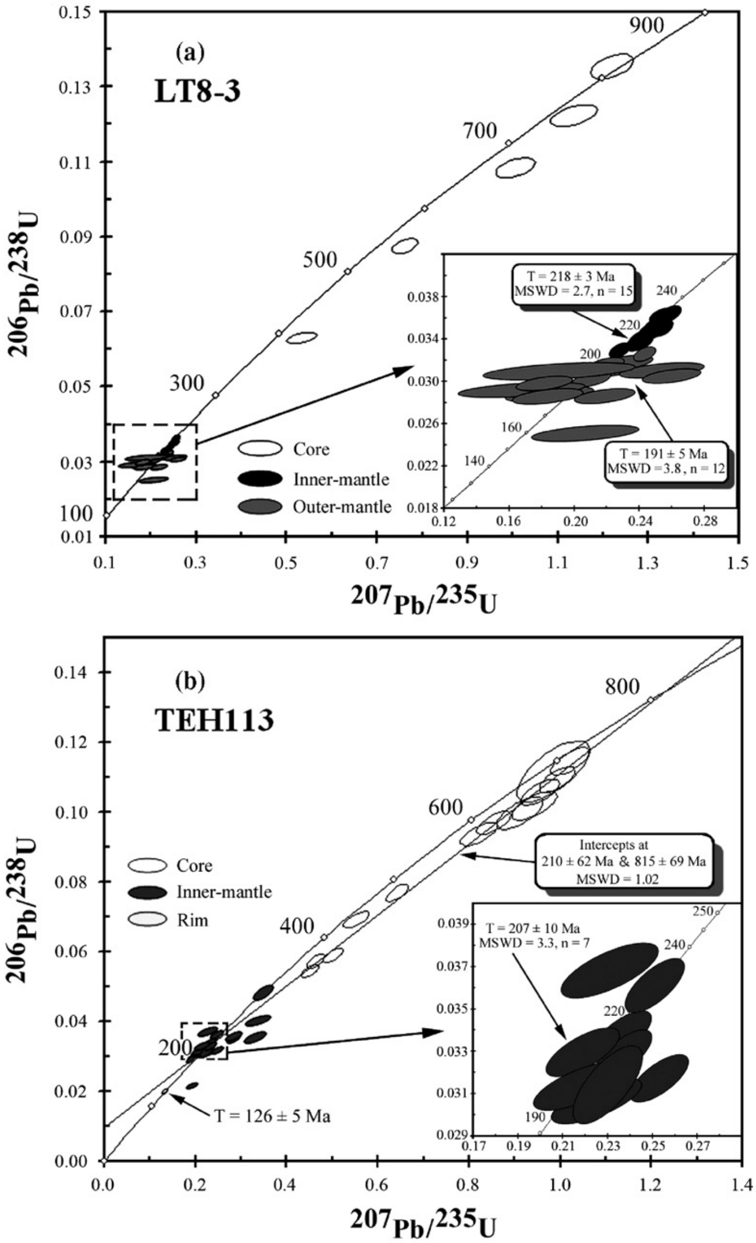

Fig. 5. Zircon SHRIMP U–Pb dating for samples LT8-3 (a) and TEH113 (b) at Jinjiapu and Ta'erhe in the northern Dabie high *T*/*P* metamorphic zone.

In summary, the zircon grains from the NDZ recorded at least four distinct age populations, i.e. Neoproterozoic (815±69 Ma−819±15 Ma), 207±10 Ma−218±3 Ma, 191±5 Ma and 126±5 Ma for core, M1, M2 and rim domains, respectively. The ages defined by M1 domains from samples TEH113 and LT8-3 are identical within error and represent peak UHP metamorphism, as indicated by diamond mineral inclusions. Because the age of 218±3 Ma from sample LT8-3 is defined by fifteen data points of $^{206}Pb/^{238}U$ concordant ages and smaller age error, it should be the best estimate for the Triassic peak metamorphism time of the NDZ. The M2 domains contain low-*P* mineral inclusions such as quartz (Fig. 3j) and distributed around the M1, so 191±5 Ma recorded in M2 domains suggest the retrogressive age. Because minerals formed during granulite-facies retrogression occur only as symplectite assemblages for the UHPM rocks in the NDZ, suggesting that either the granulite-facies retrograde metamorphism only lasted a short period of time (Liu et al., 2005a), or there was no fluid involved, which significantly limited mineral recrystallization or zircon overgrowth. By contrast, large-scale amphibolite-facies retrograded metamorphism occurred in the NDZ, i.e., most of the metamorphosed rocks in the NDZ show the amphibolite-facies with some relic of eclogite- and/or granulite-facies minerals. The retrograde mineral assemblage with amphibolite-facies contains abundant hydrous minerals such as amphibole and biotite, suggesting much activity of fluids in this retrograded metamorphic stage, which provided a suitable condition to the zircon overgrowth. Hence, the ca. 191 Ma may represent the retrograde time of amphibolite-facies. The age of 126±5 Ma recorded on the zircon rim with higher Th/U ratios should represent the timing of migmatization in the NDZ, corresponding to a large-scale post-collisional magmatic event in the Early Cretaceous in the Dabie Mountains.

5. Discussion

5.1. Isotope chronology of three UHPM crustal slices

Due to its high closure temperature and extremely slow diffusion rates, zircon often records multiple growth stages in complex metamorphic terranes (e.g. Möller et al., 2002). The complex micro-textures of zircon grains from UHPM rocks – including irregular boundaries and various core, mantle and rim domains – revealed by CL images, suggest that many conventional zircon U–Pb ages for UHPM rocks are probably mixed ages with ambiguous geologic significance (Gebauer et al., 1997; Liu et al., 2002). The capacity of the SHRIMP ion microprobe to date small domains with high resolution makes it possible to determine different ages in a single grain, especially when accompanied by an integrated study of CL or back scatter electron (BSE) images, mineral inclusions, and geochemistry (e.g., Sun et al., 2002). These techniques thus have the potential to greatly improve our understanding of subduction and exhumation of UHPM rocks in the Dabie−Su-Lu orogen. Therefore, in order to compare the peak metamorphic ages with three different UHPM slices in the Dabie orogen, we chose the previous published data of zircon SHRIMP U–Th–Pb dating for UHPM rocks for the discussion below.

In addition, the complexity of Sm–Nd isotopic systematics in eclogite has been discussed by Thöni and Jagoutz (1992) and Li et al. (2000) in details. Most of published Sm–Nd ages are essentially isochrones given by two UHPM minerals (i.e. one garnet+one omphacite) (e.g. Li et al., 1993; Chavagnac and Jahn, 1996). Because the possibility of Nd isotopic dis-equilibrium between UHPM minerals, which could lower the slop of tie-line between garnet and omphacite (Jagoutz, 1994), and garnet+whole rock containing retrograde metamorphic minerals often give older ages (Li et al., 2000), only the Sm–Nd isochron ages given by three (or more) UHPM minerals for eclogite are chosen for the discussion below.

5.1.1. The northern Dabie high T/P metamorphic zone

Recently, a reliable Sm–Nd isochron age of 212±4 Ma defined by two garnet+two omphacite from sample 98702 at Huangweihe eclogite in eastern segment of the NDZ has been reported (Liu et al., 2005a). Because eclogites from the NDZ experienced an unusual retrograde granulite-facies metamorphism, this Sm–Nd age was interpreted as a cooling age (Liu et al., 2005a). However, this Sm–Nd age is in agreement with the new reported zircon SHRIMP U–Pb age of 207±10 Ma for sample TEH113 in this paper. The consistence of the above U–Pb zircon age and Sm–Nd age implies that the geological meaning of the Sm–Nd age should be reevaluated. Because the U–Pb system of zircon cannot be reset by overprinting of granulite-facies metamorphism (Mezger and Krogstad, 1997), the Sm–Nd age of 212±4 Ma is not likely a cooling one but may also recorded the UHP metamorphic time. Besides the above two ages, we report a more precise U–Pb age of 218±3 Ma for the UHPM overgrowth zircons from garnet-bearing tonalitic gneiss in the NDZ in this paper. Although this age is relatively higher than the U–Pb age of 207±10 Ma and Sm–Nd age of 212±4 Ma, they are all consistent with each other within error. Since the three samples with the above UHPM ages are distributed over south-western, middle-northern and east-northern parts of the NDZ, respectively (Fig. 1), the age of 218±3 Ma can be considered to be the best estimate for the peak metamorphism time of the NDZ. As mentioned above, the NDZ sequentially experienced amphibolite-facies retrogressive overprint at 191±5 Ma and tectonothermal event for the migmatization at 126±5 Ma.

5.1.2. The southern Dabie UHPM zone

Li et al. (2000) dated the UHPM rocks from Shuanghe area in the SDZ, which occur as a UHPM block within the regional granitic gneiss. A Sm–Nd isochron defined by garnet+omphacite+rutile for a coesite-bearing eclogite from Shuanghe area in the SDZ yield an age of 226.3±3.2 Ma (Li et al., 2000). Another Sm–Nd isochron defined by garnet+two phengites from Shuanghe UHP gneiss yield a similar age of 226.5±2.3 Ma (Li et al., 2000). These two identical Sm–Nd ages defined by three UHP minerals suggest that Nd isotopic equilibrium between

UHP minerals in these rocks during UHP metamorphism has been achieved. In addition, Ayers et al. (2002) obtained a concordant $^{206}Pb/^{238}U$ age of 229.6±2.6 Ma with MSWD=0.71 by twenty-five analyses of zircons for Maowu eclogite, which is in excellent agreement with the Sm–Nd ages reported by Li et al. (2000), and a weighted mean $^{206}Pb/^{238}U$ age of 238±3 Ma with MSWD=0.72 by six analyses of zircons for Shuanghe jadeite quartzite from the southern Dabie UHPM zone. Consequently, the peak UHPM age for the SDZ should be 226–238 Ma. In addition, the south-western Su-Lu terrane as a UHPM zone is comparable with the SDZ. A Sm–Nd isochron age of 226.3±4.5 Ma given by garnet+omphacite+phengite (Li et al., 1994) and several zircon SHRIMP U–Pb ages ranging from 231±4 Ma to 227±2 Ma and 227.4±3.5 Ma with UHPM mineral diagnosis of zircon origin (Liu et al., 2004a,b; Li et al., 2005a) have been reported, which strongly support the above conclusion concerning the peak UHP metamorphic age of the SDZ.

Li et al. (2000) suggested that the Rb–Sr age of 219±6.6 Ma defined by phengite+garnet for UHPM gneiss from Shuanghe in the SDZ indicates the cooling time of phengite at 500 °C. Also, the Sm–Nd age of 213.3±4.8 Ma defined by garnet+biotite+epidote from granitic gneiss at Shuanghe suggests the Nd isotopic re-equilibration during retrograde amphibolite-facies metamorphism (Li et al., 2000). In addition, monazites separated from the Shuanghe jadeite quartzite display obviously core-rim zoning by CL images, and their core and rim domains yield weighted mean $^{208}Pb/^{232}Th$ age of 223±1 Ma and 209±3 Ma, respectively (Ayers et al., 2002). Because the T_{max} (700–800 °C) of the UHPM rocks from the SDZ is higher than the T_c of 650–700 °C for Pb in monazite (Mezger et al., 1991; Smith and Giletti, 1997), the monazite core age should indicate the cooling time at T=675±25 °C, while the rim age of 209±3 Ma is corresponding to recrystallization growth of monazite occurred during retrograde amphibolite-facies metamorphism (Ayers et al., 2002). Furthermore, Li et al. (2003a) reported a precise U–Pb age of 218±1.2 Ma with T_c=460 °C for rutile from the coesite-bearing eclogite in the SDZ. Therefore, the ages of 219–209 Ma in the SDZ represent the time of amphibolite-facies retrograde metamorphism (e.g., Li et al., 2000; Ayers et al., 2002; Li et al., 2003a). The similar SHRIMP U–Pb ages of 211±4 Ma and 209±3 Ma for the amphibolite-facies retrograde rims in zircon from the UHP gneisses in the south-western Su-Lu terrane (Liu et al., 2004a,b) suggest that the SDZ and SW Su-Lu terrane experienced the amphibolite-facies retrograde metamorphism in the same time.

Although the UHPM and retrograde metamorphic ages of the SDZ are older than those of the NDZ, previous studies (e.g., Hacker et al., 2000; Ayers et al., 2002; Sun et al., 2002, Zheng et al., 2003, 2004; and references therein) show that most of zircon grains from the UHPM rocks in the SDZ commonly have Neoproterozoic cores, similar to those from the NDZ, suggesting the both UHPM units have similar protolith ages and belong to subducted continental crust of the SCB.

5.1.3. The Huangzhen eclogite zone

Li et al. (2004) dated the ages of the eclogite from the HZ, and gave a Sm–Nd mineral (garnet+omphacite+rutile+kyanite) isochron age of 236±4 Ma and SHRIMP U–Pb zircon ages of 242±3 Ma and 222±4 Ma for the mantle and rim, respectively. They interpreted the UHPM metamorphic event should have occurred in the time period from 242±3 Ma to 236±4 Ma in the HZ, and the late retrogressive overprint occurred at 222±4 Ma.

5.2. Implication for decoupling within subducted continental crust

In view of the above dating results, the peak metamorphic ages for the UHPM rocks from three different crustal slices in the Dabie orogen are different from each other. The peak metamorphic age (218±3 Ma) of UHPM rocks from the NDZ is younger than the peak metamorphic age (226–238 Ma) of UHPM rocks from the SDZ, while the latter is younger than the peak metamorphic age (236–242 Ma) of UHP eclogite from the HZ. Furthermore, the amphibolite-facies retrograde metamorphic age of 191±5 Ma of UHPM rocks from the NDZ is also significantly younger than the amphibolite-facies retrograde metamorphic ages of 219–209 Ma of UHPM rocks from the SDZ, while the latter is also younger than the age of 222±4 Ma for retrograded metamorphic zircon from the eclogite in the HZ. All these show a decrease trend of metamorphic ages of the three UHPM crustal slices from south to north in the Dabie orogen. As described above, the three UHPM crustal slices from south to north in the Dabie orogen should be derived from subducted uppermost and middle part of upper crust and lower crust of the South China Block, respectively. Therefore, the decrease of the metamorphic ages from south to north in the Dabie orogen suggests that the detachment or a decoupling between the three UHPM crustal slices must be occurred separately from upper crust to lower crust during continental subduction. This decrease trend of the metamorphic ages of the three UHPM crustal slices from south to north in the Dabie UHPM belt can be explained by a decoupling within deeply subducted continental crust and multi-slice exhumation model (see Fig. 6).

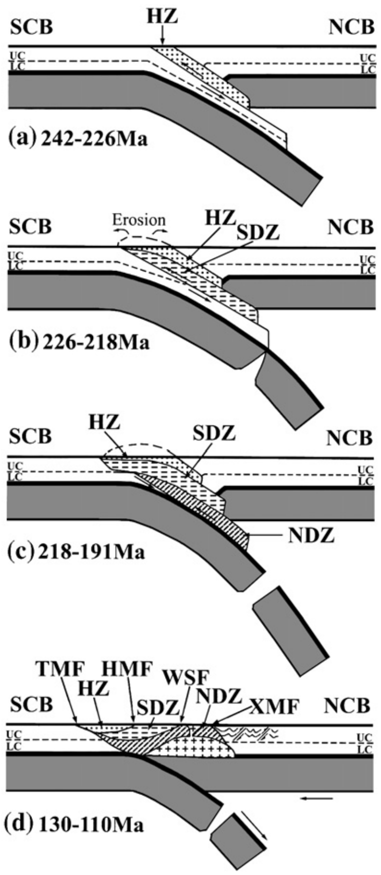

Fig. 6. A simplified tectonic model for the decoupling within deeply subducted continental crust and multi-slice exhumation in the Dabie orogen. SCB = South China Block, NCB = North China Block, UC = upper continental crust, LC = lower continental crust. The other abbreviated symbols are the same as in Fig. 1. Detailed explanations are given in the text.

The U–Pb ages of 244±5 Ma for UHPM zircon and 221±2 Ma for monazite overgrowth from a UHP granitoid gneiss cobble from the Late Jurassic Fenghuangtai Formation of the Hefei Basin (Wan et al., 2005), in the Beihuaiyang zone, are in good agreement with the zircon U–Pb ages of the Huangzhen eclogite (Li et al., 2004), suggesting the HZ exhumed at the surface by at least the Middle–Late Jurassic (Wan et al., 2005). At that time, the UHPM rocks in the SDZ and NDZ were still in upper-mid crust level (Li et al., 2000). So, the subducted Huangzhen crustal slice was firstly decoupled with the underlying subducted continental lithosphere, and then ascended driven by buoyancy forces. In the meantime, the subduction of underlying continental plate was continued (Fig. 6a).

It is interesting to note that the cooling age of 218±1.2 Ma for rutile (T_c=460 °C) from a coesite-bearing eclogite in the SDZ (Li et al., 2003a) is identical with the peak metamorphic age of 218±3 Ma for UHPM zircon from garnet-bearing tonalitic gneiss in the NDZ. It is suggested that the detachment between the SDZ and NDZ must have occurred before 218 Ma (could be at 226 Ma), which induced the uplifting of the SDZ slice along the detachment surface by thrust, while the subduction of the NDZ slice was continued (Fig. 6b).

Similarly, it can be inferred that a detachment or a decoupling within the lower continental crust could have also occurred because subducted mafic lower crust has not been exhumed in the Dabie orogen, which is supported by the existence of low-viscosity zone within lower continental crust (Meissner and Mooney, 1998). This decoupling could be occurred at 218 Ma, which caused the uplifting of upper part of felsic lower crust (i.e. the NDZ) during the time period of 218−191 Ma (Fig. 6c).

Therefore, during the period of 242−191 Ma, the subduction of continental lithosphere of the South China Block was accompanied by successive uplift of decoupled crustal slices along the detachment surface by thrust. During the Cretaceous extension (130–110 Ma), doming and extensive plutonism resulted in the present structure and distribution of tectonic units (Fig. 6d), and the detachment surfaces are reworked as ductile normal faults (Faure et al., 1999; Hacker et al., 2000; Yuan et al., 2003).

6. Conclusions

(1) The zircon grains from tonalitic gneiss in the NDZ display typical zoning structures with core, mantle (including inner- and outer-mantle) and rim domains, and at least four discrete and meaningful age groups have been discerned. Residual cores show magmatic characteristics and give a concordant age of 819±15 Ma, indicating that the protolith was a Neoproterozoic granitic intrusion. The inner-mantle domains with high U contents and lower Th/U ratios as well as eclogitic mineral inclusions such as garnet, diamond and rutile, give an age of 218±3 Ma, representing the peak UHP metamorphic time of the eclogite and gneiss in the NDZ. The age of 191±5 Ma for outer-mantle domains recorded their amphibolite-facies retrograde metamorphic time. The age of 126±5 Ma given by the rims indicates an overprinting of the Early Cretaceous magmatism and migmatization in the Dabie orogen.

(2) A decrease trend of the metamorphic ages of the three UHPM crustal slices from south to north in the Dabie orogen has been observed. This age distribution in the Dabie UHPM belt can be explained by a decoupling within deeply subducted continental crust and multi-slice exhumation model. The detachment occurred along the low-viscosity zones within subducting continental crust

during the subduction process produced several decoupled crustal slices, e.g. the NDZ, SDZ and HZ in Dabie orogen. The Huangzhen crustal slice was firstly decoupled with the underlying subducted continental lithosphere, and then exhumed due to buoyancy. In the meantime, the subduction of underlying continental plate continued. After the initiation of this process, the detachment or decoupling within subducted continental crust was repeated several times to form an imbricate megastructure in the Dabie UHPM belt. The multi-slice, multi-stage exhumation processes of deeply subducted continental crust are special for continental subduction and differ from the oceanic subduction (Li et al., 2005b).

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