



The multi-stage tectonic evolution of the Xitieshan terrane, North Qaidam orogen, western China: From Grenville-age orogeny to early-Paleozoic ultrahigh-pressure metamorphism

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ABSTRACT

The geodynamic evolution of the early Paleozoic ultrahigh-pressure metamorphic belt in North Qaidam, western China, is controversial due to ambiguous interpretations concerning the nature and ages of the eclogitic protoliths. Within this framework, we present new LA-ICP-MS U–Pb zircon ages from eclogites and their country rock gneisses from the Xitieshan terrane, located in the central part of the North Qaidam UHP metamorphic belt. Xitieshan terrane contains clearly different protolith characteristics of eclogites and as such provides a natural laboratory to investigate the geodynamic evolution of the North Qaidam UHP metamorphic terrane. LA-ICP-MS U–Pb zircon dating of three phengite-bearing eclogites and two country rock gneiss samples from the Xitieshan terrane yielded 424–427 Ma and 917–920 Ma ages, respectively. The age of 424–427 Ma from eclogite probably reflects continental lithosphere subduction post-dating oceanic lithosphere subduction at ~440–460 Ma. The 0.91–0.92 Ga metamorphic ages from gneiss and associated metamorphic mineral assemblages are interpreted as evidence for the occurrence of a Grenville-age orogeny in the North Qaidam UHPM belt. Using internal microstructure, geochemistry and U–Pb ages of zircon in this study, combined with the petrological and geochemical investigations on the eclogites of previous literature's data, three types of eclogitic protoliths are identified in the Xitieshan terrane i.e. 1) Subducted early Paleozoic oceanic crust (440–460 Ma), 2) Neoproterozoic oceanic crust material emplaced onto micro-continental fragments ahead of the main, early Paleozoic, collision event (440–420 Ma) and 3) Neoproterozoic mafic dikes intruded in continental fragments (rifted away from the former supercontinent Rodinia). These results demonstrate that the basement rocks of the North Qaidam terrane formed part of the former supercontinent Rodinia, attached to the Yangtze Craton and/or the Qinling microcontinent, and recorded a complex tectono-metamorphic evolution that involved Neoproterozoic and Early Paleozoic orogenies.

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1. Introduction

Subduction of lithospheric crust into the mantle triggers high-pressure (HP) to ultrahigh-pressure (UHP) metamorphism which involves transformation of lower pressure metabasic rocks into HP/UHP eclogites. Eclogite, formed in this way, may occur either in lithological units that are derived from subducted oceanic crust or, alternatively, form parts of tectonic slices that consist dominantly of felsic crystalline rocks derived from previously continental margins. As such these contrasting lithological rock-associations define the so-called Pacific- or Alpine-type collisional plate margins known from plate tectonic theory (e.g. Liou et al., 1996; Maruyama et al., 1996; Ernst, 2001; Liou

et al., 2004; Song et al., 2006; Ernst et al., 2007; Song et al., 2014). Moreover, this fundamental difference, expressed by the overall lithological association, can be used to identify the nature of a collisional plate margin involved in a paleo-collision belt. As such the lithological association, combined with chemical characteristics and isotope ages of metabasic protoliths and/or eclogite facies metamorphism, provides a powerful tool that can be used to unravel the geodynamic evolution of an UHP metamorphic terrane.

The Xitieshan UHP terrane, located in the central part of the North Qaidam ultrahigh-pressure metamorphic (UHPM) belt, China (Fig. 1), comprises typical Alpine-type collision lithologies that consist of granitic and pelitic gneiss enclosing minor eclogite (e.g. Zhang et al., 2005; C. Zhang et al., 2009, 2011a). The nature of the protolith of the Xitieshan eclogites is, however, still controversial. Geochemical and geochronological investigation of the Xitieshan eclogite has yielded MORB-type affinity and Neoproterozoic protolith ages (750–800 Ma). The latter data

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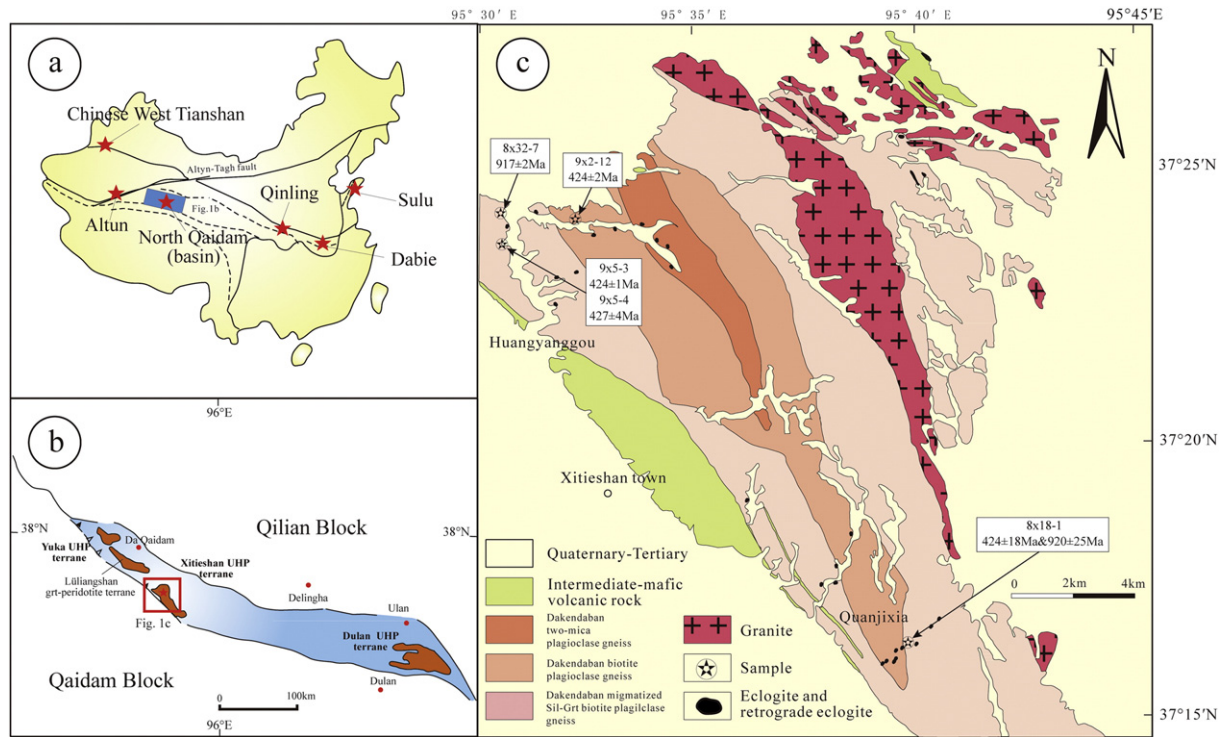


Fig. 1. Simplified geological maps. (a) The location of the North Qaidam UHPM belt in China. All Chinese UHP belts are marked with asterisks. (b) The distribution of UHP terranes in the north Qaidam UHPM belt. Geographical names used in text are indicated. The blue region in the figure illustrates the North Qaidam UHPM belt and the red square refers to the location of the Xitieshan area. (c) Geological sketch map of the Xitieshan terrane including sampling locations. Modified after Zhang et al. (2011a).

were used to argue that protoliths of Xitieshan eclogites were formed either in a continental rift setting or, alternatively after spreading and ocean floor formation, as formed part of an oceanic crust (Meng et al., 2003; Zhang et al., 2005, 2006). In contrast, Yang et al. (2006) reported that the protolith of the Xitieshan eclogites consisted of ophiolite fragments that were generated in an oceanic domain related to the break-up of the supercontinent Rodinia. These ophiolites may have been subsequently emplaced onto a continental crustal fragment that pre-dated the early Paleozoic North Qaidam orogeny (460–420 Ma). Furthermore, Paleozoic ophiolite fragments discovered in the Dulan terrane (SE side of Fig. 1b), also confirm the existence of eclogitic protoliths with an ophiolitic MORB like affinity in the North Qaidam UHPM belt (G.B. Zhang et al., 2008; Song et al., 2009b).

The nature of eclogitic protoliths forms a fundamental keystone in geodynamic models concerned with the formation and evolution of the north Qaidam UHP metamorphic belt. Unraveling the eclogite protolith controversy, described above, will thus help to clarify the geodynamic model of the orogenic belt and at the same time may solve controversies arising from different interpretations of the geochronological data of the UHP metamorphism in the Xitieshan terrane (Zhang et al., 2006; Song et al., 2011; Zhang et al., 2011a; Liu et al., 2012). Within this framework, this paper presents new U–Pb zircon geochronological data of eclogites and gneisses from the Xitieshan terrane to constrain the nature of the eclogite protolith and to re-evaluate the tectonic evolution of the North Qaidam UHPM belt, from Neoproterozoic Grenville-age orogeny to Paleozoic subduction and continental collision.

2. Geological background

The North Qaidam UHPM belt defines a typical Alpine-type continental collision/subduction zone containing the characteristic continental rock association of granitic- and pelitic gneiss with intercalated eclogite and/or garnet peridotite. From SE to NW, four discrete UHP

terrane were recognized and named: the Dulan and the Xitieshan eclogite-bearing terranes, the Liliangshan garnet peridotite-bearing terrane and the Yuka eclogite-bearing terrane (Fig. 1b). The presence of armored coesite and diamond found as inclusions in zircon and garnet proved UHPM conditions in all four terranes, comparable to physical conditions recognized within continental UHPM terranes elsewhere in China (Yang et al., 2001; Song et al., 2003b, 2004; G.B. Zhang et al., 2009, 2014, 2015; Zhang et al., 2009b; Liu et al., 2012). However, the four UHPM terranes, though spatially situated in the same orogenic belt, differ mutually from each other in numerous aspects, including a.o. the detailed shape of the clockwise P–T paths (related to UHPM), the timing of protolith formation and/or the timing of eclogite facies metamorphism (G.B. Zhang et al., 2013 and references therein). In the Dulan UHPM terrane, ophiolite sequences, retrieval from three types of eclogite, together with a serpentinized harzburgite, with N- to E-MORB affinity and coesite-bearing eclogite with continental affinity are interpreted to reflect oceanic subduction prior to continental subduction (Song et al., 2006; G.B. Zhang et al., 2008; Zhang et al., 2009b). The isotopic age data point to formation of the eclogite protolith either at ~520 Ma or at 838 ± 50 Ma. Both ages are overprinted by HP–UHP metamorphism at ~460–420 Ma (e.g. Song et al., 2003a; Mattinson et al., 2006b; G.B. Zhang et al., 2009; Zhang et al., 2010). The diamondiferous garnet-bearing lherzolite, exposed in the Liliangshan terrane, experienced Paleozoic UHP metamorphism at ~423 Ma (e.g. Song et al., 2004). The protolith of the garnet peridotite is still controversial and previously interpreted as an Alaskan type magmatic cumulate, formed at ~460 Ma or a serpentinite that once formed part of an oceanic lithosphere (Song et al., 2005; Yang and Powell, 2008; Song et al., 2009a; Zhang et al., 2011b). In contrast, based on Re–Os isotope ages from sulfides collected from dunites inside the garnet peridotites, Shi et al. (2010) interpreted the Liliangshan garnet peridotite to represent an old Archean mantle fragment that was derived from the subcratonic lithosphere, but became refertilized in Neoproterozoic and/or early Paleozoic times. In the Yuka terrane coesite was discovered in eclogite;

its occurrence is consistent with P–T conditions of 2.8–3.2 GPa and 650–700 °C (Zhang et al., 2005; G.B. Zhang et al., 2009). In-situ LA-ICP-MS and SHRIMP zircon dating on the Yuka eclogite gave a protolith age of ~850 Ma and an UHPM age of ~430 Ma (Chen et al., 2007, 2009; Song et al., 2010). Combined with geochemical characteristics, the authors proposed that at least some of the protoliths, now forming the Yuka eclogites, were derived from continental flood basalts involved in the early-Paleozoic orogeny (Song et al., 2010).

The Xitieshan terrane, the subject of the present study, is located in the central part of the North Qaidam UHPM belt and consists of pelitic gneiss and granitic gneiss with few layered or lenticular eclogites (Figs. 1c, 2a and b). On the basis of the mineral assemblages, eclogites in the Xitieshan terrane were subdivided into bimineralic-eclogite (Bim-eclogite) and phengite-bearing eclogite (Phn-eclogite). Bim-eclogite is the prevailing one while Phn-eclogite is a minor component in the

studied area and only well discernible at Huangyanggou (Fig. 1c). In general, pristine eclogite (of both types) can only be observed (locally) in centers of large block or bodies enclosed in pelitic and/or granitic gneiss. Other eclogite bodies, however, are retrogressed to various degrees and more or less transformed into garnet amphibolite and/or amphibolite. Eclogite facies P–T conditions are calculated to be around 2.71–3.17 GPa, 751–791 °C (C. Zhang et al., 2009), that plot well inside the coesite stability field which has been confirmed by the finding of coesite included in a zircon extracted from garnet–amphibolite (Liu et al., 2012). A detailed phase equilibrium study, supported by mineral–chemical EMP analyses performed on natural eclogite samples, has also demonstrated that the exhumation-path of the Xitieshan UHP eclogites was characterized by an isothermal decompression trajectory subsequently followed by coeval decreasing pressure and temperature conditions (C. Zhang et al., 2009; Zhang et al., 2011a).

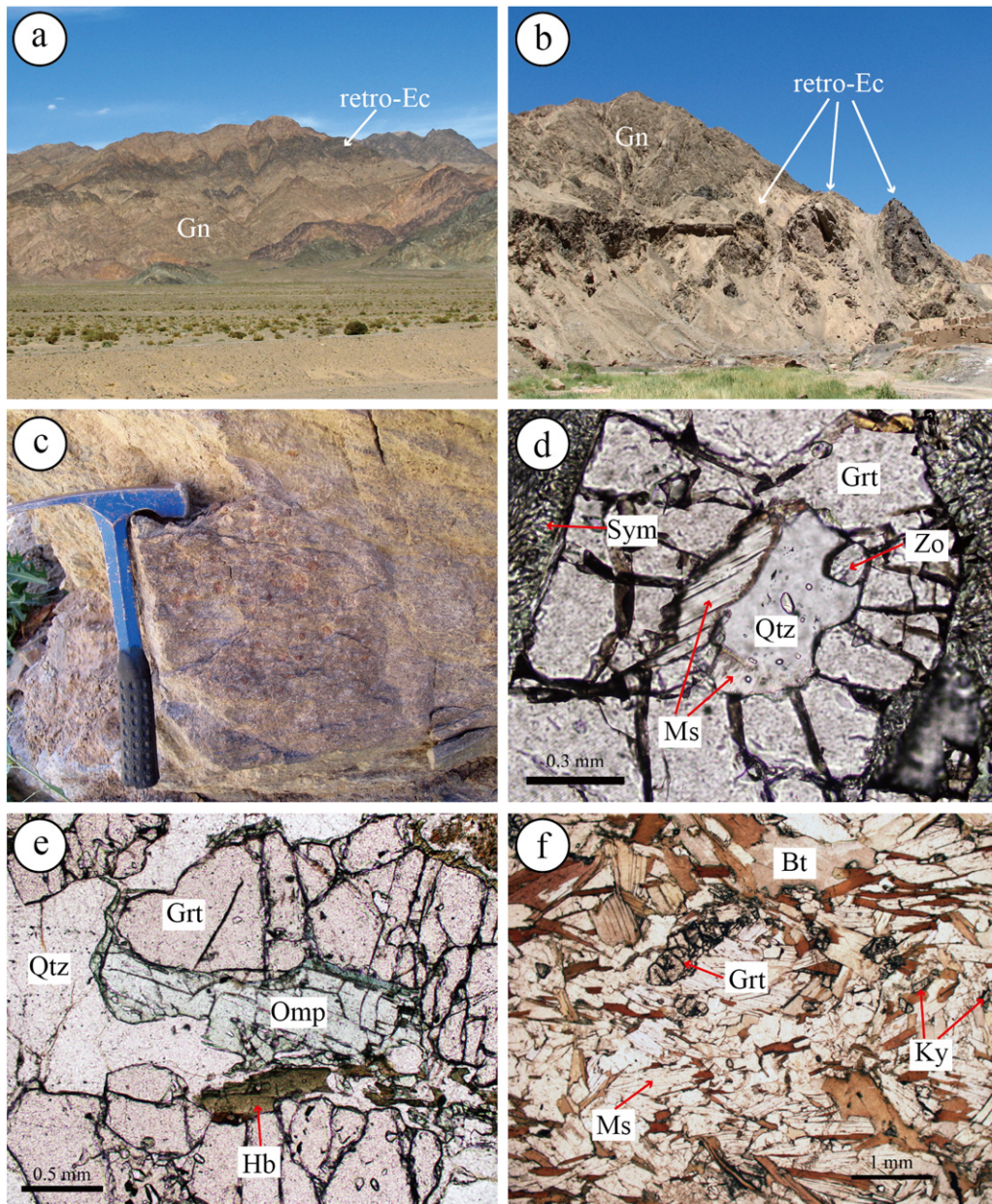


Fig. 2. Photographs showing field- and micro-structures of the investigated samples from the Xitieshan terrane. (a) Layered retrograde eclogite enclosed in gneisses. (b) Lenticular (retrograde) eclogite bodies enclosed in granitic gneiss. (c) Pelitic gneiss with kyanite and red garnet. For scale, the hammer has a length of 30 cm. (d) Muscovite (Ms) and quartz (Qtz) enclosed in garnet (Grt) in a phengite-bearing eclogite 9x12-2. (e) Phengite-bearing eclogite containing here the mineral assemblage garnet (Grt), omphacite (Omp) and quartz. Hornblende (Hb) formed during retrogression (sample 8x5-3). (f) Garnet, biotite (Bt), muscovite (Ms) with minor kyanite (Ky), the mineral assemblage of the pelitic gneiss sample 8x32-7.

In terms of bulk-rock geochemical and Sr–Nd isotope characteristics, low-Ti and high-Ti eclogite compositions have been identified in the Xitieshan terrane. Bulk rock geochemical signatures resemble N-MORB, E-MORB or near sea mount basalts (C. Zhang et al., 2013). Considering available 750–800 Ma and 877 ± 8 Ma protolith ages, preserved in zircon cores (Zhang et al., 2005, 2011a), it is inferred that some of the Xitieshan terrane eclogites originate from Neoproterozoic protoliths, interpreted to be emplaced onto the continental crust long before the early Paleozoic subduction/collision event leading to UHP metamorphism in North Qaidam (C. Zhang et al., 2013). The age of the eclogite facies metamorphism, preserved in zircon rims, was determined, both by SHRIMP and SIMS analyses, to have taken place at 440–460 Ma and 433 ± 3 Ma, respectively (Song et al., 2011; Zhang et al., 2011a; Liu et al., 2012).

The country rocks of Xitieshan eclogites are sillimanite-bearing biotite gneiss and two-mica gneiss (Fig. 2c). Kyanite is a noteworthy constituent of some samples. Two stages of amphibolite to high-pressure granulite facies metamorphism were distinguished in the same kyanite-bearing pelitic gneiss sample using geothermobarometry and phase equilibrium modeling (Zhang et al., 2009c; Zhang et al., 2012). In-situ electron microprobe monazite- and SHRIMP zircon U–Pb dating techniques were used to produce overlapping Neoproterozoic and Early Paleozoic ages, attributed to polyphase metamorphism, a phenomena also recognized in the mineral record (Zhang et al., 2012).

3. Sample description

3.1. Eclogite

In the Xitieshan terrane, metabasic layers or lenses are enclosed either in granitic or in pelitic gneiss. Two types are distinguished: Bim-eclogite and Phn-eclogite. Pristine eclogite facies parageneses are only preserved in the cores of large eclogite bodies and numerous eclogite samples of both types are pale gray or black colored due to extensive transformation towards garnet amphibolite and/or amphibolite. Three less retrogressed Phn-eclogite samples (9x12-2, 9x5-3 and 9x5-4) were collected from the core of relatively large eclogite bodies (2–3 m in diameter) from Huangyanggou, i.e. the area where fresh UHP eclogite of previous studies was sampled (Zhang et al., 2011a; Liu et al., 2012, Fig. 1c). The investigated Phn-eclogite is composed of 30–40% garnet, 10–15% omphacite, 5–10% quartz, 2–5% phengite, and 30–40% plagioclase–diopside symplectite formed after omphacite, minor amphibole and accessory rutile and zircon (Fig. 2e). Phengite is only preserved in the core of garnets and some flakes already transformed into muscovite (Fig. 2d). More detailed petrological and mineralogical descriptions have been given by Zhang et al. (2011a).

3.2. Country rock gneisses

Two gneiss samples (8x32-7 and 8x18-1) were collected, respectively, from Huangyanggou and Quanxixia in the Xitieshan terrane (Figs. 1c and 2c). Sample 8x32-7 is kyanite-bearing garnet biotite gneiss with the mineral assemblage kyanite, garnet, biotite, muscovite, plagioclase and quartz. Amphibolite facies P–T conditions of 5.3–6.5 kbar and 610–650 °C were determined by conventional geothermobarometry for the pelitic gneiss (Zhang et al., 2012). However, if the kyanite and garnet crystals (Fig. 2f) are interpreted as later blasts that did not crystallize at the same time as the other matrix components, the mineral assemblage of this pelitic gneiss can also be interpreted as a retrograde amphibolite facies assemblage superimposed on a HP granulite or even eclogite facies assemblage (e.g. J.X. Zhang et al., 2008). The second sample (8x18-1) is a quartzofeldspathic rock consisting predominantly of quartz (40–50%), garnet (30–40%) and subordinate plagioclase (10–20%) with accessory rutile and apatite grains in the matrix and/or included in garnet.

4. Analytical methods

Zircon crystals were obtained from crushed rocks by combining heavy liquid and magnetic separation techniques. Individual zircon crystals without (or only a few) cracks but include mineral inclusions were handpicked and mounted in epoxy resin. The grain mount was then polished to expose zircon cores. Prior to isotope analysis, the mineral inclusions present in the zircon grains were analyzed by Laser Raman spectroscopy in the Key Laboratory of Orogenic Belts and Crustal Evolution, Peking University. Transmitted- and reflected light-optical micrographs provided information on the shape of the zircon grains and their relative position in the grain mount. To reveal their internal microstructure and to guide spot locations for further isotope analyses, the zircons were also imaged by cathodoluminescence (CL), using a Quanta 200 FEG environmental scanning electron microscope at the School of Physics of Peking University, Beijing, with operating conditions 15 kV and 120 nA.

Zircon U–Pb isotopic analysis was carried out at Tianjin Institute of Geology and Mineral Resources using a Thermo Fisher Neptune MC-ICP-MS equipped with a 193 nm ArF (ESI UP 193-FX) laser ablation system. After each time five measurements were performed on a single sample a suite of zircon and glass standards, i.e. GJ-1, Plesovice and NIST SRM 612 was analyzed. Each spot analysis comprised approximately 20 s background acquisition and 40 s sample data acquisition. Off-line selection and integration of background and analytical signals, time-drift correction and quantitative calibration for trace element analyses and U–Pb dating were performed by ICPMSDataCal (Liu et al., 2010) and Isoplot (Ludwig, 2003). Common Pb was corrected according to the method of Andersen (2002). NIST SRM 612 glass was used to calculate the contents of Pb, Th and U in zircon (Pearce et al., 1997).

In-situ rare earth element analyses were performed with a COMPEX Pro102 laser-ablation system equipped with an 193 nm ArF-excimer laser connected to an Agilent 7500ce ICP-MS at the Key Laboratory of Orogenic Belts and Crustal Evolution, Peking University. The analytical procedures followed Yuan et al. (2004). The carrier gas helium enhanced the transport efficiency of the ablated material. The laser spot diameter was 32 μ m. All measurements were performed using NIST 610 as an external standard and ^{29}Si as an internal standard (Pearce et al., 1997). The LA-ICP-MS results are listed in Appendix Tables 1–3.

5. Results

5.1. U–Pb zircon ages of eclogite

Three Phn-eclogite samples from the Huangyanggou area were selected for zircon geochronology (see Fig. 1c for sample locations). All zircon recovered from the three samples are colorless, subhedral or near-spherical with diameters varying from 30 to 100 μ m and length/width ratios between 1 and 2. Zircon from samples 9x5-3 and 9x12-2 have more mineral inclusions than those of sample 9x5-4, i.e. garnet, rutile, quartz and minor hornblende. Omphacite was only identified in sample 9x5-3 (Fig. 3).

CL images of sample 9x5-3 show cloudy or patchy growth patterns and medium to bright luminescence with Th/U ratios of 0.01–0.03 (Fig. 3a). Clear grain boundaries (or other comparable microstructures) along the interface between core and rim of zircon crystals were not observed in CL images (Fig. 3). This latter microstructural characteristic is taken as evidence that all analyzed zircon grains were growing as new crystals during metamorphism. Sixteen U–Pb analyses from sample 9x5-3 yielded $^{206}\text{Pb}/^{238}\text{U}$ ages between 416 ± 6 Ma and 439 ± 8 Ma and define a concordant age of 424 ± 1 Ma (MSWD = 0.85; Fig. 5a, Appendix Table 1). Rare earth element (REE) patterns of the zircons are characterized by flat HREE slopes and lack of Eu anomalies ($\text{Eu}/\text{Eu}^* = 1.01\text{--}1.85$; Fig. 5a, Appendix Table 3). Zircon grains from sample 9x5-4 exhibit similar CL characteristics (Fig. 3b) and REE patterns (Fig. 5b)

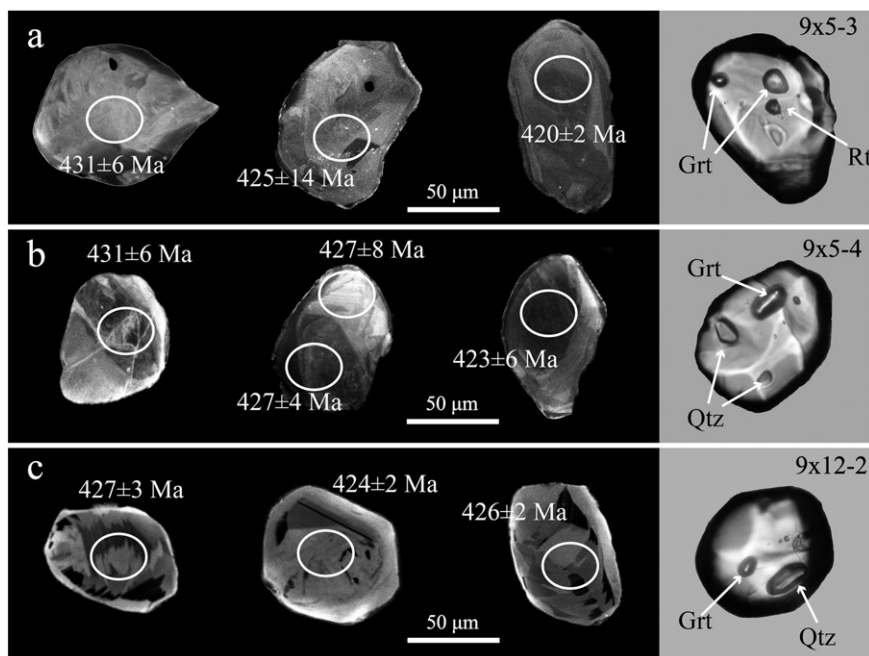


Fig. 3. Representative cathodoluminescence (CL) images (left side) and optical photomicrographs (right side) of zircons, showing mineral inclusions, location of analyzed spots and $^{206}\text{Pb}/^{235}\text{U}$ age results, from phengite-bearing eclogite samples from the Xitieshan terrane.

as sample 9x5-3 with low Th/U ratios between 0.01 and 0.09 (Appendix Table 1). Thirteen analyses from sample 9x5-4 form an approximately concordant population and define a mean $^{206}\text{Pb}/^{238}\text{U}$ age of 427 ± 2 Ma (MSWD = 0.018; Fig. 5b and Appendix Table 1).

CL imaging of zircon from sample 9x12-2 reveals different patterns from the former two samples. The zircon core and mantle show inhomogeneous CL gray-level intensities and faded fir tree and/or cloudy microstructures. Most zircon grains are surrounded by a bright, 1–10 μm thick, luminescence rim too thin for dating. These microstructures imply multi-stage metamorphic growth (Fig. 3c). Nineteen analyses of core and mantle zircons from sample 9x12-2 yielded $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 416 ± 3 Ma to 433 ± 3 Ma and define a concordant age of 424 ± 2 Ma (MSWD = 7.3, Fig. 5c). The latter age results are similar to the U–Pb ages obtained from the other two eclogite samples. REE patterns of zircon from sample 9x12-2 are typical for metamorphic zircon (Fig. 5c) with low Th/U ratios (0.01–0.03) and lack of negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.85\text{--}1.36$, only two analyses lower than 0.95; Appendix Table 3).

5.2. U–Pb zircon ages of gneiss

Zircon grains recovered from the kyanite-bearing garnet biotite gneiss 8x32-7 are colorless and oval shaped with long axes of 20–80 μm and length/width ratios between 1 and 1.5. A few calcite and quartz inclusions were identified. CL images exhibit stubby textures of “fir-tree” sector zoning, planar growth banding and radial sector zoning (Fig. 4a). Most zircon grains have a narrow (<10 μm), dark CL luminescent outer rim that is too thin for analysis, reflecting a later thermal event associated with the established HP–UHP metamorphism at 420–460 Ma. Isotopic dating of zircon from sample 8x32-7 yielded concordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages of $902 \pm 7\text{--}941 \pm 30$ Ma with a weighted mean of 917 ± 2 Ma ($n = 16$, MSWD = 3.2; Fig. 6a and Appendix Table 2).

Sample 8x18-1 contains clear, euhedral or subhedral zircon with long axis lengths of 10–100 μm and length/width ratios between 1 and 6. Garnet and rutile inclusions have been identified in zircon rims while quartz, rutile and calcite were found in the cores. The CL

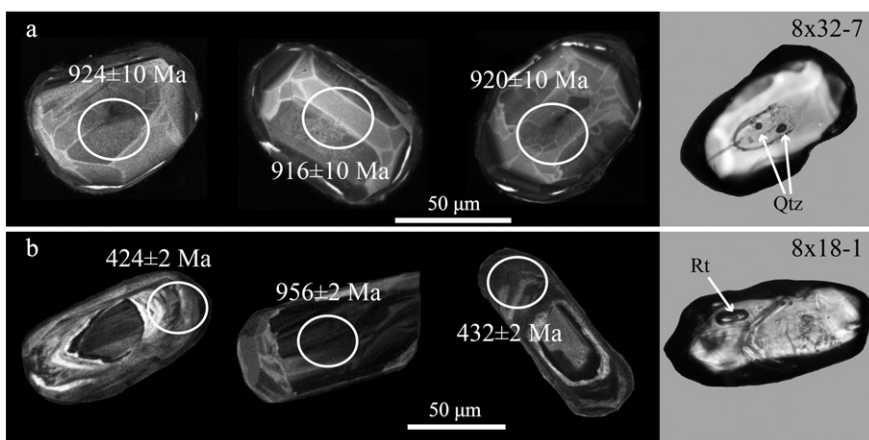


Fig. 4. Representative cathodoluminescence (CL) images (left side) and optical photomicrographs (right side) of zircons, showing mineral inclusions, location of analyzed spots and $^{206}\text{Pb}/^{235}\text{U}$ age results, from pelitic gneiss samples from the Xitieshan terrane.

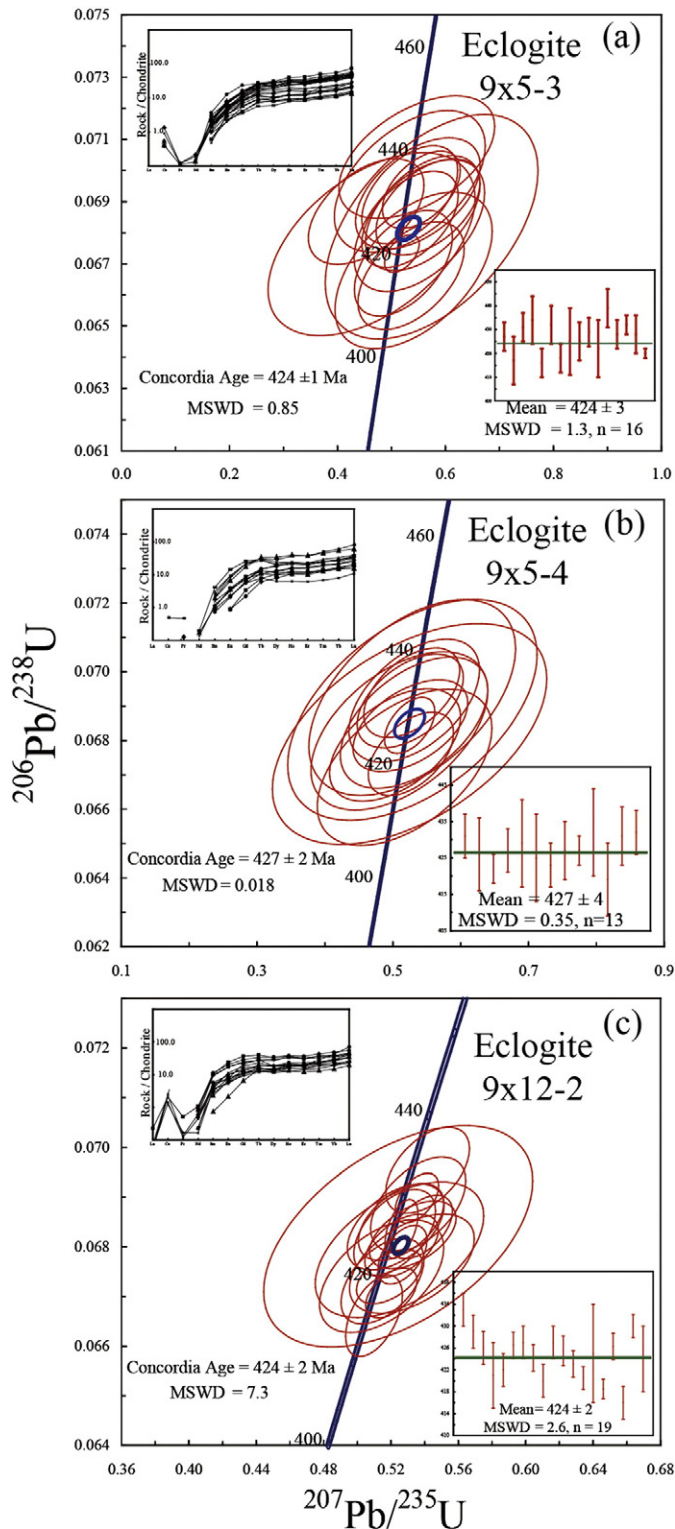


Fig. 5. LA-ICP-MS U–Pb ages and chondrite-normalized REE distribution patterns of zircons from phengite-bearing eclogite samples 9x5-3 (a), 9x5-4 (b), 9x12-2 (c).

investigations revealed conspicuous core–rim textures in most of the zircon grains. The cores are characterized by dark luminescence, cloudy or banded patterns (Fig. 4b) and higher Th/U ratios of 0.10–0.27 (Appendix Table 2), compared to their rims (0.01–0.04). Most zircon rims are narrow (5–10 μm), but some of them are wide enough for U–Pb isotope analyses (Fig. 4b). Their CL images show medium to bright luminescence with patchy or anomalous patterns. Th/U ratios

are 0.01–0.04. U–Pb isotope analyses of zircon from sample 8x18-1 yielded an upper intercept at 920 ± 25 Ma and a lower intercept at 424 ± 18 Ma with MSWD of 0.69 (Fig. 6b).

These U–Pb isotope ages, in combination with zircon UHP ages ranging between 460–420 Ma from garnet peridotite, eclogite and metapelite from other locations in the north Qaidam UHP belt and already published in the literatures (e.g. Mattinson et al., 2006b; Zhang et al., 2006; J.X. Zhang et al., 2008; Song et al., 2011; Zhang et al., 2011a, 2012), suggest that the eclogites and country rock gneisses from the North Qaidam UHP metamorphic belt have experienced at least two major epochs of metamorphism temporarily correlated with Grenville- and Caledonian-age events.

6. Discussion

6.1. The Paleozoic multi-stages metamorphism in the Xitieshan terrane

Since the discovery of coesite and diamond in orogenic belts (Chopin, 1984; Smith, 1984; Sobolev and Shatsky, 1990), more than twenty UHPM terranes have been documented on earth (Carswell and Compagnoni, 2003; Liou et al., 2004; Ernst et al., 2007; Liou et al., 2009; Dobrzynetska et al., 2011). On the basis of petrological, geochemical, mineralogical, structural and geochronological characteristics of the eclogites, peridotites and their country rock gneiss exposed in most of these UHPM belts, such as the Dabie–Sulu terrane in China (Jahn et al., 1996; Zheng, 2008), Western Gneiss Region of Norway (Carswell and Cuthbert, 2003; Hacker et al., 2010) and Kokchetav massif of Kazakhstan (Sobolev and Shatsky, 1990; Kaneko et al., 2000; Maruyama and Parkinson, 2000), they are interpreted to have formed by continent–continent collisions. Such UHP belts define fossil Alpine-type collisional plate margins. The spatial and temporal distribution of eclogite, garnet peridotite, (U)HP gneiss versus the immediately adjacent, though less subducted and severely metamorphosed, continental crust may indicate that previously extended continental lithosphere was subducted and ultimately collided with the continental crust located at the other side of the intermediate ocean after the oceanic lithosphere has been eliminated. Final continental subduction/collision is always followed by exhumation most commonly as coherent, buoyant UHP rocks bounded by major faults located at the top of the deeply subducted continental crust (Zheng et al., 2003; Brueckner and Van Roermund, 2004; Liu and Liou, 2011). In contrast, other UHPM terranes in the world, such as the Zermatt–Saas zone of the western Alps and the Chinese western Tianshan are thought to have formed by subduction/collision involving an oceanic lithospheric sequence (e.g. Zhang et al., 2002a,b, 2003; Bucher et al., 2005; Zhang et al., 2007; Lv et al., 2008). As stated in the introduction, the strike of the latter may define a fossil Pacific-type convergent plate margin. However a consequence of modern plate tectonic theory is that Pacific-type plate margins ultimately will be replaced/succeeded by Alpine-type collisional belts.

In the North Qaidam UHP metamorphic belt, the lithological assemblage of granitic and pelitic gneiss intercalated with minor eclogite and garnet peridotite and the presence of coesite and/or diamond in both, country rock gneiss and eclogites/peridotite, has led to the interpretation that the North Qaidam UHPM belt was formed by deep subduction of a previously extended, passive continental margin (e.g. Song et al., 2006; Yang et al., 2006). On the other hand, based on petrological and geochemical data, G.B. Zhang et al. (2008) reconstructed an ophiolite fragment using the protolith compositions of eclogite and serpentized harzburgite from outcrops located along the Shaliuhe cross-section in the Dulan UHPM terrane. In other words, G.B. Zhang et al. (2008) argue for an oceanic crustal origin within the North Qaidam UHPM belt. These contradicting ideas raised the intriguing and long disputed controversy whether the North Qaidam UHPM belt was primarily formed by subduction/collision between oceanic–continental or continent–continent crustal fragment. In this respect, several models have

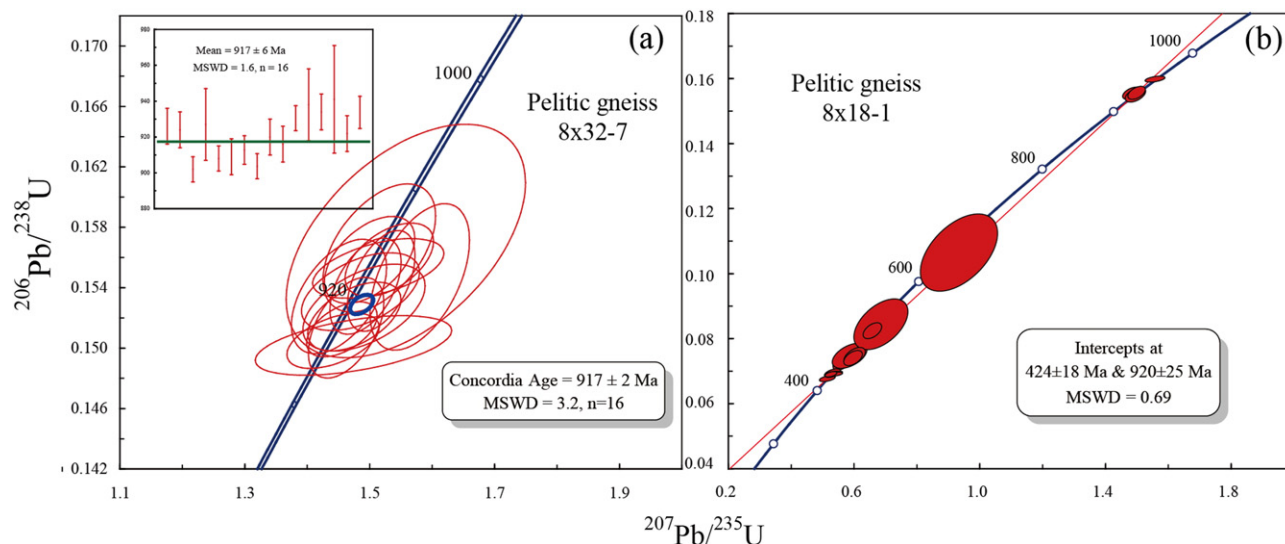


Fig. 6. Concordia- and weighted mean age diagrams showing results of LA-ICP-MS analyses of metamorphic zircons from pelitic gneiss 8x32-7 (a) and samples 8x18-1 (b). Chondrite abundances were taken from Sun and McDonough (1989).

been proposed to discuss the tectonic evolution of the North Qaidam UHPM belt (e.g. Song et al., 2006; Yang et al., 2006; Yin et al., 2007). Some models suggest that prolonged subduction of continental crust has continued during about 15–25 Ma (e.g. Mattinson et al., 2006b; Zhang et al., 2010), but other models suggest oceanic subduction is followed by continental collision late in the early Paleozoic (e.g. Song et al., 2006; G.B. Zhang et al., 2008). The reliability of the tectonic models depends on the interpretation of the geochronological data and, more importantly, the interpretation of the nature and ages of the eclogitic protoliths.

In order to decipher the Paleozoic tectono-metamorphic geodynamic evolution and to further constrain the nature of eclogite protoliths in the North Qaidam UHPM belt, we have presented in this paper new geochronological data from zircon extracted from eclogite and associated pelitic gneisses. Metamorphic zircons from three dated Phn-eclogite samples from the Xitieshan terrane contain inclusions of garnet and rutile (Fig. 3). These mineral inclusions demonstrate that the dated zircons may reflect eclogite facies metamorphism (e.g. Casado et al., 2001; Mukherjee and Sachan, 2001). The flat HREE patterns and the absence of Eu anomalies further indicate that these zircon grains grew under eclogite facies conditions i.e. during zircon growth in the absence of plagioclase and in the presence of garnet (Rubatto, 2002; Whitehouse and Platt, 2003). Furthermore, trace element patterns of zircon, used to calculate the weighted mean U–Pb ages, are similar to those of coesite-bearing zircons recently described by Liu et al. (2012) and therefore suggest the possibility that the metamorphic U–Pb ages of the investigated zircons, collected from eclogites, may even date the UHP stage. From our LA-ICP-MS zircon data, including the critical mineral inclusions and REE patterns of zircon, it is evident that the U–Pb ages of 421 ± 1 Ma, 427 ± 2 Ma and 424 ± 2 Ma obtained from zircons from eclogite, date the eclogite facies or, maybe, even UHP metamorphism in the Xitieshan terrane. The 424 ± 18 Ma lower intercept age of the associated country rock with low Th/U ratios (0.01–0.04) points to contemporaneous metamorphism with the enclosed eclogites.

The exact timing of the UHPM in the Xitieshan terrane is a matter of debate. Several researchers have proposed that the rocks underwent eclogite facies metamorphism at 460–440 Ma or even earlier (Zhang et al., 2005, 2006; Zhang et al., 2009c). The ages presented in this paper are slightly younger and substantiate recently published ages of 433 ± 3 Ma (bimineralic eclogite; Song et al., 2011) and 432 ± 14 Ma (coesite-bearing retrograded eclogite; Liu et al., 2012). Both U–Pb zircon ages were interpreted to reflect continental subduction/collision and

are consistent within errors with the age results from eclogites investigated in this study. A 437 ± 6 Ma SHRIMP zircon age from garnet- and sillimanite-bearing biotite gneiss may reflect the same event (Zhang et al., 2009c). There are even some eclogite samples that preserve evidence for two stages of early Paleozoic metamorphic growth within their zircon grains. Zhang et al. (2011a) reported metamorphic ages of ca. 461 ± 4 Ma and 440 ± 5 Ma from the same bimineralic eclogite sample from the Xitieshan terrane. Earlier, Zhang et al. (2009c) distinguished 452 ± 12 Ma and 430 ± 3 Ma U–Pb zircon ages from a metabasic rock and interpreted this as the timing of HP granulite facies metamorphism and a subsequent amphibolite facies overprint implying no eclogite facies zircon relicts were present in the sample. This metabasic rock, however, does not show compelling evidence for HP granulite facies metamorphism, e.g. the matrix plagioclase–diopside–symplectite is (most likely) not in equilibrium with the garnet rim, but this mineral assemblage was nevertheless used for geothermobarometric calculations. Furthermore, zircon is a rather stable accessory mineral and therefore primary metamorphic crystals, formed during UHP metamorphism, do not tend to be overgrown and/or dynamically recrystallized during decompression as long as partial melting does not occur and/or the eclogite does not deform (Song et al., 2011). Therefore, the U–Pb zircon age of 452 ± 12 Ma, described above, may not have to represent HP granulite facies conditions but more likely may date the eclogite facies metamorphism. Although amphibolite facies retrogression is able to modify the outer rim of an eclogite facies zircon, it is unlikely to have totally reset the U–Pb age (Liu and Liou, 2011). Alternatively, the U–Pb zircon age of 430 ± 3 Ma may also represent the eclogite facies metamorphism in consistency with our own and recently published U–Pb UHP zircon ages from Xitieshan zircons (Song et al., 2011; Liu et al., 2012). Moreover, the same kind of zircon may sometimes preserve two stages of eclogite facies metamorphism. This has been demonstrated recently in zircons collected from the Dulan terrane (Song et al., 2014). The latter clearly demonstrates that some of the North Qaidam eclogites may record multi-stage metamorphic events formed during the course of a single, early Paleozoic, orogenic event.

Summing up, the early Paleozoic metamorphic ages obtained from zircon collected from North Qaidam UHP metamorphic rocks can be sorted into two specific age groups: 1) ca. 460–440 Ma and 2) ca. 440–420 Ma. These two age groups can be interpreted to reflect subduction of oceanic crust (group 1) followed by subsequent continental subduction/collision (group 2) (Song et al., 2006). So far, fragments of subducted oceanic crust, comparable to the metamorphosed ophiolite

sequence in the Dulan area, have not been identified in the Xitieshan terrane. However, eclogite with a U–Pb zircon protolith age of 516 ± 8 Ma and an associated ultramafic rock assemblage have been identified in the adjacent Dulan terrane and interpreted as a fragment of an ophiolite, reflecting oceanic crust subduction (G.B. Zhang et al., 2008). Subduction of oceanic crust in the Dulan area is dated ca. 445 ± 7 Ma, within the 440–460 Ma age range defined by the two specific age groups described above. Almost all of the reliably dated zircon grains in the age range of 440–460 Ma from Xitieshan eclogite do not preserve Proterozoic U–Pb protolith ages in their cores (Zhang et al., 2009c, 2011a). The latter can be regarded as another remarkable phenomenon substantiating that the age of 440–460 Ma actually may represent oceanic subduction in the Xitieshan terrane. In addition, a continent–continent subduction/collision event will always take place after oceanic lithosphere subduction (e.g. Niu et al., 2003 and references therein). The trigger for continental lithosphere subduction/collision is thought to be the pulling force caused by the dense oceanic lithosphere that was previously subducted into the mantle (Brueckner and Van Roermund, 2004). Therefore, a transition from oceanic to continental subduction necessarily occurs within the domain of a subduction zone system. Although it does not form part of the same orogenic belt, the ca. 445 Ma Qilian suture zone, located northeast of the North Qaidam UHPM belt, is thought to be the major occurrence of exhumed oceanic crust of the same Paleozoic North Qaidam subduction system (Song et al., 2013 and references therein). Similar decoupling is also recognized in the Himalaya orogen (e.g. de Sigoyer et al., 2000; Mukherjee and Sachan, 2001; O'Brien et al., 2001).

The 440–420 Ma age range is widely recorded in the Xitieshan terrane eclogites and interpreted to represent continental lithosphere subduction (e.g. Zhang et al., 2009c; Song et al., 2011; Zhang et al., 2011a; Liu et al., 2012). Some pelitic gneisses adjacent to the Xitieshan eclogites have contemporary early Paleozoic U–Pb zircon ages of around 437–424 Ma (Zhang et al., 2009c, 2012 and this study) that are interpreted to reflect continental subduction. Metamorphic ages of 451–461 Ma were also obtained from zircon from a pelitic gneiss (Zhang et al., 2006), which, however, may reflect in this particular case either metamorphosed terrigenous sediment deposited in a fore-arc or accretionary wedge geometry that captured some fragments of oceanic crust or ocean floor sediment. A U–Pb age of 431 ± 3 Ma, obtained from zircon rims from a granitic gneiss from the nearby Yuka terrane, provides further evidence for the 440–420 Ma continental subduction/collision event in the North Qaidam UHPM belt (Zhang et al., 2006).

As discussed above the variable nature of the eclogitic protoliths allows for another method, which uses the zircon microstructure in combination with the U–Pb ages, that can be used as a tool to subdivide eclogitic protolith types into two groups: i.e. 440–420 Ma zircon U–Pb ages in combination with the presence (or absence) of Proterozoic magmatic zircon cores. This topic will be discussed in detail in the following section.

6.2. The Neoproterozoic metamorphism and its geological significance

From the early Paleozoic U–Pb metamorphic ages preserved in zircon rims discussed above and the presence or absence of Proterozoic magmatic zircon cores, we may deduce that the protoliths of the Xitieshan eclogite stem from various environments including Paleozoic oceanic crust and/or Neoproterozoic material of controversial nature. According to Zhang et al. (2005, 2006) igneous precursors of eclogite that contain roughly 750–800 Ma U–Pb ages in zircon cores, were formed either in an (initial) oceanic basin or in a continental rift setting. In an alternative model, based on low-Ti contents and positive ε_{Nd} -values, Yang et al. (2006) interpreted the eclogite protolith as a Proterozoic ophiolite fragment attached to the juvenile continental crust that together as a coherent slice became subducted, deformed and (U) HP-metamorphosed during the early Paleozoic. Though geochemical

studies of all Xitieshan eclogite showed that they share MORB signatures (e.g. Meng et al., 2003; Zhang et al., 2005; Yang et al., 2006; C. Zhang et al., 2013), this geochemical fingerprint does not necessarily imply an oceanic formation environment because MORB signatures are also observed in mafic rocks that intruded continental crust during initial rifting (e.g. Herzig and Jacobs, 1994; Leventhal et al., 1995; Rubatto et al., 1998; Casado et al., 2001).

On the basis of mineral content, two types of eclogite have been identified in the Xitieshan terrane, i.e. biminerale and phengite-bearing eclogite (C. Zhang et al., 2009). Both types show different geochemical and isotopic characteristics (C. Zhang et al., 2013). Some Bim-eclogites are characterized by low Ti contents and low I_{Sr} ratios preserve both an eclogite protolith U–Pb zircon age of 877 Ma and a continental lithosphere subduction U–Pb zircon age whereas other Bim-eclogites, characterized by high Ti contents and high I_{Sr} ratios, only show in their U–Pb zircon record the 440–460 Ma oceanic subduction ages but the Neoproterozoic zircon cores are lacking (Zhang et al., 2011a). The phengite-bearing eclogite with continental subduction ages studied in this contribution also have no magmatic zircon cores.

According to the discussion above, we propose that the protoliths of the Xitieshan eclogite at least have three different origins: 1) Paleozoic oceanic lithosphere 2) Neoproterozoic intrusions into continental crust and 3) Neoproterozoic mafic–ultramafic ophiolite fragments. The Neoproterozoic intrusions into the continental crust (ca. 877 Ma) may be related to the initiation of the break-up of Rodinia. The ca. 850 Ma mantle plume-related geothermal event in the adjacent Yuka area and the 838 ± 50 Ma protolith age of the coesite-bearing eclogite substantiate this interpretation (Chen et al., 2009; Song et al., 2010; Zhang et al., 2010). The protolith of the Neoproterozoic mafic–ultramafic ophiolite fragment was also formed during the opening of an ocean related to break-up of the supercontinent Rodinia.

Internal CL microstructures of zircons from the pelitic gneiss sample 8x32-7 resemble those of zircons formed by high-grade (granulite facies) metamorphism (e.g. Vavra et al., 1996). The 902–941 Ma metamorphic LA-ICP-MS U–Pb ages (weighted mean 917 ± 2 Ma) together with the 920 ± 25 upper intercept age obtained from another gneiss sample in this study, should represent a high-grade metamorphic event in the Neoproterozoic, in agreement with metamorphic U–Pb zircon ages of ca. 890 Ma (J.X. Zhang et al., 2008), 945 ± 7 Ma (Zhang et al., 2012) and 928 ± 12 Ma (Song et al., 2012) from pelitic gneisses from the Xitieshan terrane. These pelitic gneiss formed part of the country rocks of the eclogite. The rock-forming minerals garnet and kyanite either grew during Grenville-age high-grade- or during Paleozoic UHP metamorphism. Zircon from a number of pelitic gneisses have no or contain only very thin rims; an appearance typical for high-grade metamorphism, suggesting that the sediment might have already been metamorphosed into a pelitic gneiss during the Neoproterozoic Grenville orogeny. The metamorphic zircon growth was hampered during the Caledonian-age UHP metamorphism because of the relatively dry conditions during continental collision (Song et al., 2010, 2012; Zhang et al., 2012). The contemporaneous (ca. 1000–900 Ma) granitic gneiss, which forms the major component of the North Qaidam UHP metamorphic belt, is spatially restricted within the same narrow limited area as the pelitic gneiss (e.g. Mattinson et al., 2006a; J.X. Zhang et al., 2008; Song et al., 2012). Therefore, the Neoproterozoic Grenville-age metamorphism and the magmatic belt occurred coevally and most probably form remnants of an active continental margin (Song et al., 2012, 2014; Yu et al., 2013).

The extend of the Grenville orogeny, defined as a worldwide orogeny formed in the time span 1300–900 Ma, has been outlined on a geographical map illustrating the global outline of the former supercontinent Rodinia (Fig. 12 in Rino et al., 2008). Its major phase, recorded in the Grenville Province of southern Laurentia, in the Albany–Fraser and Musgrave orogenies of central Australia and the Sibao orogeny of southern China, ranges from around 1.3 to 1.0 Ga (e.g. Borg and DePaolo, 1994; Li et al., 2002; Davidson, 2008). The ca. 1.0–0.9 Ga orogeny

preserved in the North Qaidam orogen is a bit younger but comparable with the 1.0–0.9 Ga high-grade metamorphism in the Rayner Province of eastern Antarctica, the eastern Ghats belt of India (Fitzsimons, 2000; Kelly et al., 2002) or the Sveconorwegian domain in SW Norway. The ~950–900 Ma volcanism at the northern margin of the Yangtze Craton and the ~983–873 Ma granitic gneisses of the Qinling micro-continent (Bader et al., 2013 and therein; Ling et al., 2003; Lu et al., 2005) are contemporary with the magmatism in the North Qaidam belt; it most probably experienced a Grenville-age orogeny and was a part of the supercontinent Rodinia together with the Yangtze Craton and the Qinling micro-continent. Speculatively, it could have been the western extension (modern coordinates) of the latter in the Neoproterozoic.

6.3. The tectonic evolution of the North Qaidam UHPM belt

Published and new geochemical and geochronological data demonstrate that the North Qaidam UHPM belt records at least two major orogenies, one during the Neoproterozoic and another in Early Paleozoic times. The Neoproterozoic Grenville-age orogeny reflects the amalgamation and break-up of the supercontinent Rodinia (Fig. 12 in Rino et al., 2008) while the Early Paleozoic Caledonian-age orogeny revealed a complex scenario with transitions from oceanic subduction to continental subduction and collision. Due to the similar Proterozoic basement characteristics and a Caledonian-age orogenic overprint, the Qilian suture zone and the North Qaidam UHPM belt are usually investigated together (Song et al., 2012 and references therein). Several tectonic models of the early Paleozoic evolution of the North Qaidam UHPM belt are presented in the literature (Yang et al., 2002; Song et al., 2006; Mattinson et al., 2007; Yin et al., 2007). Based on geochronological investigations, Yang et al. (2002) concluded that the North Qaidam UHPM belt and the North Qilian oceanic suture zone were two independent subduction zones. In contrast to that, Song et al. (2006) proposed that there is no need for the existence of two

independent subduction zones but that the overall orogenic picture evolved from oceanic subduction to continental collision.

Based on the data presented in this paper, a similar integrated tectonic model is proposed in this contribution. This model, illustrated in Fig. 7, demonstrates the complex multiple-stage orogenic evolution of the North Qaidam UHPM belt from the Neoproterozoic to the early Paleozoic. The tectonic model is based on the data presented in this paper and previous literature and can be summarized by the following 6 steps described below:

- 1) The Neoproterozoic Grenville-age orogeny assembled the supercontinent Rodinia at ca. 1000–900 Ma.
- 2) As the eclogites exposed in the North Qaidam UHPM belt have clearly distinct Neoproterozoic origins, two stages, here called 2a and 2b, are proposed here to illustrate the orogenic evolution in the time span between ~900 Ma and ~750 Ma.
- 2a) The initial breakup of the supercontinent, which may have been triggered by mantle plume activities or some other unknown process, causing the intrusion of mafic rocks into the continental crust.
- 2b) Rifting was followed by spreading and ocean floor formation separating continental segments of the former supercontinent Rodinia. During subsequent subduction fragments of Neoproterozoic oceanic crust became emplaced onto the continental crust.
- 3) A Paleozoic ocean, here called the Qilian Ocean, was formed around ca. 520 Ma.
- 4) The oceanic crust was subducted at 460–440 Ma. Outside the North Qaidam UHPM belt this event is also recorded by the North Qilian suture zone; within the North Qaidam UHPM belt it is recorded in the Shaliuhe section of the Dulan terrane.
- 5) Following oceanic subduction, a continental crustal fragment that formerly was attached to the NE side of the South China Craton and that already incorporated embedded Neoproterozoic oceanic fragments probably collided (at 440–420 Ma) with North China

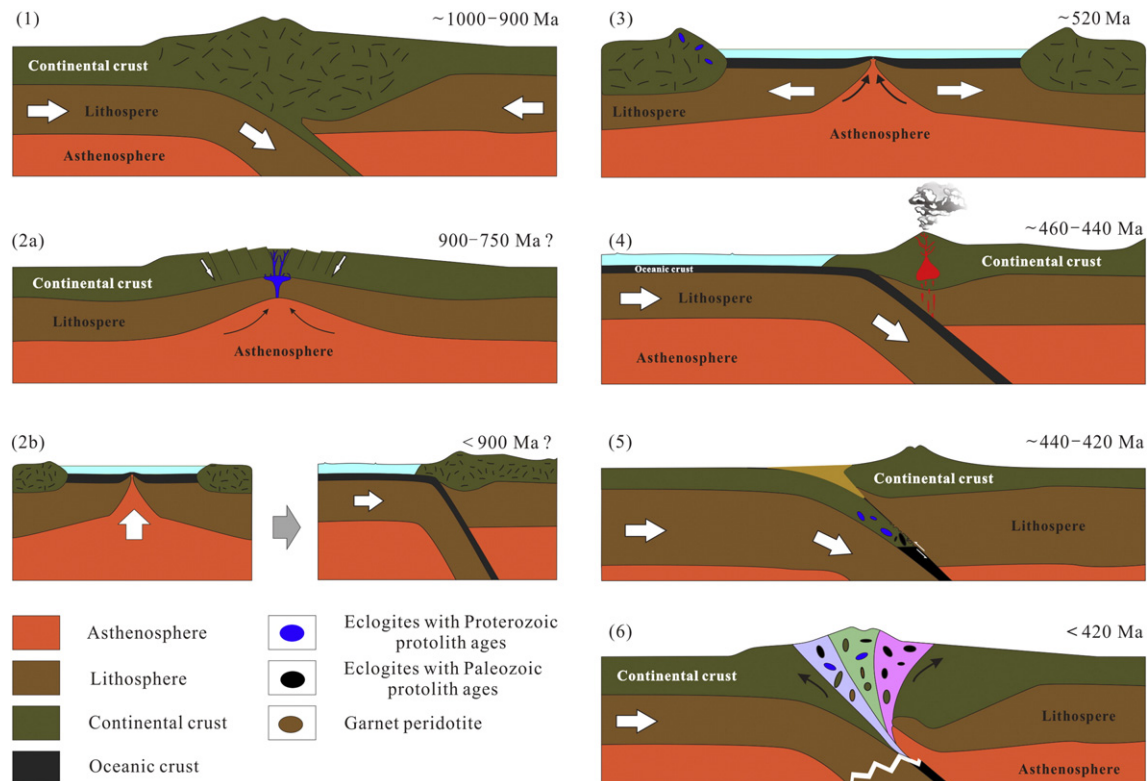


Fig. 7. Model illustrating the proposed tectonic evolution of the North Qaidam orogenic belt from the Neoproterozoic to the early Paleozoic. See text for further details.

Craton. Parts of the already exhumed Paleozoic oceanic material might have been trapped by the subducting continental crust. As a result it experienced multi-stage metamorphism in the early Paleozoic.

- 6) The oceanic slab broke off from the subducting continental lithosphere and the (U)HP unit consisting of eclogites having multiple precursors, garnet peridotite from the mantle wedge and associated country gneisses were exhumed after ca. 420 Ma. Exhumation from mantle depths was enhanced by the buoyancy force of the dominant subducted country rock gneiss.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.gr.2015.04.011>.

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