Early Paleozoic polyphase metamorphism in northern Tibet, China

Abstract The Altun–Qilian–Kunlun orogenic system in the northern Tibetan Plateau is considered as the northernmost orogenic collage of the proto-Tethyan domain. Early Paleozoic polyphase tectonothermal events related to the subduction of the proto-Tethyan ocean and subsequent collisional orogeny produced two dominant metamorphic belts: the North Altun (NAT)–North Qilian (NQL) HP/LT metamorphic belt, and south Altun (SAT)–north Qaidam (NQD) UHP metamorphic belt. The NAT–NQL HP/LT metamorphic belt mainly consists of blueschist, eclogite and HP metasediments. Eclogites record metamorphic conditions of 420–550 °C and 21–25 Kbar, at 510–460 Ma. The HP/LT metamorphic belt is associated with ophiolite, subduction-accretion complex, and arc magmatic rocks, suggesting that the NAT–NQL is a typical early Paleozoic accretionary orogenic belt. In contrast, the SAT–NQD UHP metamorphic belt is characterized by eclogite and garnet peridotite enclosed within continental orthogneiss and paragneiss. These rocks record UHP metamorphism at $T > 700$ °C and $P > 27$ Kbar. Geochronology suggests that the UHP metamorphism occurred at 500–423 Ma, and eclogite protolith ages of 850–750 Ma suggests protoliths are related to Neoproterozoic continental rifting. Field relationships, petrology and geochronology suggest that the SAT–NQD UHP metamorphic belt resulted from the deep subduction of continental crust. Moreover, in the SAT–NQD

UHP metamorphic belt, two types of HP granulites have been recognized. The first type of HP granulite was formed by overprinting of eclogites during exhumation. The second type of HP granulite has a single metamorphic history and similar age to that of UHP eclogite. Penecontemporaneous metamorphic ages but different geothermal gradients between HP granulites and related UHP eclogite define a possible paired metamorphic belt, which may be considered to be a diagnostic characteristic of collisional orogens. High grade metamorphic rocks in the SAT–NQD commonly record Barrovian type metamorphism, although it remains unclear whether or not all of these rocks have an earlier (U)HP metamorphic history. The low-medium-P Barrovian metamorphism and associated magmatism are about 20–50 Ma later than UHP metamorphism. Newly recognized eclogites in the northern part of the East Kunlun Mountains, to the south of Qaidam basin, have a similar field relationship (enclosed in continental gneiss) and mineral assemblage to the NQD eclogites, and a similar or slightly younger metamorphic age (410–430 Ma). The occurrence of similar continental type eclogites on two sides of the Qaidam basin makes it necessary to reconsider the nature of the Qaidam block. The polyphase metamorphism in northern Tibet can be linked to accretion and collisional orogenesis related to the evolution of Prototethys through the early Paleozoic.

Key words: Early Paleozoic, Northern Tibet, polyphase metamorphism, accretion, collision, Prototethys

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1. Introduction

The (Qinghai–) Tibetan Plateau generally consists of three huge orogenic systems, which are the early Paleozoic Altyn Tagh (Altun)–Qilian–Kunlun (AQK) orogenic system in northern Tibet, the late Paleozoic–Early Mesozoic Qiangtang–Sanjiang orogenic system in middle Tibet, and the late Mesozoic–Cenozoic Gangdese–Himalaya orogenic system in southern Tibet (e.g. [Pan et al., 2012](#)). These orogenic systems are related to the evolution of the proto-Tethyan ocean, Paleo-Tethyan ocean and Neo-Tethyan ocean, respectively.

The AQK orogenic system in the northern Tibetan Plateau is considered as the northernmost orogenic collage of the proto-Tethyan domain. In contrast to the central Asia orogen to the north characterized by long-lived accretionary processes ([Sengör et al., 1993](#); [Jahn, 2001](#); [2004](#); [Xiao et al., 2006](#)), the architecture of these Tethyan orogenic collages is commonly regarded as resulting from collisions between various continental terranes (fragments) derived from the northern margin of Gondwana ([Chang et al., 1986](#); [Sengör, 1987](#); [Dewey et al., 1988](#); [Matte et al., 1996](#); [Dilek and Moores, 1999](#); [Tapponnier et al., 2001](#); [Spurlin et al., 2005](#); [Gehrels et al., 2011](#), [Stampfli, 2013](#), [Zhang Z et al., 2014](#)). However, some authors suggest that northern

Tibet experienced a typical accretionary orogeny characterized by the development of an evolving arc-accretion complex growing southward along the margin of the Tarim and north China Craton during Paleozoic time (Sengör, 1993, Sengör and Natal'in, 1996; Gehrels et al., 2003a and b; Yin et al., 2007; Xiao et al., 2009). Therefore, Early Paleozoic accretion vs. collision in north Tibet remains a controversial issue.

In the past decade, the early Paleozoic metamorphism in northern Tibet has become a major research topic since ultrahigh-pressure (UHP) eclogite and associated metamorphic rocks have been found (Yang J.S. et al., 1998, 2001; Song et al., 2003, 2004, 2005; Zhang J. et al., 2001a; 2002; Liu et al., 1996, 2002; Yang J.J., 1994). Abundant studies have revealed various metamorphic rocks including high-pressure (HP)/low-temperature (LT) metamorphic rocks, UHP metamorphic rocks, HP granulites and low-medium pressure metamorphic rocks, which record a polyphase tectonometamorphic evolution in northern Tibet (Yang J.S. et al., 2003; Song et al., 2005, 2006, 2009, 2013, 2014a; Zhang J. et al., 2005a, 2006, 2009a, 2010, 2014; Liu et al., 2012; Yang J.J., 2008; Zhang G., 2013, Zhang C., 2011, 2015; Yu et al., 2011, 2012, 2014, 2015). These metamorphic rocks hold important insights for early Paleozoic orogenesis in northern Tibet.

In this contribution, based on published and our new data, we present a synthesis of the geological, petrological, chronological studies of early Paleozoic metamorphic rocks in northern Tibet. These data allow a relatively detailed insight into the polyphase tectonometamorphic history and associated orogenesis including subduction-accretion, collision, and orogenic collapse in northern Tibet during the early Paleozoic.

2. Tectonic outline of early Paleozoic orogenic systems in northern Tibet

The early Paleozoic Altun–Qilian–Kunlun (AQK) orogenic system in northern

Tibet extends in a WNW–ESE direction for ~1000 km, and is bounded to the north by the Alxa block and to the south by the late Paleozoic-Mesozoic South Kunlun–Qiangtang–Ganze orogenic system (Fig. 1). This orogenic system was cut by the Altyn Tagh fault. Abundant evidence supports the interpretation that the main geological units in the Altun Mountains are the western extension of those in the Qilian–North Qaidam Mountains. Therefore, on the basis of geologic mapping and lithotectonic characteristics, the AQK orogenic system can be subdivided into four tectonic units: the North Altun–North Qilian subduction-accretion complex, the Qilian–Central Altun micro-continental block, the North Qaidam–South Altun subduction-collision complex, and the Qaidam–North Kunlun block (Fig. 1).

The North Altun (NAT)–North Qilian (NQL) subduction-accretion complex is an elongate, WNW–ESE trending belt that lies between the Alxa block–Dunhuang block to the north and the Qilian (QLB)–Central Altun (CAB) microcontinental block to the south (Fig. 1). The Altyn Tagh fault separates this belt into two parts: the NAT and the NQL. The NAT subduction-accretion complex, which is discontinuously exposed along the northeastern part of the Altyn Tagh from Hongliugou to Lapeiquan, consists mainly of clastic and volcanic rocks with rare mafic and ultramafic intrusive rocks. Well-preserved pillow lavas and serpentinized ultramafic rocks suggest that these rocks are part of an ophiolite suite. A HP/LT metamorphic terrane, characterized by blueschist and eclogite, occurs as a tectonic block or slab in the subduction-accretion complex. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of eclogite and blueschist suggests that HP/LT metamorphism occurred at 490–512 Ma (Zhang J. et al., 2007a, see below). The NQL subduction-accretion complex consists of ophiolitic mélanges, HP/LT blueschists and eclogites, island-arc volcanic rocks with granite plutons, and Silurian flysch formations, which are unconformably covered by Devonian molasses and Carboniferous to Triassic sedimentary cover sequences (Xu et al., 1994; Zhang J. et al., 1998, 2012). The NQL is regarded as the product of subduction of an Early Paleozoic ocean plate between the Alxa block and Qilian block (Xiao et al., 1978; Xu et al., 1994; Zhang J. et al., 1998, 2012; Xia et al., 2003, Ker et al., 2015, described below).

The CAB-QLB is located between the NAT-NQL subduction-accretion complex and the North Qaidam–South Altun subduction-collision complex. The CAB consists of the Altun Group and Tashidaban (or Jinyanshan) Group. The Altun Group is comprised of amphibolite-facies quartzo-feldspathic gneisses, pelitic gneisses, marbles, and amphibolites, and was considered to represent Precambrian craton basement rocks of lower Proterozoic–Archean age (BGMX, 1993). However, recent radiometric data demonstrate that the Altun Group formed at 800–1000 Ma (e.g., Wan et al., 2001; Gehrels et al., 2003a; Zhang J. et al., 2011). The Tashidaban Group is dominated by mid- to upper Proterozoic metasedimentes that consist of thick carbonate-rich continental margin sequences containing variable amounts of volcanics and clastics.

The QLB, located between the NQL subduction-accretion complex and the NQD subduction-collision complex, consists mainly of Precambrian basement overlain by Neoproterozoic to Mesozoic sedimentary sequences. From west to east, the lower part of the basement is known as the (a) Yemananshan Group, (b) the Huangyuan and Hualong Groups and (c) the Maxianshan Group. The basement consists of paragneiss, granitic gneiss, marble, amphibolite and localized granulite. Granitic gneisses yield protolith ages of 950–870 Ma (Wan et al., 2001; Xu et al., 2007; Tung et al., 2007, 2012, 2013; Yu et al., 2013). The Precambrian basement rocks were partly reworked during early Paleozoic orogeny. The QLB was previously considered to be a fragment rifted from the North China craton, but recent geochemical and geochronologic data demonstrate that the metamorphic basement has a close affinity to the Yangtze craton (South China block; e.g. Wan et al., 2001, 2006; Tung et al., 2007) or Gondwana supercontinent (Tung et al., 2012, 2013; Yu et al., 2013). However, along the northern margin of the Qilian block, several Alaska-type, zoned mafic complexes and “I” type granites with an age of ca. 500 Ma (Zhang Q. et al., 1997; Wu et al., 2009; Huang et al., 2015; Zhang J. et al., unpublished data) have geological and geochemical features that indicate an origin related to the southward subduction of the north Qilian ocean (Gehrels et al., 2003a, b; Xiao et al., 2009). Moreover, a microcontinent fragment, called the Quanji massif (or Oulongbuluke microcontinent), is recognized in the

southern margin of the Qilian block (Lu et al., 2008; Gong et al., 2012; Chen et al., 2013; Liao et al., 2014). Compared to the other parts of the Qilian block, the Quanji massif has older metamorphic basement composed of Paleoproterozoic granitic gneisses, paragneisses, marbles and minor mafic granulites (e.g. Zhang J. et al., 2001b; Lu et al., 2008; Chen et al., 2013; Wang et al., 2015). The basement rocks are unconformably covered by Neoproterozoic to Mesozoic strata. The relation of the Quanji massif to other parts of the Qilian block remains unclear and further work is necessary.

The South Altun (SAT)-North Qaidam (NQD) subduction-collision complex, located between the CAB-QLB and Qaidam Block, consists mainly of para- and orthogneisses enclosing blocks of eclogite, garnet peridotite and mafic granulite. They thrust over, or are overlain by, lower Paleozoic volcanic and sedimentary rocks, and are intruded by granites. Eclogites and garnet peridotites in the SAT and NQD record UHP metamorphic conditions, and coesite-bearing paragneisses are also recognized in the Dulan area of the eastern NQD (Fig. 1; Yang et al., 2002; Song et al., 2003, 2005; Liu et al., 2002; Zhang J. et al., 2002, 2009b, 2010; Zhang G. et al., 2009a,b). Zircon U–Pb ages and Sm–Nd from paragneiss, eclogite, and peridotite of the SAT–NQD have been interpreted to record varying peak metamorphism between 423–500 Ma (Yang et al., 2001, 2002; Song et al., 2003, 2005, 2006; Zhang J. et al., 2001a, 2005a, 2008, 2010; Mattinson et al., 2006b, 2009; see below).

Although the Qaidam basin is covered by Cenozoic sediments, its basement has been considered as part of a rigid, stable craton consisting of Precambrian metamorphic basement coherent with high grade metamorphic rocks in the north Kunlun (NKL) (BGMQ, 1991). The metamorphic basement of the NKL consists of the Paleo- and Mesoproterozoic Jinshuikou Group, intruded by Neoproterozoic granites (e.g. Chen et al., 2006; Lu et al., 2006; He et al., 2015). Some data suggest that the Jinshuikou Group experienced early Paleozoic amphibolite-granulite facies metamorphic overprinting (Chen et al., 2006, 2007; Zhang J. et al., 2003). Recently, eclogite and retrogressed eclogite have been recognized in the high grade metamorphic rocks in the western and eastern NKL, and preliminary geochronology

yielded metamorphic ages of 411–430 Ma (Meng et al., 2013, Qi et al., 2014). These data imply that the metamorphic basement of the Qaidam–NKL block witnessed early Paleozoic orogeny (see below).

3. HP/LT metamorphism related to oceanic subduction

In northern Tibet, HP/LT metamorphic rocks are mainly distributed in two areas—North Qilian (NQL) and North Altun (NAT). For the two areas, we review key rock types, mineral assemblages, P–T estimates, and geochronology where available. Based on these data, we will then compare the two areas in order to identify common metamorphic and tectonic relations.

3.1. NAT HP/LT metamorphic rocks

The NAT HP/LT metamorphic rocks occur as a tectonic block or slab in the subduction-accretion complex (Zhang J. et al., 2005b, Fig. 2A). The HP/LT slab is elongate, 2–5 km wide and 40 km long, and is separated by a shear zone (fault) from ophiolitic mélangé (Fig. 2). HP/LT rock types include garnet- and chloritoid-bearing mica schist (metapelite), quartz-mica schist, calc-schist, and metabasite composed of eclogites and blueschists (Zhang J. et al., 2005b). Blueschist and eclogite pods occur within pelitic schist and calc-schist. Most eclogite and blueschist pods are elliptical and range in size from ~10 cm to ~10 m (Fig. 3). The long axis of the pods is parallel to the regional foliation. Some eclogite pods are characterized by folded, millimeter-scale alternating layers of eclogite and calc-schist (Fig. 3c).

Eclogite consists of garnet, omphacite, phengite and quartz with varying amounts of glaucophane, Ca–Na amphibole (barroisite), epidote (zoisite or clinozoisite), paragonite, chlorite, albite, carbonate and titanite. The alignment of omphacite, minor phengite, paragonite and quartz defines a foliation in the matrix as well as within the garnet (Fig. 4a). Some eclogites preserved relicts of lawsonite eclogite-facies

assemblages within garnet (Zhang and Meng, 2006). Blueschist is characterized by idioblastic garnets in a fine-grained matrix consisting of oriented glaucophane, barroisite, phengite, paragonite and quartz. The assemblage Grt + Gl + Phn + Pg + Qtz is volumetrically dominant, and is interpreted to represent the peak metamorphic assemblage. Chlorite and epidote occur as porphyroblasts, contain inclusions of relict glaucophane, and cut the foliation (Fig. 4b). Metapelite contains a peak-stage assemblage of Grt + Cld + Phn + Pg + Qtz in addition to retrograde albite + chlorite and accessory epidote, apatite, tourmaline and hematite (Fig. 4c and d). Oriented phengite and chloritoid define a foliation. In strongly overprinted domains, garnet is totally replaced by chlorite and hematite.

P–T estimates yield peak conditions of 430–540 °C, 20–23 Kbar for lawsonite-bearing eclogite (Zhang J. et al., 2007b; Zhang and Meng, 2006). Blueschists evaluated using bulk composition phase diagrams (pseudosections) yield lower peak P–T conditions of ~15 Kbar and 450–500°C (Lin et al., unpublished data). Phengite from eclogite yields a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 512 ± 3 Ma. Paragonite from blueschist sample gives a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 491 ± 3 Ma (Zhang J. et al., 2007a).

3.2. NQL HP/LT metamorphism

The north Qilian (NQL) HP/LT metamorphic belt lies in the middle segment of the north Qilian Mountains and extends for about 200 km along the NQL suture. It occurs as WNW-trending tectonic slices within arc-type volcanic and volcanoclastic rocks that experienced greenschist-facies metamorphism (Fig. 5). These slices are mainly composed of various metabasite (blueschists and eclogite) blocks within metasediments or locally within serpentinite, representing a deep unit of an accretionary wedge or a fossil subduction channel, which is separated from lightly metamorphosed volcanic-sedimentary sequences (Zhang J. et al., 1998).

Metabasites

The term "eclogite" is used for rocks in which the modes of garnet + omphacite are more than 70%, "eclogitic metabasite" for the rocks with < 70 % omphacite +

garnet, but are present as an equilibrium assemblage, and “blueschist” for metabasite with glaucophane but without omphacite.

Eclogites or eclogitic metabasites occur as pods or blocks (0.1–50 m in size) within blueschists and metasediments (Fig. 6). Some eclogites are also intercalated with blueschist layers on a centimeter to decimeter scale (Fig. 6b and c). The main constituent minerals of the eclogites and eclogitic metabasites are garnet, omphacite, quartz, epidote/clinozoisite, amphibole (glaucophane and actinolite) and white mica (mainly phengite but also locally paragonite), with small amounts of rutile, titanite, chlorite, albite, and opaque minerals (Fig. 7a and b). The idioblastic garnet typically contains inclusions of omphacite, epidote/clinozoisite, glaucophane, quartz and rutile. Minor lawsonite and abundant lawsonite pseudomorphs characterized by rectangular epidote/clinozoisite-paragonite intergrowths occur as inclusions within garnet of eclogites and eclogitic metabasites, and coexist with omphacite, glaucophane and quartz (Zhang and Meng, 2006; Zhang J. et al., 2007b). Peak-pressure conditions estimated from lawsonite-omphacite-phengite-garnet assemblages were 21–24 Kbar at temperatures of 420–510 °C, in or near the stability field of lawsonite eclogite (Zhang J., 2007b). In eclogites, the omphacite is fine-grained, subidioblastic, and together with phengite, glaucophane and clinozoisite constitutes the bulk of the rock matrix. These minerals define the eclogite facies foliation and lineation (Fig. 7a). Omphacite grains show undulose extinction and the formation of subgrains, indicating dynamic recrystallization related to deformation during eclogite-facies conditions. In retrogressed domains, omphacite is surrounded by secondary glaucophane, actinolite, epidote, phengite and paragonite, defining the blueschist-facies foliation and lineation. In strongly retrogressed domains, large actinolite and epidote porphyroblasts are oblique to the foliation. Garnet is partly replaced by chlorite, and the secondary glaucophane is partially replaced by Act + Ab. Chlorite and albite also occur in the fractures of garnets. Blueschists consist mainly of garnet and glaucophane with varying amounts of epidote, phengite, actinolite, chlorite, quartz and albite (Fig. 7c). Some blueschists are intercalated with eclogites, suggesting they experienced a common peak eclogite facies metamorphism, whereas some blueschists within

metasediments possibly experienced only a peak blueschist facies metamorphism before exhumation.

Metasedimentary rocks

HP metasedimentary rocks consist mainly of mica schist and metachert, with minor calc-schist and marble. All mica schists contain garnet and varying amounts of chloritoid, glaucophane and omphacite. Omp-bearing mica schists consist predominantly of garnet, glaucophane, omphacite, phengite and quartz with minor paragonite, rutile, epidote/clinozoisite and chlorite (Fig. 7d). Compared with eclogites and eclogitic metabasites, Omp-bearing mica schists are rich in quartz and phengite which define the schistosity. Rectangular epidote/clinozoisite, paragonite and quartz intergrowths, suggesting the former presence of lawsonite, were also observed in garnet of Omp-bearing mica schists (Zhang et al., 2007b). The oriented omphacite and glaucophane have straight grain boundaries, indicating textural equilibrium (Fig. 7d). Evidence of retrogression is indicated by the occurrence of chlorite, actinolite and albite in the fractures of garnet and omphacite. Using Grt–Cpx–Phe geobarometry and Grt–Cpx geothermometry, coexisting garnet, omphacite and phengite in Omp-bearing mica schists gave equilibrium conditions of 450–570 °C and 19–24 Kbar, consistent with those in eclogites (Zhang J. et al., 2012).

Glaucophane-bearing mica schists contain a mineral assemblage similar to Omp-bearing samples but omphacite is absent. Chloritoid-bearing mica schists contain a mineral assemblage of Grt + Cld + Phn + Ep + Qtz ± Gln with minor rutile and carbonate minerals. Chloritoid and garnet occur as porphyroblastic crystals and are replaced partly by chlorite (Fig. 7e). Phase equilibrium calculations of Wei and Song (2008) determined peak P–T conditions from 21 Kbar at 540 °C to 24 Kbar at 580 °C for chloritoid-bearing mica schists.

Metacherts commonly occur as interlayers within the other metasediments and rarely as interlayers within eclogites. They have mineral assemblages of quartz + garnet + white mica (phengite + paragonite) ± glaucophane ± rutile. Garnet grains are euhedral and most of them have very small grain sizes (<0.15 mm). Some metacherts

contain spessartine-rich garnet and piedmontite (Fig. 7f), suggesting that they are probably derived from manganese-rich siliceous strata which were deposited on the ocean floor.

Available $^{40}\text{Ar}/^{39}\text{Ar}$ data on phengites and glaucophanes from blueschists and mica schists yield ages of 440–460 Ma, interpreted to represent blueschist-facies metamorphism, or cooling time (Liou et al., 1989; Wu et al., 1993; Zhang J. et al., 1997, Liu et al., 2006). SHRIMP U–Pb dating of zircons from eclogites gave ages of 463–489 Ma, which were regarded as the ages of eclogite-facies metamorphism (Song et al., 2004, 2006; Zhang J. et al., 2007b).

3.3. Comparison between the NAT and NQL HP/LT metamorphic belt

The above data show that the both NAT and NQL HP/LT metamorphic belt contains similar rock associations, experienced similar peak metamorphic conditions and P–T history, and are associated with ophiolitic mélange. In consideration of large scale displacement along the Altyn Tagh fault, the NAT HP/LT metamorphic belt has been considered as the western extension of the NQL HP/LT metamorphic belt. However, the present geochronological data suggest that the NAT HP/LT metamorphic belt may have formed earlier than the NQT HP/LT metamorphic belt, implying a diachronous HP/LT metamorphism along the North Altun–North Qilian suture zone. A similar case of diachronous HP metamorphism along the suture zone occurred in the Tongbai–Hong'an orogen, central China (Liu et al., 2013).

4. (U)HP/MT metamorphism related to continental subduction

UHP metamorphism, defined by the P–T conditions of the coesite stability field ($P > 27$ Kbar, depths > 80 km), is commonly considered as a product of continental subduction and collision (e.g. Coleman and Wang, 1995), although a few UHP

examples related to the oceanic subduction have been reported (Reinecke, 1991; Zhang L et al., 2002; Lv et al., 2008). Eclogite and garnet peridotite were first reported in the South Altun and North Qaidam in the 1990's (Liu et al., 1996; Yang et al., 1994, 1998), and later work led to the discovery of UHP evidence in eclogite, pelitic gneiss and garnet peridotite (e.g., Yang et al., 2001, 2002; Song et al., 2003 2004, 2005, Zhang J et al., 2002, 2009b, 2010; Zhang G., 2009b; Liu et al., 2002; 2012). Recently, eclogites enclosed within continental gneisses were also discovered in the east Kunlun Mountains, to the south of the Qaidam basin, although UHP evidence has not been recognized. These data suggest a widely distributed (U)HP/intermediate-temperature (MT) metamorphism in northern Tibet.

4.1. SAT–NQD UHP/MT metamorphism

The UHP metamorphic rocks are exposed in the Dulan, Xitieshan, Luliangshan and Yuka areas in the North Qaidam (NQD), and at Bashiwake and Jianggelesayi in the South Altun (SAT) (Fig. 1). We herein briefly review the geology, petrology and geochronology of UHP metamorphic rocks in the South Altun and the North Qaidam, which have been well assessed in some recently published papers (see reviews by Mattinson et al., 2007; Zhang G., 2013; Song et al., 2014).

4.1.1. Geology of the UHPM terranes along the SAT–NQD

In all UHP metamorphic exposures of the SAT–NQD, the eclogite and peridotite occur as blocks, boudins, or layers in the host para- and orthogneisses, and typically are tens to 1 m across, but locally are up to hundreds of meters across. Similar to the Dabie–Sulu UHP belt and the Western Gneiss Region of the Caledonian orogenic belt in Norway, which were considered as typical UHP terranes related to deep continental subduction, eclogites are dominantly UHP/MT eclogites (Mattinson et al., 2007; Song et al., 2014 and references therein).

The SAT–NQD UHP metamorphic belt is mainly composed of orthogneisses and paragneisses, similar to most continental type UHP terranes worldwide. Although

most orthogneisses and paragneisses enclose UHP eclogite blocks, HP and UHP assemblages are less preserved in these gneisses, which might be partially explained by the more extensive retrograde recrystallization, typical of felsic rocks (e.g., Proyer, 2003). The magmatic protolith ages of most orthogneisses in the SAT–NQD are Late Mesoproterozoic–Early Neoproterozoic (890–1030 Ma) (Wan et al., 2001, 2006; Zhang J. et al., 2008; Zhang C., 2012; Gehrels et al., 2003a; Mattinson et al., 2006a; Wang C. et al., 2007, 2013; Yu et al., 2013; Song et al., 2012). Some paragneisses record an almost concurrent metamorphism at 895–945 Ma (Zhang J. et al., 2008; Zhang C., 2012; Yu et al., 2013). The Late Mesoproterozoic–Early Neoproterozoic tectonothermal event in SAT–NQD has been interpreted as a Grenvillian orogeny that assembled the supercontinent Rodinia (Wan et al., 2006; Zhang J. et al., 2008; Song et al., 2012; Yu et al., 2013; Wang et al., 2013). This is also similar in age to the Jinning (or Sibao) orogeny commonly recognized in the South China block (Yangtze block), which is absent from the North China block. A few orthogneisses in Dulan area, eastern NQD, have Mesoproterozoic to Paleoproterozoic protolith ages (Song et al., 2013; Yu and Zhang, 2011; Mattinson et al., unpubl.). Similar Mesoproterozoic–Paleoproterozoic gneisses are commonly recognized in the Quanji massif (Olongbuluke microcontinent) to the north of Dulan UHP terrane. This suggests that parts of the Quanji massif may have been subducted, either on the downgoing plate, or by tectonic erosion of the upper plate (Yin et al., 2007).

Most SAT–NQD eclogites have protolith ages ranging from 750 Ma to 850 Ma (Zhang J. et al., 2005b, 2010; Song et al., 2010; Liu et al., 2012). A similar protolith age was obtained in SAT garnet peridotite and garnet pyroxenite (Wang et al., 2011; Li et al., 2015). Combining the ages with geochemical data suggests that the protoliths of these eclogites and garnet peridotites formed during the continental rifting that broke up Rodinia (Zhang J. et al., 2005b, 2010, 2011; Song et al., 2010; Wang et al., 2011, 2013; Li et al., 2015). Together with the major component of Grenville-age gneisses, this suggests that the subducted continental slab may represent part of the Rodinia Supercontinent. In addition to these continental-derived protoliths, oceanic-derived protoliths are also present. An eclogite from the Shaliuhe section of

the Dulan UHP terrane yielded a protolith age of 516 Ma (Zhang G., et al., 2008), and geochemical data suggest that the protolith of this eclogite was derived from gabbroic cumulates, representing part of an ophiolite sequence (Zhang G. et al., 2008). This sample is interpreted to record oceanic subduction that preceded continental subduction and collision (Song et al., 2006, 2014; Zhang G., et al., 2013).

4.1.2. Petrology and *P–T* evolution of the UHP terranes along the SAT–NQD

Petrologic and thermobarometric evidence for UHP metamorphism is recognized in several UHP exposures in the SAT–NQD. Petrologic evidence includes the presence of coesite in garnet and zircon from eclogite and paragneiss at Dulan, Xiteishan and Yuka of the NQD, diamond in zircon from garnet peridotite at Luliangshan of the NQD, and coesite pseudomorphs in garnet from eclogite at Jianggalesayi of the SAT (Yang et al., 2001, 2002; Song et al., 2003, 2005; Zhang J., 2002, 2009b, 2010; Zhang G., 2009a, b; Liu et al., 2012). The *P–T* estimates give similar MT (670–800 °C) and UHP (27–33 Kbar) peak metamorphic conditions for eclogites from the various UHP units (Zhang J., et al., 2001, 2010; Song et al., 2003, 2006; Chen et al., 2009; Zhang C. et al., 2009, 2011; Zhang G. et al., 2009a). Thermobarometry of garnet peridotite at Luliangshan of the NQD yields a higher peak *P–T* condition up to 46–65 Kbar and 980–1130 °C (Song et al., 2004, 2005). However, the retrograde *P–T* paths are disparate for different UHP units. UHP rocks at Yuka and north Dulan record near-adiabatic decompression to amphibolite-facies conditions (Zhang J., et al., 2005b; Chen et al., 2009; Zhang G., 2009a; Fig. 8). In contrast, eclogites at Xitieshan, Luliangshan and Jianggelesayi record high-temperature (HT) granulite-facies conditions during decompression (Zhang J., 2005b; Zhang C., 2011; Fig. 8), corresponding to the Barrovian metamorphic overprinting (see below).

4.1.3. Metamorphic ages for UHP terranes along the SAT–NQD

A large number of zircon U–Pb ages have been reported for UHP metamorphic rocks of the SAT–NQD. For the SAT, all geochronological data show that the age of

the UHP metamorphism recorded in eclogite and garnet peridotite is 500–482 Ma. However, timing of UHP metamorphism for some NQD UHP rocks remains controversial. The previous TIMS U–Pb data of Yuka eclogites, western NQD, gave ages ranging between 486–495 Ma, and $^{40}\text{Ar}/^{39}\text{Ar}$ dating gave ages of 466–477 Ma (Zhang J., 2005b). The TIMS age was recently explained as a possible mixing age of metamorphic domains and residual cores, and $^{40}\text{Ar}/^{39}\text{Ar}$ dating data have a possibility of excess Ar (Liu et al., 2009; 2012). Recently, rutile U–Pb dating of eclogites in western NQD gave an age at ca. 410Ma, interpreted as the cooling age (down to 530 °C (Zhang G., 2014). Most zircon SHRIMP and LA–ICPMS U–Pb dating data yielded ages ranging from 420 to 460 Ma. Combining ages with petrological and geochemical data, Song et al. (2006, 2014) suggested an earlier oceanic subduction (440–460 Ma), followed by continental subduction (420–440 Ma). Although an earlier oceanic subduction can not be excluded, most of the published data show eclogite and host gneiss have a similar age range, suggesting an *in situ* relationship. We therefore prefer to explain that the NQD UHP metamorphism may be diachronous or protracted during continental subduction and collision (Mattinson et al., 2006b, 2007; Zhang J. et al., 2008, 2010).

A relevant question that arises from the above description is how to explain the different UHP metamorphic age between the SAT and NQD. Based on the difference of UHP metamorphic ages, some authors suggest that the SAT and NQD possibly originated from different tectonic belts, and do not correlate across the Altyn Tagh fault (e.g. Liu et al., 2012). However, within the same orogenic belt, different (U)HP exposures may have significant age variation. For example, in the Alps, the age of (U)HP metamorphism in different (U)HP nappes varies over more than 55 Ma, from the Cretaceous (ca. 91 Ma) in the Pohorje Mountains of the Eastern Alps (Miller et al., 2005) to ca. 65 Ma in the Sesia–Lanzo zone (Rubatto et al., 1999), to ca. 35 Ma in the Dora Maria massif (Gebauer et al., 1997). Another well-confirmed example comes from the Tongbai–Hong'an–Dabie–Sulu HP/UHP metamorphic belt. The ages of different HP/UHP slices from this belt are also different, lasting from ca. 255 Ma to ca. 220 Ma (Liu et al., 2004, 2007, 2009, 2010).

4.2. NKL eclogites enclosed in felsic gneisses

Eclogites recently discovered in the eastern part of the East Kunlun Mountains (Meng et al., 2013) occur as lenses within paragneiss of the Jinshuikou Group, which was previously considered to represent the Precambrian metamorphic basement of the north Kunlun–Qaidam block (Wang and Chen, 1987; Wang et al., 2004, 2007; Chen et al., 2006). These eclogite lenses are about 20 m long and 5–10 m wide, and the rims are partially retrogressed to garnet amphibolite. Ultramafic blocks composed of serpentized peridotite and tremolitized pyroxenite are also distributed within paragneisses as lenses. The paragneisses mainly consist of muscovite, biotite, plagioclase, K-feldspar and quartz, with minor garnet. They show a well-developed foliation defined by oriented biotite and muscovite. Eclogite consists of Grt + Omp + Qtz + Rt. Garnet compositions are Alm_{48–55}Prp_{16–29}Grs_{19–29}Sps_{1–2}, and omphacite has a varying jadeite content of 21–63%. The peak metamorphic assemblage of eclogites records a P–T condition of >16 Kbar and 590–650 °C. Zircon U–Pb dating of the inherited magmatic zircons from eclogites reveals a Neoproterozoic age of 934 Ma, representing the protolith age of the eclogite. Zircons with inclusions of garnet, omphacite and rutile yield a weighted mean age of 428 ± 2 Ma, which is interpreted as the metamorphic age of the eclogite.

Recently, retrogressed eclogite was also recognized at Xiarihamu, in the western part of the east Kunlun Mountains (Qi et al., 2014). Similar to the eclogites in the eastern part of the east Kunlun Mountains, these eclogites occur as lenses with the Jinshuikou Group gneisses. They show strong amphibolization with rare omphacite relicts (Jd = 30–37 mol%). U–Pb zircon dating gave a metamorphic age of 411 ± 2 Ma. Considering the strong amphibolite overprinting, it remains unclear if this age represents the timing of eclogite facies metamorphism or later amphibolite facies overprinting.

5. HP/(U)HT granulite facies metamorphism

In the SAT-NQD, HP felsic and mafic granulites are recognized at Bashiwake of the SAT, and Luliangshan, Xitieshan, and Aercituoshan (Dulan area) of the NQD. To discuss the paragenetic relationship between HP mafic granulite and associated eclogite, this section emphasizes HP mafic granulite. Based on field geology, petrological and geochronological data, two types of HP mafic granulites have been recognized in the SAT-NQD (Zhang J., 2009c, 2014; Yu et al., 2011, 2014). One type of HP mafic granulite (i.e. Luliangshan) was formed by overprinting of eclogite during exhumation. Another type of HP mafic granulite (i.e. Bashiwake, and Aercituoshan of Dulan) experienced a single metamorphic evolution distinct from the UHP eclogites.

5.1. Luliangshan HP mafic granulite

The Luliangshan HP mafic granulites occur as lenses ranging in size from <1 m to tens of metres long within garnet-kyanite (sillimanite)-biotite gneisses. Petrologic and mineralogical data indicate a multi-stage metamorphic history. An earlier eclogite-facies metamorphism is deduced from the clinopyroxene-plagioclase intergrowths and rare omphacite inclusions within garnet (Zhang J. et al., 2007c) (Fig. 9). The HP granulite assemblages consist of garnet, clinopyroxene, plagioclase and quartz (Fig. 9a and b), yielding P–T conditions of 9.6–13.7 Kbar and 730–870 °C, similar to P–T conditions of 11–13 Kbar at 800°C for the Grt–Ky–Kf–Pl–Qtz assemblage in the host felsic granulite (Zhang J. et al., 2008). Later reactions led to growth of orthopyroxene around garnet or the symplectite domains (Fig. 9c and d), indicating a significant drop in pressure (P = 6.2–8.5 Kbar) under similar temperatures (T = 720–860 °C), corresponding to medium-low pressure granulite facies overprinting (see below).

SHRIMP U–Pb dating of zircons of mafic and felsic granulites reveals two age groups: ca. 450 Ma and ca. 425 Ma. The former was interpreted to represent the age of HP granulite metamorphism based on rare inclusions of Grt + Rt, and the later reflects the time of middle-low pressure granulite facies metamorphism, based on Pl

+ Sil inclusions in zircons of felsic granulite (Zhang J. et al., 2008, see below). However, Grt + Rt inclusions are also consistent with eclogite facies metamorphism. In this case, the HP granulite facies metamorphic overprinting should happen between 450 Ma and 425 Ma. In addition, the Luliangshan unit is intruded by granite plutons of 428 ± 10 Ma, so HP granulite metamorphism must be earlier than ca. 428 Ma (Zhang J., et al., 2008).

5.2. South Dulan HP/HT granulite

The Dulan UHP metamorphic unit was previously subdivided into the South Dulan Belt (SDB) and the North Dulan Belt (NDB). The main distinction was based on the interpretation that SDB eclogite experienced post-peak HP granulite-facies metamorphism (Song et al., 2003). However, new data suggests that eclogites from the two sub-belts experienced similar metamorphic histories without HP granulite-facies overprinting (Zhang G. et al., 2009a; Zhang J. et al., 2010). Recently, a small HP granulite unit, which is predominantly composed of mafic HP granulite with minor felsic HP granulite, paragneiss, orthogneiss and amphibolite, was recognized at the western margin of the SDB (Zhang J. et al., 2009c; Yu et al., 2009, 2011, 2014; Christensen, 2011). However, some authors also consider the Dulan mafic HP granulite to represent overprinted eclogite (Song et al., 2003; 2014b). Based on field structural relationship, petrologic and chronologic data, we interpret that the Dulan HP granulite did not originate from eclogite because: (1) The garnet, clinopyroxene and plagioclase are in textural equilibrium and the clinopyroxene-plagioclase intergrowths distinctive of omphacite breakdown are absent (Fig. 10b and c). (2) The inclusions of amphibole, epidote and plagioclase, together with typical zoning in garnet suggest that the HP granulite evolved from epidote-amphibolite-facies to HP granulite-facies without recording eclogite-facies metamorphism. (3) Geochronologic data suggest that HP granulite metamorphism occurred at 449–418 Ma, which overlaps the ages of UHP metamorphism for adjacent eclogite (430–446 Ma) (Yu et al., 2014; Christensen, 2011; Zhang J. et al., 2010). This is not concordant with the overprinted eclogite model that requires HP

granulite to be younger than eclogite. (4) The latest petrologic research in the area suggests that the south Dulan eclogite directly retrogressed to amphibolite-facies during decompression without HP granulite-facies overprinting (Zhang G. et al., 2009a; Zhang J. et al, 2010). (5) In the field, no direct contact between the eclogite unit and HP granulite unit has been observed, and a fault contact between the two rocks types is inferred.

Thermobarometric data suggests that the south Dulan HP granulite experienced peak metamorphic P–T conditions of 14–18 Kbar and 800–950 °C (Yu et al., 2009, 2011; Christensen, 2011). Petrographic observations show that the HP granulite preserves features diagnostic of anatexis and locally may be described as migmatite consisting of pale plagioclase-rich quartzofeldspathic layers (leucosome) and dark garnet-clinopyroxene-rich melanosome domains (Fig. 10a). The leucosome is interpreted as the former sites of melt segregation and/or accumulation, and melanosome as the residuum from which melt has been extracted (Yu et al., 2012; 2014, Song et al., 2014b). The relative proportion of leucosome and melanosome varies widely. The leucosome ranges in composition from tonalite to granite and contains small amounts of garnet, clinopyroxene and kyanite in addition to feldspar and quartz, and thus is called “felsic HP granulite” although it represents melt formed by anatexis (Fig. 10d). The leucosome component shows a chemical resemblance to adakites (Yu et al., 2012; Song et al., 2014b, Zhang G., 2015), and probably resulted from partial melting of thickened mafic lower crust (>50 km) compatible with peak P–T estimates from mafic HP granulites (Yu et al., 2012).

Zircon U–Pb dating yields ages of 449 ± 3 , 435 ± 3 , 434 ± 3 , and 418 ± 2 Ma for mafic and intermediate HP granulite, and 433 ± 5 , 437 ± 3 , and 438 ± 4 Ma for felsic HP granulite (leucosome), which were interpreted as timing of the peak metamorphism and partial melting (Yu et al., 2014; Christensen, 2011). $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole ages of 423–432 Ma are interpreted to represent amphibolite-facies retrograde metamorphism and suggest a rapid cooling during exhumation of the HP granulites (Yu et al., 2014). These geochronologic data, combined with field relationships, petrology and geochemistry suggest that HP granulite-facies

metamorphism and the partial melting that produced adakitic melts represent the same tectonic event. In this case, the felsic HP granulites (leucosome) formed from an adakitic melt derived from partial melting of mafic HP granulite in the overriding plate in a relatively higher geothermal gradient (15–18 °C/km), leaving garnet-cumulate and/or meta-ultramafic (mainly garnet pyroxenite) as the residual component (Zhang J. et al., 2009c; Yu et al., 2011, 2012, 2014). In contrast, the nearby UHP eclogite is thought to have formed in the subducted plate in a relatively lower geothermal gradient (6–10 °C/km) (see discussion section).

5.3. Bashiwake HP/(U)HT granulite

In the SAT subduction-collision complex, a HP granulite-garnet peridotite unit has been recognized in the Bashiwake area. It occurs as a tectonic block of HP felsic granulite, mafic granulite and garnet peridotite, separated from amphibolite-facies gneisses by ductile shear zones (Zhang J. et al., 2005c, 2014). Felsic granulites (leucogranulites) predominate within this unit, whereas mafic granulites and garnet peridotites are subordinate and occur as lenses within felsic granulites (Fig. 11). The peak assemblages are represented by garnet + kyanite + perthite (former ternary feldspar) + quartz in felsic granulite, and garnet + clinopyroxene ± perthite ± kyanite + plagioclase + quartz in mafic granulite (Zhang J. et al., 2005c) (Fig. 11). Major mineral thermobarometry suggests that HP granulite experienced peak P–T conditions of 870–1050 °C and 19–25 Kbar, followed by a medium-high pressure granulite facies overprint (780–820 °C, 9.5–12 Kbar), which is defined by the formation of secondary clinopyroxene ± orthopyroxene + plagioclase at the expense of garnet + early Al-rich clinopyroxene in the mafic granulites, as well as by growth of spinel, sapphirine and plagioclase at the expense of garnet and kyanite in the felsic and mafic granulite (Fig. 11e and f). These data show ultrahigh temperature (UHT) conditions at high pressure. These unusual P–T conditions are higher than those of the vast majority of granulites in the world, but are similar to those of (U)HP/UHT granulites in the Bohemian Massif of the European Variscan orogen (Carswell and

O'Brien, 1993; Rötzler and Romer, 2001; O'Brien and Rötzler, 2003; Kotkova, 2007; O'Brien, 2008, and references therein). Field relations and petrographic observations show that the formation and/or post-peak evolution of the Bashiwake granulite involved some degree of melting (Zhang J. et al., 2005c, 2014), but the extent of melting and its relation to the granulite P–T path are still unclear.

Zircon U–Pb geochronology yielded ages of 493 ± 7 Ma and 495 ± 4 Ma for the felsic granulite (Zhang J. et al., 2005c, 2014), 497 ± 11 Ma for mafic granulite (Zhang J. et al., 2005c), interpreted as dating the HP/HT (UHT) granulite facies metamorphism (Zhang J. et al., 2005c). Similar metamorphic ages were also obtained by zircon U–Pb dating of garnet peridotite (Zhang J. et al., 2005c; Wang et al., 2011, Li et al., 2015). Rutile U–Pb dating of felsic and mafic granulites obtained an age of ca. 450 Ma which is interpreted as timing of the post-peak reheating under MP/MT granulite-facies conditions, in combination with Zr-in-rutile thermometry (Zhang J. et al., 2014).

6. Regional Barrovian type metamorphism

Before UHP metamorphism was recognized in collisional orogeny, Barrovian type (MP) metamorphism was considered to be a characteristic of collisional orogenesis (e.g. Dewey and Bird, 1970; England and Thompson, 1984; Wiederkehr et al., 2008; Berger et al., 2011; Jolivet et al., 2003). Since the discovery of coesite in eclogites and associated rocks from Alps (Chopin, 1984) and Norwegian Caledonides (Smith, 1984), UHP metamorphic rocks have been reported from a number of collisional orogenic belts over the world (Liou et al., 2004, Maruyama et al., 2010 and references therein). However, UHP metamorphic rocks occupy a volumetrically minor part of the whole collision orogen. The predominant metamorphic rocks are still Barrovian type metamorphic rocks. Some authors suggest that the rare preservation of UHP–HP metamorphic rocks is due to the overprint of the widespread Barrovian type

metamorphism (e.g. [Liou et al., 2004](#); [Winter, 2001](#)). Recently, [Aoki et al. \(2014\)](#) suggest that the classic Barrovian metamorphism of Scotland may also have overprinted a higher pressure pre-history. However, the presence of Barrovian type metamorphism is still typical of many collisional orogens, although Barrovian type metamorphism has received insufficient attention in the past twenty years, compared with UHP metamorphism. A common feature of collisional orogens is coeval anatexis (partial melting) and granitic magmatism related to Barrovian type metamorphism (e.g. [Keay et al., 2001](#); [Whitney et al., 2003](#) and references therein). As for the SAT–NQD, similar to most collisional orogens worldwide, the predominant metamorphic rocks of the SAT–NQD are low-medium pressure metamorphic rocks, in which rare or no early HP–UHP evidences were preserved.

6.1. SAT Barrovian type metamorphism and anatexis

In the SAT, UHP eclogites, HP granulite and garnet peridotite are only recognized in a few localities (Fig. 1). The predominant high-grade metamorphic rocks, called the “Altun Group”, mainly consist of amphibolite- to granulite-facies granitic gneiss, pelitic gneiss, migmatite, marble, quartzite, amphibolite, and mafic granulite. Here we report a typical Barrovian type metamorphic association in the Tula area of the SAT (Fig. 12). Based on new petrologic and chronologic data in combination with previous work, we will constrain the relationship between Barrovian type metamorphism, partial melting and granite intrusion in the SAT.

In the Tula area of the SAT (Fig. 12), granulite-facies associations include migmatitic metapelites and graphite-bearing marbles that host minor mafic granulite lenses and layers within them ([Zhang J. et al., 2000](#)). These rocks form a unit extending for about 20 km E–W. They are truncated by the ENE–WSW Altyn Tagh main fault on the south, but the boundary to the northern eclogite-bearing unit remains unclear (Fig. 12).

Migmatitic metapelites consist of garnet, sillimanite, biotite, feldspar and quartz with minor graphite and accessory zircon and monazite. The aligned sillimanite and

biotite define a foliation (Fig. 13a and b). Quartzofeldspathic leucosomes parallel to the foliation occur as thin layers (several mm to cm wide) in the metapelite (Fig. 13a). Minor garnet grains observed in the leucosomes are interpreted to be peritectic. Under the microscope, highly cusped, arcuate K-feldspar grains envelop the quartz grains or elongated, veinlet-like K-feldspar intrude into garnet, or a K-feldspar + quartz + plagioclase assemblage is included in garnet, which could be interpreted as pseudomorphs of former melts (Fig. 13c and d). These features suggest *in situ* partial melting of metapelites. Mafic granulite mainly consists of orthopyroxene (hypersthene), clinopyroxene, brown amphibole, biotite and plagioclase with or without garnet (Fig. 13e–h). Previous geothermobarometry gave a peak P–T condition of 8–12 Kbar and 700–850°C for the mafic granulites and metapelite (Zhang J. et al., 2000; Table 1). Our new data give a slightly lower pressure of 6.5–8.0 Kbar and similar temperature 780–820°C using the GASP barometer (Grt–Sil–Pl–Qtz) and Grt–Bt thermometer for metapelites, and the GADS barometer and Grt–Cpx thermometer for mafic granulites (Table 1).

The previous zircon U–Pb dating yielded ages of 450 ± 4 Ma (TIMS) for mafic granulite and 448 ± 7 Ma (SHRIMP) for migmatitic metapelite (Table 1; Zhang J. et al., 2000, 2011). Our new zircon U–Pb analyses by SHRIMP and LA–ICPMS gave ages of 436 ± 4 Ma for mafic granulite and 457 ± 2 Ma for migmatitic metapelite (Fig. 14). These ages are interpreted as the timing of granulite-facies metamorphism and associated anatexis in the Tula area of the SAT.

Similar ages have been commonly reported in various rocks of the other areas of the SAT. For example, at Jianggelesayi, a main locality in which eclogites are exposed, Grt–Bt±Sil±Ky gneiss hosting eclogite lenses gave ages of 450 ± 3 and 450 ± 5 Ma, whereas eclogites have a peak metamorphic age at ca. 482–500 Ma and a granulite facies overprinting age at ca. 450 Ma (Zhang J. et al., 2001a, unpublished data; Liu et al., 2012; Mattinson et al., unpublished data); in the Bashiwake area, the ca. 450 Ma age is recognized in both mafic granulite and felsic granulite, and is interpreted to reflect the timing of MP granulite-facies metamorphic overprinting (or reheating), after an earlier HP granulite-facies (or eclogite facies) metamorphism (Zhang J. et al.,

2005c; 2014). These data also imply that a common MP (Barrovian) granulite-facies metamorphic event happened throughout the SAT at 450 Ma, which postdates an earlier (U)HP eclogite facies metamorphism by about 30–50 Ma. However, it remains unclear if all SAT Barrovian type granulite facies metamorphic rocks have an earlier (U)HP history.

Moreover, similar to the timing of MP granulites, 440–460 Ma granite intrusions also were recently recognized in different localities in the SAT (Zhang J. et al., 2014). Geochemical data suggest that all these granites have characteristics of high-K calc-alkaline S-type granite and might be derived from partial melting of pelitic-arenaceous sedimentary rocks in a lower crustal environment (ca. 800 °C and 10 Kbar) (Cao et al., 2010; Yang et al., 2012; Kang et al., 2013, 2015).

6.2. NQD Barrovian type metamorphism and anatexis

Similar to the SAT, the predominant high grade metamorphic rocks are felsic gneiss (schist) in the NQD. Although rare (U)HP evidence (i.e. coesite inclusions in Dulan paragneiss; relict (U)HP mineral assemblages in Yuka metapelite) are recognized in some gneisses (Yang et al., 2002; Song et al., 2003; Zhang J. et al., 2004), the outstanding characteristics of these gneisses are the preservation of the low to medium-P amphibolite- to granulite-facies assemblages. Based on published petrologic and chronologic data, in this section we examine the relationship between Barrovian metamorphism, anatexis and granite intrusion in the Luliangshan and Xitieshan areas.

In both Xitieshan and Luliangshan units, the paragneisses mainly consist of garnet, kyanite, sillimanite, K-feldspar, plagioclase, quartz, and biotite with accessory rutile, zircon and monazite (Fig. 15). The mineral assemblage Grt + Sil + Bt + Pl + Qtz and GASP equilibria ($\text{Grs} + 2\text{Sil} + \text{Qtz} = 3\text{An}$) give temperatures of 740–830 °C and pressures of 6–8 Kbar (Zhang J. et al., 2008), reflecting low-medium pressure granulite-facies conditions. A HP granulite-facies assemblage of Grt + Ky + Pl + Kfs

+ Qtz + Rt is locally preserved, and yields pressures of 11–13 Kbar at 800 °C (see above, [Zhang J. et al., 2008; 2009a](#)). Mafic granulite lenses (<1 m to tens of meters long) within paragneisses are also recognized in the Luliangshan unit. They are mainly composed of garnet, clinopyroxene, orthopyroxene, plagioclase, amphibole, and quartz with minor rutile, ilmenite and zircon. Petrographic data and P–T calculations suggest a low-medium pressure, granulite-facies stage at 6.2–8.5 Kbar and 730–850 °C after a HP granulite-facies stage (10–14 Kbar and 720–830 °C) and a possible eclogite-facies stage (see above).

Field and microscopic observation support a common migmatization and anatexis for gneisses. Quartzofeldspathic leucosomes occur as thin layers in the gneisses. The proportion of thin leucosomes varies greatly from outcrop to outcrop and the leucosomes range in thickness from millimeters to decimeters ([Yu et al., 2015](#)). The leucosomes are generally aligned subparallel to the foliation defined by oriented biotite and sillimanite. Microscopic evidence includes: (1) highly cusped, elongated feldspar grains along quartz–quartz and quartz–feldspar boundaries, (2) cusped wedge-shaped pockets of K-feldspar + quartz + plagioclase ± muscovite along the boundaries of quartz and/or plagioclase, and (3) felsic veinlets of K-feldspar + quartz ± plagioclase ± muscovite along grain boundaries ([Yu et al., 2015](#)).

U–Pb dating of zircons, combining with trace element analyses and mineral inclusions in zircon, reveals two Early Paleozoic age groups for migmatitic paragneisses: ca. 444–460 Ma represents the age of (U)HP metamorphism, whereas ca. 425–433 Ma reflects the time of low-medium pressure granulite-facies metamorphic overprint and associated anatexis ([Zhang J. et al., 2008; Yu et al., 2014, 2015](#)).

Granitic magmatism (ca. 428 Ma) is synchronous with low-medium P granulite facies metamorphism in the Luliangshan and Xitieshan areas ([Meng et al., 2005; Meng and Zhang, 2008; Zhang J. et al., 2008](#)). The Luliangshan granitic pluton occupies an area of ~60 km². Field observation shows an intrusive contact relation with the surrounding gneiss. Geochemical data suggest that the Luliangshan granite has characteristics of calc-alkaline and peraluminous rocks with high initial ⁸⁷Sr/⁸⁶Sr ratios of 0.7108 and εNd_t values of –5.5 to –4.6, and was inferred to be derived from

melting of metasedimentary rocks similar to country paragneisses (Meng and Zhang, 2008). SHRIMP U–Pb dating of zircons from the Luliangshan granite gave an age of 428 ± 8 Ma. The Xitieshan granite pluton is a long, SSE trending, ~ 15 km² intrusion. Geochemical data suggest that the Xitieshan granite has major and trace element compositions similar to surrounding felsic gneiss, implying that it originated from a deeper partially molten source with a composition similar to the felsic gneiss of the Xitieshan unit. TIMS U–Pb dating of zircons gave an age of 428 ± 1 Ma (Meng et al., 2005), nearly coeval with low-medium pressure granulite-facies metamorphism of the host gneisses.

The data above show that regional-scale Barrovian metamorphism in the SAT–NQD has a close spatial and temporal relationship to granitoid emplacement. Coeval metamorphism and magmatism represent responses to an increased geothermal gradient caused by conductive heating during crustal thickening related to collision, or by thermal relaxation after (U)HP metamorphism related to continental subduction. The low-medium pressure Barrovian metamorphism is about 25–50 Ma later than the (U)HP metamorphism.

7. Discussion: Linking metamorphism to orogenesis

Orogenesis is a complex concept that refers not only to mountain building but also to the formation of continental crust and major orogenic structures (e.g. Ota and Kaneko, 2010). Regional metamorphic rocks, which occupy the orogenic core and hence are the most important element of an orogen, record information that may be used to determine the tectonothermal evolution of the crust with time in orogenic systems (e.g. Brown, 2006). Observation in modern active convergent plate margins and comparison with ancient analogues suggests two types of orogenic systems, i.e. oceanic subduction-related accretionary-type and continent–continent collision-type. The former, also called “Pacific-type” (Matsuda and Uyeda, 1971) or “Cordilleran

type” (Coney et al., 1980), is characterized by the formation of subduction–accretion complexes with a HP/LT metamorphic belt involving blueschists and eclogites, and extensive calc-alkaline magmatism that contributes significantly to the volume of continental crust. It forms by ongoing plate convergence in the absence of continental collision. Typical examples include the Paleozoic Central Asia Orogen, and the Mesozoic-Cenozoic Circum-Pacific Orogen (Coney, 1992; Sengör and Natal’in, 1996). In contrast, orogenesis in a collision-type orogenic system is characterized by the formation of a regional HP–UHP metamorphic belt related to continental subduction, but contributes very little to continental growth, because it involves no more than the reworking of pre-existing continental material. Typical examples are the Cenozoic Alpine–Himalayan orogen, and Mesozoic Dabie–Sulu orogen in eastern China. These two orogenic types, however, do not represent two end members of one spectrum, as the former is destined to change into the latter with time.

Distinct orogenic processes and mechanisms determine the differences of metamorphic pattern between the two types of orogenic systems. In an accretionary orogenic system, juvenile materials are produced mainly by the formation of an accretionary wedge and calc-alkaline magmatic arc, which are related to the subduction of oceanic lithosphere. It is oceanic subduction that results in the formation of HP/LT metamorphic belts consisting mainly of blueschist and LT eclogite. Contemporaneously, devolatilization of subducted, hydrated oceanic crust promotes the generation of calc-alkaline arc melts and LP/HT metamorphism in island arc zone, forming classic paired metamorphic belts, which are the hallmark of accretionary orogeny (Miyashiro, 1961; Ernst, 2005, 2010; Brown, 2007, 2008, 2009, 2010). In a collisional orogenic system, the consumption of ocean lithosphere causes subduction of a continental plate beneath another continental plate to mantle depth, resulting in the UHP metamorphism of continental crust. Underthrusting and collision between two continent blocks can also lead to crustal thickening and shortening, and HP granulites may form in the thickened orogenic lower crust (e.g. eastern Himalaya, Liu and Zhong, 1997). Moreover, in collisional orogenic systems, another important characteristic is widespread Barrovian type regional metamorphism, which may mask

an earlier (U)HP metamorphic history (e.g. in Himalayan and Caledonian orogens, see Liou et al., 2004; Walsh and Hacker, 2004 and references therein). In collisional orogenic systems, different types of metamorphism (e.g. UHP metamorphism & HP granulite metamorphism) may occur contemporaneously in different thermal environments (Konopasek and Schuilmann, 2005; Zhang J. et al., 2009c, 2014), suggesting another type of “paired metamorphic belt”, i.e. UHP eclogite facies belt vs. HP granulite facies belt, which may be characteristic for collisional orogeny (Zhang J. et al., 2009c, see below). Brown (2009) also extends the concept of “paired metamorphic belts” more widely than accretionary orogens, outside the original usage of Mihashiyo (1961), to collisional orogens and incorporates all types of dual metamorphic belts.

The present data suggest a polymetamorphism for the Altun–Qilian–Kunlun (AQK) orogenic system of northern Tibet during the early Paleozoic (Fig. 16; Table 2). The polymetamorphism can be linked to early Paleozoic orogenesis. The NAT–NQL HP/LT metamorphism is related to accretionary orogenesis during early Paleozoic oceanic subduction. In particular, the lawsonite eclogite and carpholite-bearing metapelite suggest that subducted oceanic crust has transported abundant water into mantle (Zhang and Meng, 2006; Zhang J. et al., 2007b; Song et al., 2007; Wei and Song, 2008). The devolatilization of these sinking, hydrated oceanic materials promotes the generation of calc-alkaline arc melts in the NAT–NQL (Zhang J. et al., 1997; Xia et al., 2003; Wu et al., 2005), and produced an early-Paleozoic trench-arc-basin system (e.g. Xu et al., 1994; Xia et al., 2003), reflecting a northward subduction direction (convergence) of the Paleo-Qilian ocean (Prototethys). Moreover, along the northern margin of the Qilian block (southern margin of NQL), several Alaska-type, zoned mafic complexes and arc granites with an age of ca. 500 Ma have been recognized (Zhang Q. et al., 1997, Wu et al., 2009, Zhang J. et al., unpublished data), nearly coeval with the oldest eclogite age (489 Ma) in the NQL. The igneous rocks have geological and geochemical features that indicate an origin related to the southward subduction of the north Qilian ocean (Gehrels et al., 2003a, b; Xiao et al., 2009; Zhang J. et al., 2012). Our new data suggest the

occurrence of ca. 500 Ma LP/HT metamorphic rocks (Grt–Sil–Crd gneiss) associated with arc magmatism in the northern margin of the Qilian block (at Qingshizhui and Kekeli, [Zhang J. et al., unpublished data](#)), also reflecting southward subduction and a possible paired metamorphic belt together with NQL HP/LT metamorphic rocks.

The SAT–NQD is characterized by the occurrence of UHP eclogites, garnet peridotites and predominant felsic gneisses. Although some eclogites may be related to the subduction of oceanic crust during the early Paleozoic (e.g. [Song et al., 2006](#); [Zhang G. et al., 2008](#)), petrological and geochronological data suggest that the protolith of most eclogites was derived from middle Neoproterozoic (750–850 Ma) mafic igneous rocks in a continental rifting setting, and most host gneiss protoliths were derived from early Neoproterozoic granite and Neo-Meso-Proterozoic sedimentary rocks ([Zhang J. et al., 2005a, 2006, 2010](#); [Liu et al., 2009](#), [Song et al., 2010](#); [Yu et al., 2013](#)). All these continental rocks were subducted to mantle depth during the early Paleozoic (500–420 Ma) ([Zhang J. et al., 2005a, 2006, 2008, 2010](#); [Yang et al., 2001, 2002, 2005](#); [Song et al., 2003, 2005, 2006](#); [Zhang G., 2008, 2009a, Mattinson et al., 2006b, 2009](#)). This is similar to the scenarios in typical collisional orogens worldwide (e.g. Alps, Himalaya and Dabie–Sulu). The occurrence of HP granulite is another characteristic of the SAT–NQD. At Bashiwake of the SAT and Aercituoshan of the NQD, HP granulites ages are similar (ca. 485–500Ma at Bashiwake, ca. 418–449Ma at Aercituoshan) to that of the adjacent UHP eclogites, but experienced a higher peak temperature and lower peak pressure conditions. This suggests that UHP eclogite and HP granulite formed in different thermal environments at same time, i.e. the UHP eclogite formed in the subducted continental crust in a relatively lower geothermal gradient (6–10 °C/km), and the HP granulite formed at the base of thickened crust of the overriding plate in a relatively higher geothermal gradient (15–18 °C/km) ([Zhang J. et al., 2009c, 2014](#)) (Fig. 17). As discussed above, penecontemporaneous metamorphic ages but different geothermal gradients between HP granulites and related UHP eclogite define a possible paired metamorphic belt generated in a subduction-collision setting associated with the continent collisional orogeny during early Paleozoic ([Zhang J. et](#)

al., 2009c; 2014; Yu et al., 2011, 2012, 2014), similar to the more common classic paired metamorphic belt in oceanic subduction orogens (accretion orogens), in which an inboard high dT/dP metamorphic belt is juxtaposed against an outboard low dT/dP metamorphic belt along a tectonic contact (Miyashiro, 1961; Brown, 2009). Therefore, this type of paired metamorphic belt may be a diagnostic characteristic of collisional orogens, consistent with the interpretation that the SAT–NQD is a typical collisional orogenic belt.

Moreover, as described above, in the SAT–NQD, almost all high grade metamorphic rocks experienced a Barrovian type overprint although it remains unclear that whether or not all Barrovian type rocks have an earlier (U)HP metamorphic history. The regional Barrovian type metamorphism and syn-kinematic granitoids with ages ranging from 460–440 Ma in the SAT (Zhang J. et al., 2000, 2011; Cao et al., 2010; Kang et al., 2013; Zhang J. et al. unpublished data), which are about 30–50 Ma later than the formation ages of UHP eclogites (ca. 480–500 Ma). In the NQD, although polymetamorphism leads to some geochronologic ambiguity, chronologic data combined with petrographic evidence indicates that low-medium-P metamorphism and associated magmatism (400–428 Ma) are about 20–30 Ma later than the UHP metamorphic times (423–460 Ma). This scenario may be analogous to the Cenozoic situation of the Himalayan orogen, where UHP eclogites and adjacent gneisses were formed at mantle depths >100 km at 46 to 55 Ma, whereas the widely distributed Barrovian amphibolite- to granulite-facies metamorphism and associated magmatism occurred at 30 to 15 Ma (Liou et al., 2004 and references therein).

The discussions above indicate that accretionary orogeny and collisional orogeny developed in the North Altun–North Qilian and South Altun–North Qaidam regions, which are separated by the Qilian–Central Altun microcontinental block. In North Altun–North Qilian, the metamorphic pattern defined by HP/LT metamorphism and possible LP/HT metamorphism is consistent with an accretionary orogenic system related to oceanic subduction. In contrast, in North Qaidam–South Altun, the metamorphic pattern characterized by UHP metamorphism, HP granulite and

Barrovian type metamorphism is characteristic of a collisional orogenic system. This implies that there were two parallel early Paleozoic orogens of distinct types side by side; the NAT-NQL accretionary orogen and the SAT-NQD collisional orogen, and both had extensive dimensions with lengths of some 1000 km. The age differences of HP/LT metamorphism between the NAT and NQL, and UHP, HP granulite and Barrovian metamorphism between the SAT and NQD may demonstrate diachronous accretion and collisional orogenesis. This is unsurprising for an orogen with a scale of more than 1000 km. Moreover, although debate remains, HP/LT metamorphism in the NAT-NQL and UHP metamorphism in the SAT-NQD generally developed synchronously. Therefore, they probably resulted from two independent subduction systems (e.g. [Yang J.S. et al., 2002](#), [Zhang G. et al., 2013](#)), rather than from a single oceanic subduction-continental collision process (e.g. [Song et al., 2006, 2014a](#)). The detailed discussion on the tectonic evolution of Altun-Qilian-North Qaidam is outside the scope of this paper.

The NKL eclogites in the East Kunlun Mountains have similar field relationships (enclosed in continental gneiss) and mineral assemblage to the NQD eclogites, although their P-T condition has not been well constrained. The present chronological data show that the NKL eclogites have a similar or slightly younger metamorphic age compared to the NQD eclogites; the NQD and NKL are separated by the Qaidam basin covered by Cenozoic sediments. The occurrence of similar continental type eclogites on two sides of the Qaidam basin make it necessary to reconsider the nature of the Qaidam block (i.e. basement of Qaidam basin), which was previously considered as a cratonic block consisting of Precambrian metamorphic rocks coherent with high grade metamorphic rocks in the NKL ([BGMQ, 1991](#)). Further detailed investigation is needed to determine the relationship between the NQD UHP eclogites and the newly recognized NKL eclogites.

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Figure captions

Fig. 1 Geological sketch map of the Altun–Qilian–Kunlun (AQK) orogenic system in the northern Tibet. References signed by number are listed in Table 2.

Fig. 2 (A) Simplified geological map showing major litho-tectonic units in the north Altun (NAT) (modified after Zhang et al., 2005a). (B) Local structure map of HP/LT metamorphic slab.

Fig. 3 Field pictures showing relationship between eclogite, blueschist and metasedimentary rock in the NAT. Ecl=eclogite, BS=blueschist, QS=quartz mica schist, CaS=calcareous schist.

Fig. 4 Microtextures of the NAT HP/LT metamorphic rocks. (a) Garnet porphyroblast in eclogite contains oriented inclusions of omphacite, extending to matrix defined well-developed foliations (BSE image); (b) Garnet porphyroblast in blueschist is surrounded oriented glaucophane and barroisite. Epidote porphyroblasts cross-cut the foliation defined mainly by glaucophane (BSE image); (c) Garnet porphyroblast in mica schist is surrounded by oriented phengite and quartz, and phengite is replaced locally by chlorite (plane polarized light, PPL); (d) Oriented chloritoid defines a foliation in Cld-bearing mica schist (PPL).

Fig. 5 Simplified geological map showing major litho-tectonic units in the north Qilian Mountains (modified after Zhang et al., 2007b)

Fig. 6 Field pictures showing relationship between eclogites, blueschists and metasedimentary rocks in the NQL. (a) Block of eclogitic rocks (Ecl) in mica schist (MS); (b and c) eclogite (Ecl) interlayered with blueschist (BS); (d) small eclogite pod (Ecl) within mica schist (MS).

Fig. 7 Microtextures of the NQL HP/LT metamorphic rocks (PPL). (a) Sub-idioblastic

garnet is surrounded by oriented omphacite, phengite and zoisite (eclogite); (b) Idioblastic garnet is surrounded by omphacite and glaucophane (eclogitic metabasite); (c) Sub-idioblastic garnet is surrounded by oriented glaucophane (blueschist); (d) Oriented omphacite and glaucophane define a foliation, and omphacite and glaucophane have straight boundaries (Omp-bearing micaschists); (e) Chloritoid and garnet porphyroblasts are surrounded by oriented glaucophane, phengite and quartz (chloritoid-bearing mica schist); (f) Oriented piemontite defines a foliation (metachert).

Fig. 8 P–T path for the eclogites, garnet peridotites and HP granulites in different UHP metamorphic units along the NQD–SAT. Reference sources: 1–Zhang J et al. (2005a) and Zhang G et al. (2009a); 2–Song et al.(2003), Zhang G. et al. (2009b) and Zhang J. (2010); 3–Zhang J et al. (2005) and Zhang C. et al. (2011); 4–Yang and Powell (2008); 5–Song et al. (2005); 6–Song et al. (2003) and Yu et al. (2011); 7–Liu et al. (2002); 8–Zhang et al. (2005b); 9–Zhang et al. (2001) and Liu et al. (2012). The petrogenetic P–T grid is modified from [Liou et al. \(1998\)](#). Metamorphic-facies abbreviations: AM = amphibolite; Amp-EC = amphibolite-eclogite; BS = blueschist; EA=epidote amphibolite; EC= eclogite; Ep-EC = epidote-eclogite; GR = granulite; GS = greenschist; HGR = high pressure granulite; Lw-EC = lawsonite-eclogite.

Fig. 9 Microtextures of HP granulite at Luliangshan, NQD. (a) Garnet porphyroblast is surrounded by amphibole and symplectite of clinopyroxene + plagioclase (PPL); (b) Clinopyroxene + plagioclase symplectite shows a pseudomorph after earlier omphacite (?) (crossed polarized light, CPL); (c) Orthopyroxene + amphibole + plagioclase corona occurs between garnet and orthopyroxene + plagioclase symplectite (PPL); (d) Omphacite occurs as inclusion in Garnet porphyroblast (BSE image).

Fig. 10 Field picture and photomicrographs of HP granulite at Aercituoshan of the south Dulan area, NQD. (a) Migmatite consists of mafic granulite (melanosome) and felsic granulite (leucosome); (b) and (c) Garnet + clinopyroxene + kyanite +

1556 plagioclase assemblage in HP mafic granulite (b: PPL; c: CPL); (d) Oriented kyanite,
1557 feldspar and quartz define the foliation in HP felsic granulite (leucosome) (CPL).

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1559 Fig. 11 Field pictures and photomicrographs of HP granulite at Bashiwake, SAT. (a)
1560 and (b): Mafic granulites occur as lenses within felsic granulites; (c) Garnet +
1561 kyanite + perthite (former ternary feldspar) + quartz assemblage in felsic granulite
1562 (CPL); (d) Garnet + clinopyroxene + plagioclase + quartz + rutile assemblage in
1563 mafic granulite (PPL); (e) Spinel grows between kyanite and garnet in felsic
1564 granulite (PPL); (f) Sapphrine + plagioclase symplectite in mafic granulite (PPL).

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1566 Fig. 12 Geological map showing sample locations of low-medium pressure mafic
1567 granulite and migmatitic metapelites at the Tula area, SAT.

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1569 Fig.13 Field picture and photomicrographs showing the low-medium pressure
1570 granulite-facies assemblage and associated anatexis in the Tula area, SAT. (a) Field
1571 picture showing the migmatitic texture of metapelite; (b) Oriented sillimanite define
1572 the foliation in migmatitic metapelite (PPL); (c) and (d) Highly arcuate K-feldspar
1573 grains envelop the quartz grains, and veinlet-like K-feldspar intrude into garnet,
1574 reflecting pseudomorphs of former melts (c: PPL; d: CPL); (e) and (f) Orthopyroxene
1575 + clinopyroxene + amphibole + plagioclase assemblage in mafic granulite (e: PPL; f:
1576 CPL); (g) and (h) Garnet + orthopyroxene + clinopyroxene + amphibole +
1577 plagioclase assemblage in mafic granulite (g: PPL; h: BSE image).

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1579 Fig. 14 Zircon U–Pb concordia diagrams for mafic granulite and migmatitic
1580 metapelite in the Tula area.

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1582 Fig. 15 Microtextures of migmatitic metapelites at Luliangshan and Xitieshan, NQD
1583 (PPL). (a) and (b) Garnet, sillimanite, biotite, feldspar and quartz assemblage in
1584 Luliangshan paragneisses. (b) Kyanite (or pseudomorph) is rimmed by sillimanite; (c)
1585 garnet and kyanite porphyroblasts in Xitieshan paragneiss. (d) garnet, sillimanite,

1 1586 biotite, feldspar and quartz assemblage in Xitieshan paragneiss. Sillimanite and
2 1587 biotite define the foliation.
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6 1589 Fig. 16 Geological sketch map showing dating data of various early Paleozoic
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8 1590 metamorphic rocks in the AQK orogenic system, northern Tibet. References signed by
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10 1591 number are listed in Table 2.
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12 1592
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14 1593 Fig. 17 Model showing geodynamic setting of formation for HP granulites and
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16 1594 associated eclogites.
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Table 1 Peak assemblage, P–T estimates and U–Pb dating data of mafic granulite and migmatitic metapelites

Samples	Peak assemblages	Peak P–T conditions	U–Pb age	References
97A20-8	Grt+Sil+Kf+Pl+Qtz	723–806°C, 8 Kbar	448±7 Ma	Zhang J. et al., 2011
97A20-4	Grt+Opx+Cpx±Amp–Pl–Qtz	715–813°C, 8.6–10 Kbar	450±4 Ma	Zhang J. et al., 2000
97A20d	Grt+Sil+Kf±Pl+Bt+Qtz			Zhang J. et al., 2000
AQ11-8-4.1	Opx–Cpx–Pl–Qtz		436±4 Ma	This study
AQ11-8a	Grt+Sil+Kf+Pl+Bt+Qtz	750–810°C, 6.5–8.0 Kbar	457±2 Ma	This study
AQ11-8h	Grt+Sil+Kf+Bt+Qtz	760–805°C, 6.5–8.0 Kbar		This study
AQ11-8i	Grt+Opx+Cpx±Amp+Pl+Qtz	780–820°C, 7–8.1Kbar		This study

Table 2 Dating data for Early Paleozoic metamorphism in the AQK orogenic system, Northern Tibet

Reference No.	Sample locations	Rock type	Dating mineral and Method	Age	Explanation	References
North Qilian						
1	Baijingsi	blueschist	Phengite, Ar–Ar	459±3Ma, 462±3Ma	Blueschist facies metamorphic age	Zhang J. et al., 1997
1	Wayaogou	blueschist	Glaucophane, Ar–Ar	455±7Ma	Blueschist facies metamorphic age	Zhang J. et al., 1997
2	Qingshuigou	blueschist	glaucophane/phengite, Ar–Ar	380–448Ma	Blueschist facies metamorphic age or cooling age	Liou et al., 1989
3	Qingshuigou	HP metasediment	Phengite, Ar–Ar	442–454	Blueschist facies metamorphic age or cooling age	Liu et al., 2006
4	Xiangzigou	eclogite	Zircon, U–Pb SHRIMP	462±5Ma	Eclogite facies metamorphic age	Song et al., 2004
4	Baijingsi	eclogite	Zircon, U–Pb SHRIMP	468±9Ma	Eclogite facies metamorphic age	Song et al., 2004
5	Wayaogou	eclogite	Zircon, U–Pb SHRIMP	477±16Ma	Eclogite facies metamorphic age	Zhang J. et al., 2007b
5	Xiangzigou	eclogite	Zircon, U–Pb SHRIMP	489±7Ma	Eclogite facies metamorphic age	Zhang J. et al., 2007b
6	Jiugequan	Lawsonite-bearing blueschist	Glaucophane, Ar–Ar	413±5Ma	Blueschist facies metamorphic age	Lin et al., 2010
	Jiugequan	Epidote blueschist	Phengite, Ar–Ar	415±7Ma	Blueschist facies metamorphic age	Lin et al., 2010
North Altun						
7	Hongliuquan	eclogite	Phengite, Ar–Ar	512±3Ma	Cooling age(?)	Zhang J. et al., 2007a
7	Hongliuquan	blueschist	Paragonite, Ar–Ar	491±3Ma	Cooling age (?)	Zhang J. et al., 2007a
South Altun						
8	Jianggelesayi	eclogite	Zircon, U–Pb TIMS	504±5Ma	UHP eclogite facies metamorphic age	Zhang J. et al., 2001a
8	Jianggelesayi	eclogite	Sm–Nd Wr – Grt – Omp	500±10Ma	UHP eclogite facies metamorphic age	Zhang J. et al., 2001a
9	Jianggelesayi	Paragneiss enclosing eclogite	Zircon, U–Pb SHRIMP	450±7Ma	Granulite facies overprinting age	Zhang J. et al., unpublished data
10	Jianggelesayi	eclogite	Zircon, U–Pb LA–ICPMS	500±7Ma	UHP eclogite metamorphic age	Liu et al., 2012
10	Jianggelesayi	eclogite	Zircon, U–Pb LA–ICPMS	455±2Ma	Granulite facies overprinting age	Liu et al., 2012
11	Western Tula	Grt–Opx–Cpx–granulite	Zircon, U–Pb TIMS	450±4Ma	MP granulite facies metamorphic age	Zhang J. et al., 2000
12	Western Tula	Grt–Opx–Cpx–granulite	Zircon, U–Pb LA–ICPMS	436±5Ma	MP granulite facies metamorphic age	This study

13	Danshuiquan	Garnet pyroxenite	Zircon, U–Pb LA–ICPMS	475±4Ma	HP granulite facies metamorphic age	Liu et al., 2009
14	Danshuiquan	Pelite granulite	Zircon, U–Pb LA–ICPMS	486±5Ma	HP granulite facies metamorphic age	Cao et al., 2009
15	Bashiwake	Garnet pyroxenite	Sm–Nd isochron (Wr–Grt –Cpx)	493±24Ma	HP granulite facies metamorphic age	Li et al., 2015
16	Bashiwake	HP felsic granulite	Zircon, U–Pb SHRIMP	493±5Ma	HP granulite facies metamorphic age	Zhang J. et al., 2005c
16	Bashiwake	Garnet peridotite	Zircon, U–Pb SHRIMP	501±16Ma	HP granulite facies metamorphic age	Zhang J. et al., 2005c
17	Bashiwake	Garnet peridotite	Zircon, U–Pb LA ICPMS	498±3Ma	UHP metamorphic age	Wang et al., 2011
18	Bashiwake	HP mafic granulite	Amphibole, Ar–Ar	474±5Ma	Cooling age	Zhang J. et al., unpublished data
19	Bashiwake	HP granulite	Rutile, U–Pb LA ICPMS	440–460Ma	HP granulite overprinting age	Zhang J. et al., 2014
North Qaidam						
20	Yuka	Eclogite	Ar–Ar (amphibole)	478±8Ma	Cooling age (?)	Zhang J. et al., 2005a
20	Yuka	Eclogite	Ar–Ar (phengite)	466±1Ma	Cooling age (?)	Zhang J. et al., 2005a
20	Luofengpo	Eclogite	U–Pb TIMS (zircon)	488±6Ma	Eclogite facies metamorphic age (?)	Zhang J. et al., 2005a
21	Yuka	Eclogite	U–Pb TIMS (zircon)	495±7Ma	Eclogite facies metamorphic age (?)	Zhang J. et al., 2000
22	Yuka	Eclogite	LA ICPMS (zircon)	436±3Ma, 431±4Ma	Eclogite facies metamorphic age	Chen et al., 2009
22	Yuka	Paragneiss (schist)	LA ICPMS (zircon)	431±3Ma, 432±19Ma	Eclogite facies metamorphic age	Chen et al., 2009
23	Yuka	eclogite	LA ICPMS (zircon)	443±4Ma	Eclogite facies metamorphic age	Xiong et al., 2012
24	Yuka	eclogite	SHRIMP(zircon)	433±20Ma,	Eclogite facies metamorphic age	Song et al., 2010
25	Lvliangshan Shenglikou	Garnet peridotite	U–Pb SHRIMP (zircon)	423±5Ma	UHP metamorphic age	Song et al., 2005
26	Lvliangshan Shengyikou	Garnet peridotite	U–Pb ICPMS (zircon)	429±2Ma	UHP metamorphic age	Xiong et al., 2011
26	Lvliangshan Shenglikou	Migmatitic gneiss	U–Pb ICPMS (zircon)	468±4Ma	Prograde metamorphic age	Xiong et al., 2011
26	Lvliangshan Shenglihou	gneiss	U–Pb ICPMS (zircon)	430±5Ma	UHP metamorphic age	Xiong et al., 2011
27	Lvliangshan Shenglikou	Felsic gneiss	U–Pb SHRIMP (zircon)	454±6Ma	HP granulite facies metamorphic age	Zhang J. et al., 2008
27	Lvliangshan Shenglikou	Felsic gneiss	U–Pb SHRIMP (zircon)	427±3Ma	Medium pressure granulite facies overprinting age	Zhang J. et al., 2008
28	Xitieshan	eclogite	Sm–Nd Wr–Grt–Omp	435±49Ma	Cooling or late overprinting age	Zhang J. et al., 2005a
28	Xitieshan	eclogite	U–Pb SHRIMP(zircon)	480±16Ma	Eclogite facies metamorphic age	Zhang J. et al., 2005a
28	Xitieshan	eclogite	Ar–Ar (amphibole)	409±1Ma	Cooling age	Zhang J. et al., 2005a
23	Xitieshan	eclogite	LA ICPMS (zircon)	440±3Ma	Eclogite facies metamorphic age	Xiong et al., 2012

29	Xitieshan	Paragneiss	U–Pb SHRIMP(zircon)	451–461	HP granulite facies metamorphic age	Zhang J. et al., 2009a
29	Xitieshan	Paragneiss	U–Pb SHRIMP(zircon)	423–427	Low-med pressure granulite facies overprinting age	Zhang J. et al., 2009a
30	Xitieshan	Paragneiss	U–Pb EMP(monazite)	455–460	Prograde metamorphic age	Zhang C. et al., 2012
30	Xitieshan	Paragneiss	U–Pb EMP(monazite)	422–425	Amphibole facies overprinting age	Zhang C. et al., 2012
31	North Dulan unit	eclogite	Sm–Nd Wr–Grt–Omp	458±10Ma,	Eclogite facies metamorphic age	Song et al., 2003
32	North Dulan unit	eclogite	U–Pb SHRIMP(zircon)	457±7Ma	Eclogite facies metamorphic age	Song et al., 2006
32	North Dulan unit	eclogite	U–Pb SHRIMP(zircon)	426±24Ma	Retrograde metamorphic age	Song et al., 2006
33	North Dulan unit	Coe-bearing gneiss	U–Pb SIMS (zircon)	452±14Ma	UHP metamorphic age	Yang et al., 2005
33	North Dulan unit	Coe-bearing gneiss	U–Pb SIMS (zircon)	419±14Ma	Retrograde metamorphic age	Yang et al., 2005
34	North Dulan unit	Coe-bearing gneiss	U–Pb SHRIMP (zircon)	423±6Ma	UHP metamorphic age	Song et al., 2006
34	North Dulan unit	Coe-bearing gneiss	U–Pb SHRIMP (zircon)	403±9Ma	Retrograde metamorphic age	Song et al., 2006
35	North Dulan unit	eclogite	U–Pb SHRIMP(zircon)	422–449Ma	Eclogite facies metamorphic age	Mattinson et al., 2006
36	North Dulan unit	paragneiss	U–Pb SHRIMP(zircon)	426±4Ma, 431±5Ma	Eclogite facies metamorphic age	Mattinson et al., 2009
37	South Dulan unit	eclogite	U–Pb SHRIMP(zircon)	445±7Ma	Eclogite facies metamorphic age	Zhang G. et al., 2008
38	South Dulan unit	Coe-bearing eclogite	U–Pb SHRIMP (zircon)	440±6Ma	UHP metamorphic age	Zhang G. et al., 2009a
39	South Dulan unit	Coe-bearing eclogite	U–Pb SHRIMP (zircon)	430–446Ma	UHP metamorphic age	Zhang J. et al., 2010
40	South Dulan unit	Coe-bearing eclogite	U–Pb SHRIMP (zircon)	440±6Ma	UHP metamorphic age	Yu et al., 2013
40	South Dulan unit	Gneiss	U–Pb ICPMS (zircon)	438–439Ma	Eclogite facies metamorphic age	Yu et al., 2013
41	South Dulan unit	HP mafic granulite	U–Pb ICPMS (zircon)	447±7Ma	HP granulite facies metamorphic age	Yu et al., 2010
42	South Dulan unit	HP granulite	U–Pb SHRIMP/LA–ICPMS (zircon)	430–443Ma	HP granulite facies metamorphic age	Yu et al., 2014
43	South Dulan unit	HP mafic granulite	U–Pb SHRIMP (zircon)	411–435	HP granulite facies metamorphic age	Song et al., 2014
North Kunlun						
44	Wenquan	eclogite	U–Pb SHRIMP (zircon)	428±2Ma	Eclogite facies metamorphic age	Meng et al., 2013
45	Qingshuiquan	Mafic granulite	U–Pb SHRIMP (zircon)	508±8Ma	Granulite facies metamorphic age	Li et al., 2007
46	Qingshuiquan	Mafic granulite	U–Pb SHRIMP (zircon)	517±5Ma	Granulite facies metamorphic age	Chen et al., 2003
47	Nuomuhong	Mafic granulite	U–Pb SHRIMP (zircon)	460±8Ma	Granulite facies metamorphic age	Zhang J. et al., 2003
47	Nuomuhong	Migmatitic gneiss	U–Pb SHRIMP (zircon)	402±6Ma	Anatectic age	Zhang J. et al., 2003
48	Xiarihamu	Retrograde eclogite	U–Pb LA–ICPMS (zircon)	411±2Ma	Eclogite facies metamorphic age(?)	Qi et al., 2014