



Research Paper

Tectonic evolution of the West Kunlun Orogenic Belt along the northern margin of the Tibetan Plateau: Implications for the assembly of the Tarim terrane to Gondwana



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ABSTRACT

The West Kunlun orogenic belt (WKOB) along the northern margin of the Tibetan Plateau is important for understanding the evolution of the Proto- and Paleo-Tethys oceans. Previous investigations have focused on the igneous rocks and ophiolites distributed mostly along the Xinjiang-Tibet road and the China-Pakistan road, and have constructed a preliminary tectonic model for this orogenic belt. However, few studies have focused on the so-called Precambrian basement in this area. As a result, the tectonic affinity of the individual terranes of the WKOB and their detailed evolution process are uncertain. Here we report new field observations, zircon and monazite U-Pb ages of the “Precambrian basement” of the South Kunlun terrane (SKT) and the Tianshuihai terrane (TSHT), two major terranes in the WKOB. Based on new zircon U-Pb age data, the amphibolite-facies metamorphosed volcano-sedimentary sequence within SKT was deposited during the late Neoproterozoic to Cambrian (600–500 Ma), and the flysch-affinity Tianshuihai Group, as the basement of the TSHT, was deposited during the late Neoproterozoic rather than Mesoproterozoic. The rock association of the volcano-sedimentary sequence within SKT suggests a large early Paleozoic accretionary wedge formed by the long-term low-angle southward subduction of the Proto-Tethys Ocean between Tarim and TSHT. The amphibolite-facies metamorphism in SKT occurred at ca. 440 Ma. This ca. 440 Ma metamorphism is genetically related to the closure of the Proto-Tethys Ocean between Tarim and the Tianshuihai terrane, which led to the assembly of Tarim to Eastern Gondwana and the final formation of the Gondwana. Since the late Paleozoic to early Mesozoic, the northward subduction of the Paleo-Tethys Ocean along the Hongshihu-Qiaertianshan belt produced the voluminous early Mesozoic arc-signature granites along the southern part of NKT-TSHT. The Paleo-Tethys ocean between TSHT and Karakorum closed at ca. 200 Ma, as demonstrated by the monazite age of the paragneiss in the Kangxiwa Group. Our study does not favor the existence of a Precambrian basement in SKT.

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1. Introduction

The West Kunlun Orogenic Belt (WKOB) is bounded by the Tarim Basin to the north, the Tibetan Plateau to the south, and the Pamir Plateau to the west (Yin and Harrison, 2000; Gibbons et al., 2015). WKOB is offset from the East Kunlun Orogen and the Songpan-Ganzi terrane by the Altyn sinistral strike-slip fault to the east

(Fig. 1a). As one of the major tectonic units of the Tibetan Plateau and the central orogenic belt in China (i.e., the West Kunlun-Eastern Kunlun-Qilian-Qinling-Dabie orogen, see Dewey et al., 1988; Jiang et al., 1992), WKOB is important for understanding the evolution of the Proto- to Paleo-Tethys Ocean. Nevertheless, fundamental geological data and knowledge of the tectonic evolution of the WKOB are limited due to access difficulty and harsh natural conditions before 1990s. Studies on the WKOB since 1990s (e.g., Pan, 1990, 1993, 1996; Matte et al., 1992, 1996; Pan and Wang, 1994; Mattern et al., 1996; Yang et al., 1996; Xiao et al., 1998; Mattern and Schneider, 2000; Yin and Harrison, 2000) have provided new insights on the tectonic evolution of the WKOB (e.g., Yuan, 1999;

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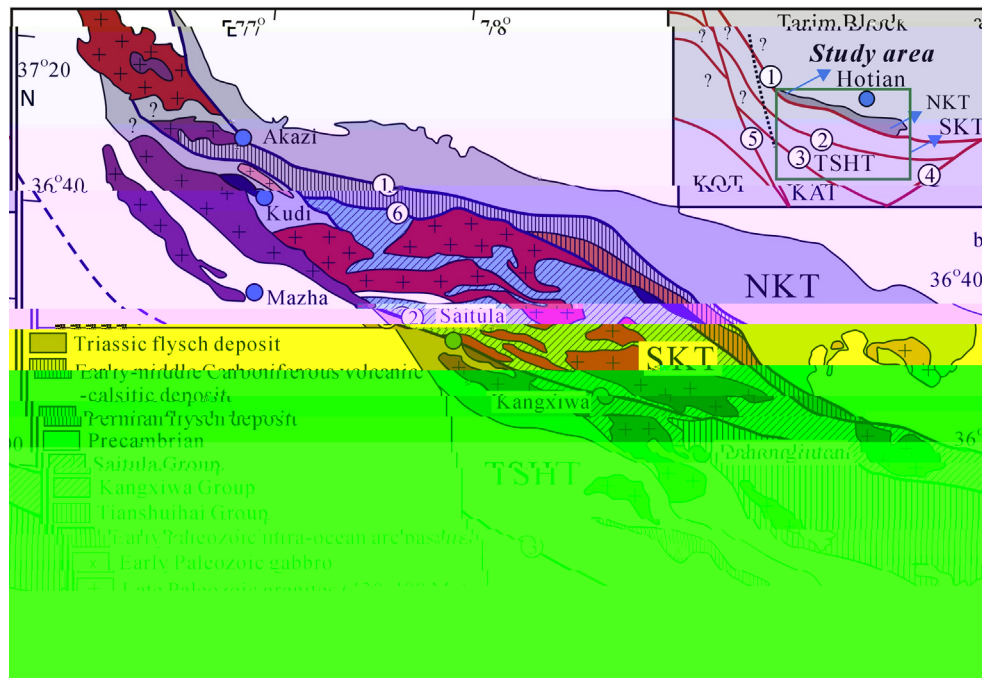


Figure 1. (a) Tectonic framework of the West Kunlun orogenic belt (WKO) and its adjacent areas showing the main tectonic units of the WKO. The dashed line represents the boundary between the two distinct segments of the WKO as deduced from their individual aeromagnetic anomaly and recent studies (see Ji et al., 2004); (b) sketch geological map of the eastern section of the WKO (see details in the text). The faults marked in (a) and (b): ① the Kegang-Akazi fault, ② the Kangxiwa fault, ③ the Qianertianshan–Hongshanhu fault, ④ the Altyn fault, ⑤ the Tashikoergan fault, ⑥ the Talong fault.

Jiang et al., 2002, 2005, 2008, 2013; Wang et al., 2002, 2004; Xiao et al., 2002a, b, 2005; Yuan et al., 2002, 2004, 2005; Ducea et al., 2003; Wang, 2004; Zhang et al., 2006a, 2007a). Most geologists favor the notion that the southward subduction of the Proto-Tethys Ocean beneath the South Kunlun Terrane (SKT) since Sinian led to the closing of this ocean basin and the amalgamation of the North Kunlun Terrane (NKT) and SKT during the Early Paleozoic, with only the remnants of the Proto-Tethys oceanic crust being preserved along the Qytag-Kudi suture zone (Pan, 1996; Xiao et al., 1998; Mattern and Schneider, 2000; Jiang et al., 2002). During the late Paleozoic to mid-Mesozoic, the southerly located Paleo-Tethys Ocean was consumed beneath the SKT and produced a Late-Carboniferous to mid-Jurassic magmatic arc in the southern SKT and the Tianshuihai Terrane (TSHT). Arc magmatism affected the southern SKT and the large Karakorum accretionary prism which formed as a result of the consumption of the Paleo-Tethys ocean (Mattern and Schneider, 2000; Zhang et al., 2016a). The dextral shear sense of ductile faults parallel to the South Kunlun/Karakorum boundary, suggests oblique plate convergence with a dextral component during the early to middle Jurassic (Mattern and Schneider, 2000).

Previous studies have focused on the igneous rocks and some major geological units such as the ophiolites along the Xingjiang-Tibet road and the China-Pakistan road (e.g., Xu et al., 1994; Yang et al., 1996; Zhang et al., 1996; Mattern and Schneider, 2000; Zhou et al., 2000; Wang et al., 2002; Zhang et al., 2004; Mahar et al., 2014; Liu and Wang, 2016). Few scientists have studied the widely distributed so-called Precambrian basement in WKO (Zhang et al., 2007a). In addition, the orientation and the process of oceanic crust subduction, the timing of the closing of the Proto- and Paleo-Tethys oceans, and the final formation of the WKO, remain to be determined.

In recent years, local geologists have completed 1/250,000 geological mapping of the WKO which have significantly improved our geologic knowledge of the WKO (Han et al., 2001,

2002, 2004; Ji et al., 2004; Cui et al., 2006a,b, 2007a). Based on these data, we revisit this major orogenic belt for a better understanding of the tectonic evolution of the Tibetan Plateau. In this contribution, we report our new field observations and zircon and monazite U-Pb ages for the metamorphic rocks from the so-called Precambrian basement in the eastern section of the WKO. The aims of this study are to: (a) determine the ages and their tectonic attribution of the so-called Precambrian basement, (b) decipher the coupling relationship between oceanic crust subduction, terrane accretion, metamorphism and igneous activities, and (c) construct a more accurate model for the tectonic evolution of the WKO.

2. Regional geology

2.1. Tectonic framework of the West Kunlun

The West Kunlun is tectono-stratigraphically subdivided into three main units: the North Kunlun Terrane (NKT) (also termed as the southern margin of the Tarim Block, the Tiekeliike uplift in literature, e.g., Xinjiang BGMR, 1993; Pan, 1996; Zhang et al., 2003), the narrow South Kunlun Terrane (SKT), and the Tianshuihai Terrane, also known as Uyur Terrane (TSHT, e.g., Mattern and Schneider, 2000) (Fig. 1a). NKT and SKT are separated by the ophiolite-bearing Kudi-Qimanyute suture (Fig. 1b). It was believed that this suture zone extended toward northwest to Oytagh, based on the presence of the Oytagh plagiogranite (Jiang et al., 2002). However, recent studies have revealed that the Oytagh plagiogranite emplaced at ca. 330 Ma and thus is not a member of the early Paleozoic ophiolite complex between NKT and SKT (Zhang et al., 2006; Jiang et al., 2008). Thus, the orientation of the suture zone between NKT and SKT is still unclear. The Kangxiwa fault was regarded as the suture zone between SKT and TSHT, which trends E–W in the eastern section of the WKO. To the west, some geologists suggested that it was switched off by the Cenozoic N–S-trending Tashikoergan fault (Jiang et al., 2013; Zhang et al., 2016a).

Recent studies have revealed clear differences between the western and eastern sections of the WKOB (Robinson et al., 2004, 2007, 2016; Zhang et al., 2007a, 2018a; Ji et al., 2011). This conclusion is also supported by the pronounced difference in the regional geophysical field between the two segments (Matte et al., 1996; Yuan, 1996; Gao et al., 2000). A NNW extending strike-slip fault can divide the WKOB into western and eastern parts on the basis of the aeromagnetic anomaly features, but we know little about this fault due to access difficulty (marked as dashed line in Fig. 1a). This study focuses on the eastern section of the WKOB (Fig. 1b).

2.2. The North Kunlun Terrane (NKT)

NKT is an uplifted terrane of the Tarim block (Zhang et al., 2013). The major Precambrian rock series of NKT are mainly composed of the Paleoproterozoic Heluositan complex (2.34–2.41 Ga, Zhang et al., 2007b; Wang et al., 2014; Ye et al., 2016) (Fig. 2a), the Mesoproterozoic greenschist- to amphibolite-facies metamorphosed and intensively folded sedimentary sequences (the Kalakashi Group), the mid-Neoproterozoic greenschist-facies metamorphosed and folded volcanic-sedimentary sequences, and the late Neoproterozoic unmetamorphosed carbonate-clastic-tillite sequences (see details in Zhang et al., 2016b) (Fig. 2a). The Mesoproterozoic to late Neoproterozoic tectonostratigraphic features revealed the assemblage and breakup process of NKT during the evolution of the Rodinia supercontinent (Xu et al., 2013; Zhang et al., 2016b). The ca. 1.0 Ga metamorphic age of the Kalakashi Group may be related the assembly of the Tarim to the Rodinia supercontinent (Zhang et al., 2003). In NKT, Devonian red molasse unconformably overlies the broadly folded, unmetamorphosed Neoproterozoic–Cambrian rocks and the tightly-folded, amphibolite-facies metamorphic Mesoproterozoic rocks, and subsequently is overlain by the Carboniferous–Permian shallow marine carbonate. The coal-bearing upper Triassic–Cenozoic molasse sedimentary sequence unconformably overlying on the late Paleozoic

rocks was the far away effects of the closing of the Paleo-Tethys ocean (Mattern and Schneider, 2000; Yin and Harrison, 2000).

2.3. The South Kunlun Terrane (SKT)

SKT was often regarded as a drifted Precambrian terrane from the southern margin of the Tarim Block during the late Neo-

Fig. 0175TD5196 (Mes)

The Precambrian member in TSHT is termed as the Tianshuihai Group. This group mainly consists of meta-greywackes and limestone and is in fault or unconformable contact with the late-Paleozoic to early Mesozoic accretionary wedge (Fig. 2c). The thick monotonous and partly metamorphosed successions of clastic marine deposits exhibit a flyschoid character (Mattern and Schneider, 2000).

3. Field observations and sample description

The metamorphic rocks in the eastern section of SKT were termed as the Kangxiwa Group in southern SKT and as the Saitula Group in northern SKT (Fig. 1b). The Saitula Group is in fault contact with the late Paleozoic back-arc basin sequences and the early Paleozoic low greenschist-facies metamorphic Taxidaban Group. Late Cambrian to early Ordovician ophiolite relics tectonically intermingled in the northern margin of the Saitula Group (Fig. 1b). Previous works demonstrated that this ophiolite belt was thrust from north to south after the closing of the Proto-Tethys ocean (Zhou et al., 1999; Li and Zhang, 2014). On the south side, the Saitula group is in fault contact with the late Paleozoic to early Mesozoic flysch and the Kangxiwa Group by the sinistral strike-slip Kangxiwa fault (Fig. 1b). Similar with the scenario of NKT, Devonian red molasse unconformably overlies the Saitula Group (Fig. 2). N–S cross section observations show that the schistosity and the

stratification are parallel to each other in most places and dip to north with the dip angle varying from 75° to 45° from north to south. The 1:250,000 mapping revealed that voluminous early Paleozoic granites (mostly in the northern part) and some early Mesozoic granites (mostly along the southern part) intruded into the Saitula Group (Fig. 1b). At several outcrops, granite-granodiorite gneiss sheets 1–2 m thick, intrude the Saitula Group. In line with our field observations and previous studies (Xinjiang BGMR, 1993; Cui et al., 2006a; Zhang et al., 2007a), the Saitula Group is mainly composed of gneiss-schist and layers or lens of amphibolite with minor marble at the top of this group (the marble member was termed as the Sangzhutage Group in the early literature, e.g., Xinjiang BGMR, 1993). At several outcrops, amphibolite and biotite plagioclase-quartz granofels, with variable thickness, interbedded with each other (Fig. 3a and b). However, in one locality (northeast of Saitula town) the amphibolite occurs as a pluton ca. 2500 m long and 500–1500 m wide in the gneiss-schist and shares common foliation with the wall rocks (Fig. 3c). We infer that the amphibolite was a mafic intrusive pluton and underwent similar tectonic events after its emplacement. The layered amphibolites (or amphibolite gneiss) in the gneiss-schist are fine- to medium-grained, exhibit gneissic structure, and comprise mainly plagioclase (40%–50%), hornblende (40%–50%), biotite (5%–10%) with occasional quartz (1%–5%) and Fe-Ti oxides (3%–10%). Some hornblende was replaced by chlorite (Fig. 4a). Apatite and zircon occur as accessory

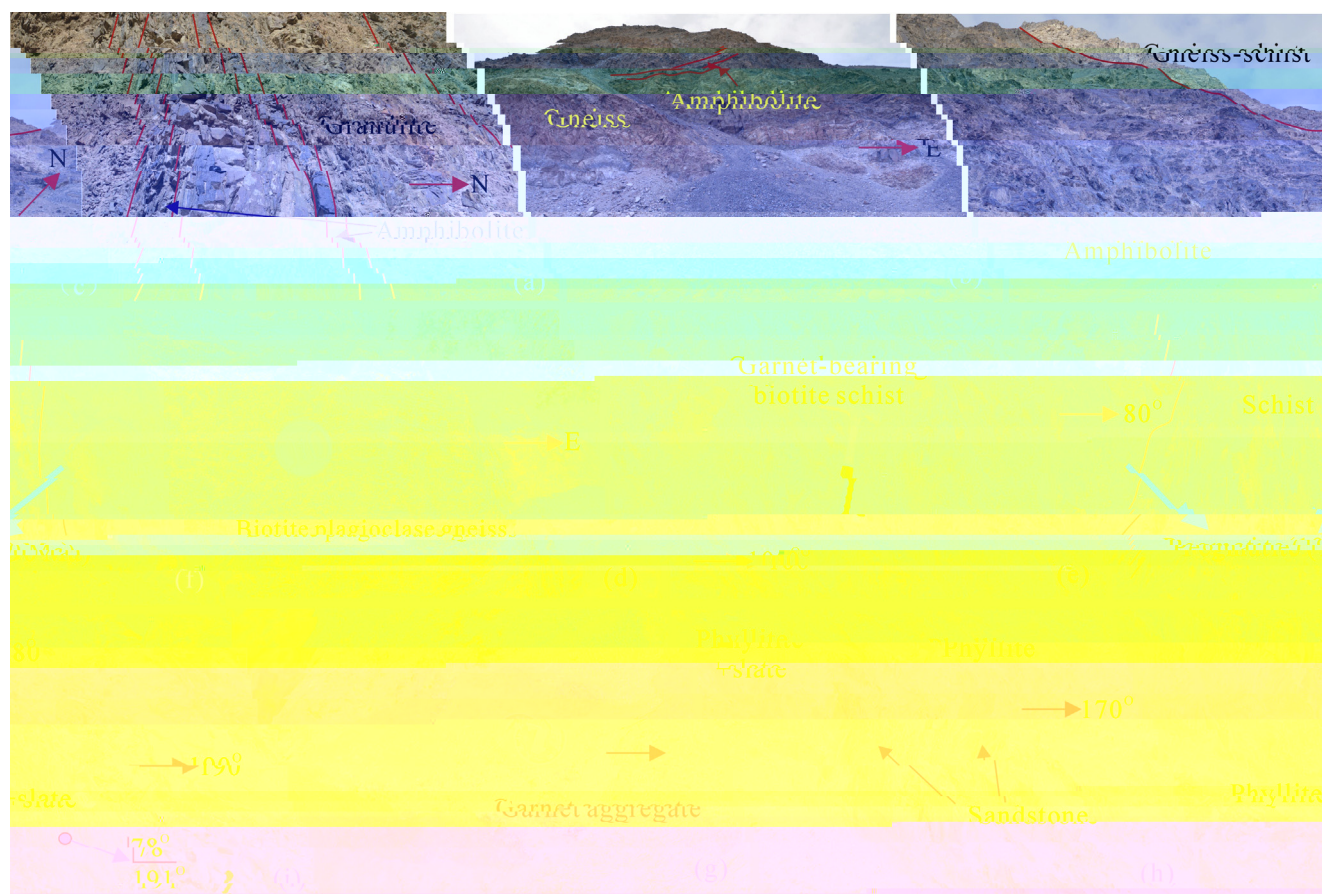


Figure 3. Representative field photographs of the studied metamorphic sequences in SKT and TSHT. (a, b) The interlayer structure of the amphibolite and the granofels from Saitula Group, indicating the precursor of the amphibolite was most likely basalt or mafic sheet; (c) the amphibolite occurs as a pluton (with ca. 2500 m in length and 500–1500 m in width) in the gneiss-schist, its precursor was likely a mafic intrusion; (d) the hornblende-bearing gneiss from the Saitula Group, its precursor was likely rhyolite; (e) garnet-bearing biotite schist from the Kangxiwa Group, the bedding was completely replaced by foliation; (f) biotite schist intruded by the deformed pegmatite dykes, monazite U-Pb dating revealed the pegmatite emplaced at 209 Ma; (g) garnet biotite schist from the Kangxiwa Group, and some garnet aggregate is seen at outcrops; (h) the sandstone layer in the phyllite and slate from the Tianshuihai Group; (i) phyllite and slate in the Tianshuihai Group, foliation was parallel with the bedding plane.

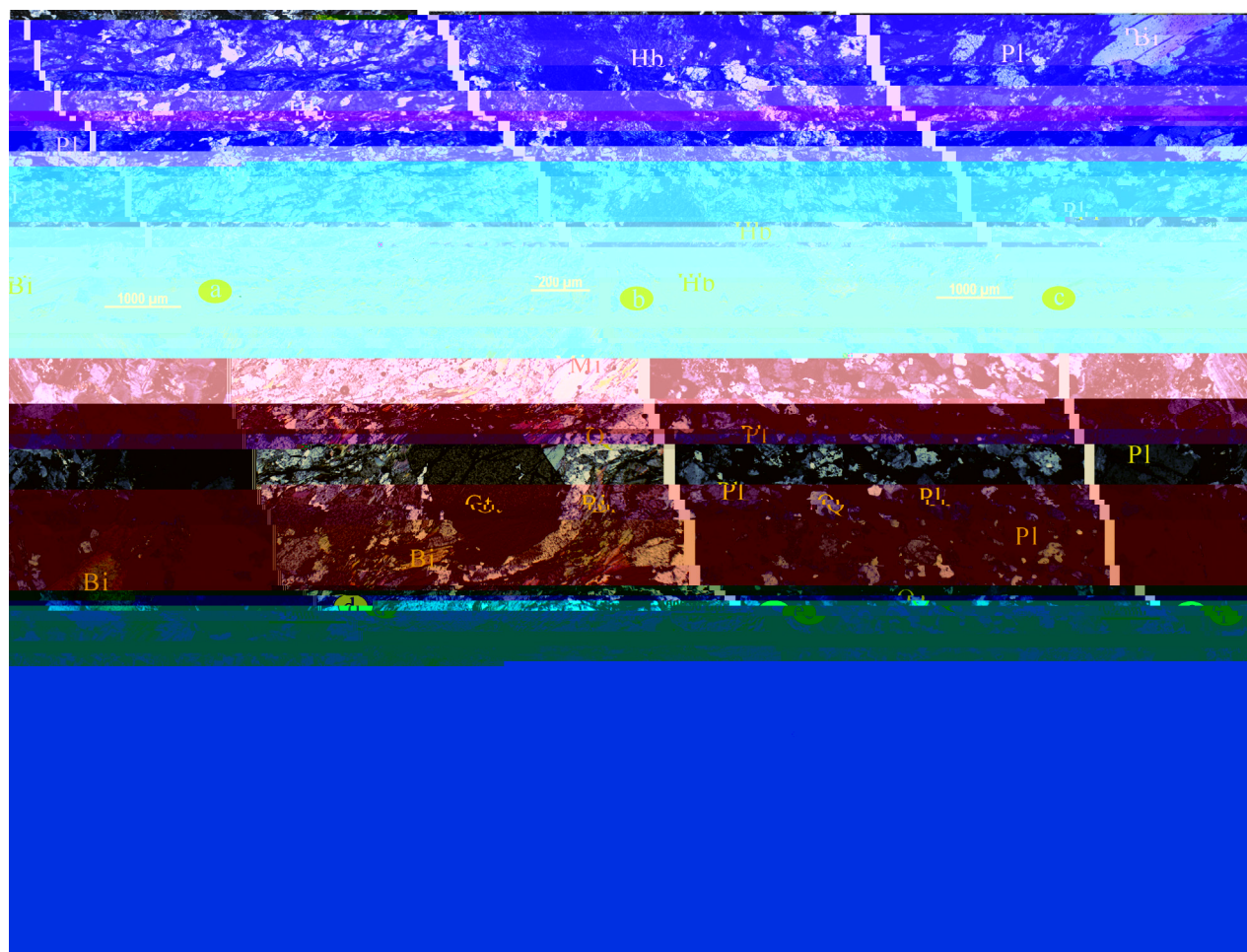


Figure 4. Photomicrographs of the representative rocks for zircon and monazite U-Pb age analysis from the Saitula Group, Kangxiwa Group and Tianshuihai Group. (a) Fine-grained plagioclase-amphibolite gneiss layer from the Saitula Group (see Fig. 3a, sample 2015D012); (b) altered gabbro intrusion in the Saitula Group (sample 2015D018); (c) biotite plagioclase gneiss from the Saitula Group (sample 2015D008); (d) garnet bearing gneiss (sample 2015D12-2); (e) quartz plagioclase granofels from the Saitula Group (sample 2015D015); (f) gneissic granodiorite (sample 2015D016); (g) garnet biotite schist from the Kangxiwa Group (sample 2015D005-2); (h) biotite quartz schist; (i) quartz sandstone from the Tianshuihai Group (sample 2015D001) (see details in the text). Abbreviations: Bi—biotite, Gt—garnet, Q—quartz, Pl—plagioclase, Hb—Hornblende.

minerals. Based on the mineral assemblage, and in combination with their layered structure observed in the field, we infer that their protoliths are probably basalt or mafic sheets, indicating that they were coeval with the gneiss-schist association. The amphibolite occurring as a pluton is of coarse-grained, and is composed mainly of hornblende (50%–60%), plagioclase (20%–30%), Fe-Ti oxides (2%–5%) and minor quartz (less than 1%) (Fig. 4b). Some hornblende grains could be replacement product of clinopyroxene according to their clinopyroxene pseudomorph (Fig. 4b). The Saitula Group include biotite plagioclase gneiss, garnet-bearing schist and gneiss, and biotite schist, and have variable contents of biotite (5%–30%), quartz (15%–45%), plagioclase (10%–40%), garnet (1%–15%), and amphibole (1%–10%). According to the mineral assemblage and texture, most of the gneisses are metamorphosed from clastic rocks involved with variable volcanic debris, whereas the garnet-bearing schist and gneiss might have been metamorphosed from clastic protoliths, judging from the presence of highly aluminous minerals in these rocks (Fig. 4c and d). Granofels layers were observed in the gneiss-schist and are mainly composed of plagioclase (50%–60%, including some microcline) and quartz (35%–45%) with minor biotite (1%–5%). In line with mineral composition, we infer that its precursor is most likely rhyolite or granitic sheets (Fig. 4e). Deformed granite-granodiorite dykes are composed of 30%–40% plagioclases, 15%–25% perthite, 20%–30% quartz, 5%–10% biotite

and accessory minerals, such as zircon, apatite and ilmenite. In thin sections, some fine-grained felsic aggregates and the variable degree of foliation structure indicate dynamic metamorphism after their emplacement (Fig. 4f).

The Kangxiwa Group mainly consists of diverse schist and gneiss, including the garnet (bearing) biotite schist, two-mica quartz schist, sillimanite-garnet-biotite schist or gneiss, and garnet-bearing gneiss (Fig. 3e). Strongly deformed felsic pegmatites are occasionally seen on the outcrops (Fig. 3f). The paragneisses are of medium- to coarse-grained foliated phaneritic texture and/or porphyritic phaneritic texture, and gneissic or schistose structure (Fig. 4g and h). Main minerals include sillimanite (1%–10%), diopside (little to 1%), garnet (1%–20%, some up to 50%, as phenocryst Fig. 3c), biotite (10%–25%), muscovite (1%–10%), quartz (20%–40%), plagioclase (1%–5%, some up to 15%), and potassium feldspar (1%–5%). At several outcrops, garnet aggregates are seen (Fig. 3g).

The Tianshuihai Group was considered as the early Mesoproterozoic basement of TSHT (Xinjiang et al., 1993). This group is mainly composed of clastic rocks with minor limestone and underwent low greenschist facies metamorphism and tightly folded deformation (Fig. 3h and i). The Tianshuihai Group was unconformably covered by the late Paleozoic flysch deposit and intruded by the ca. 530 Ma gabbro and Mesozoic granites (Hu

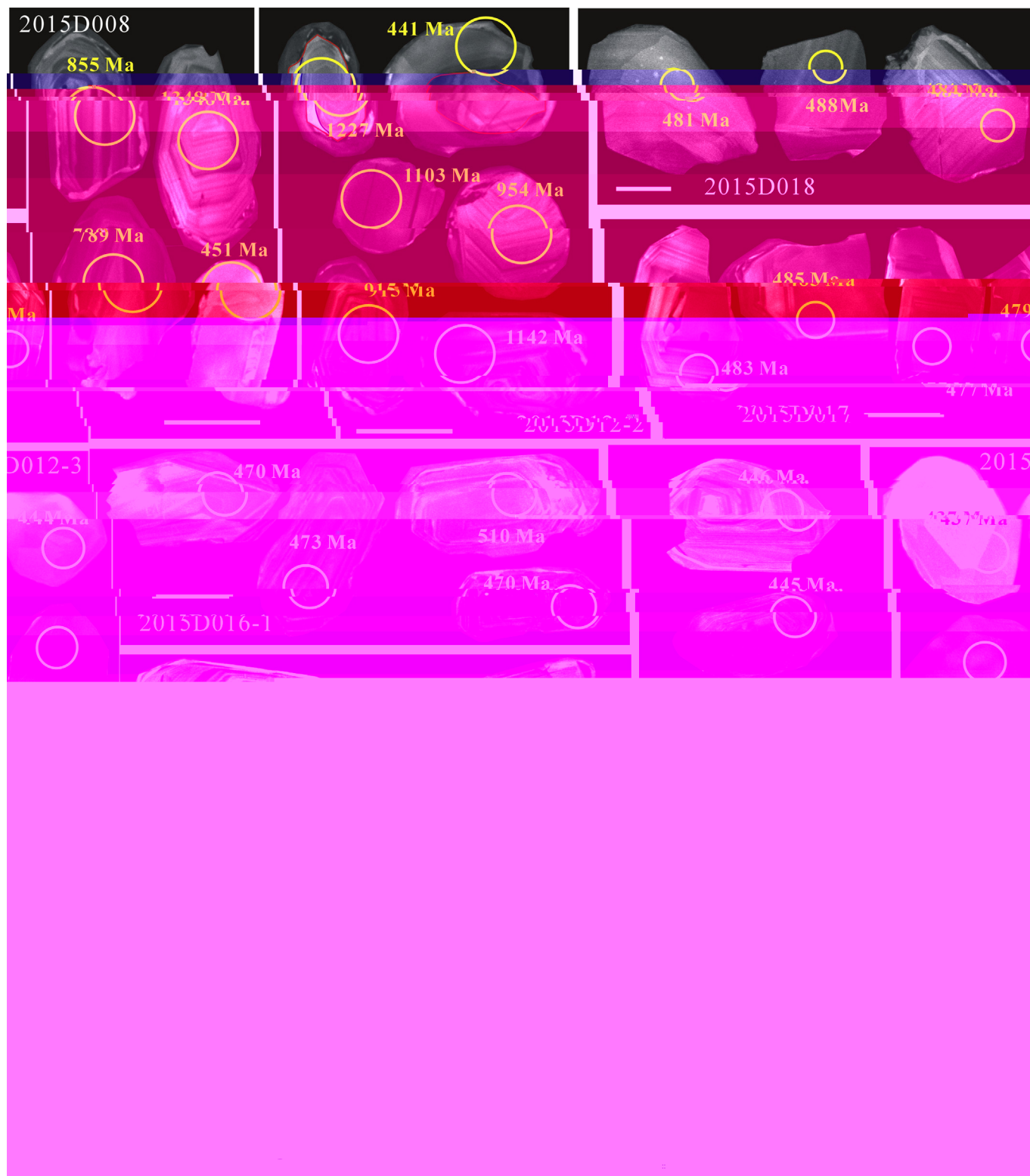


Figure 5. Representative cathodoluminescence images of the zircons from the representative rocks from the Saitula Group, the Kangxiwa Group and the Tianshuihai Group (see details in the text). The scale bar is 50 μm.

et al., 2016). In line with field observations, the main rocks include sericite-chlorite (quartz) schist, siltstone, fine-grained sandstone and plagioclase-quartz greywacke (Fig. 4h and i). Low greenschist facies metamorphic minerals such as biotite, sericite and chlorite are commonly seen in most rock types. Hu

et al. (2016) reported 480–530 Ma granite and gabbro intruding into the Tianshuihai Group, which provided a minimum deposition age. Due to its tight folding, the precise thickness of the Tianshuihai Group sedimentary sequence is unknown (Xinjiang BGM, 1993; Hu et al., 2016).

Seven geochronological samples were collected from the Saitula Group. The rock types include garnet biotite quartz schist (gneiss), gneiss, amphibolite and gneissic granitic dykes within the gneiss-schist. Two samples from two individual granodiorite plutons intruding the Saitula Group were collected for zircon U-Pb and Hf isotope analysis. Sample locations and rock types are given in [Supplementary Table 1](#). Three samples were collected from the Kangxiwa Group. Sample 2015D005-2 and 2015D005-3 are garnet plagioclase gneiss and garnet biotite schist at the same location. Sample 2015D010 was collected from a deformed leucogranite dyke intruding the Kangxiwa Group. Sample 2015D001 and sample 2015D019 collected from the Tianshuihai Group are sandstone samples from a layer within the phyllite, composed of quartz (70%–80%), plagioclase (10%–20%), debris (5%–10%), opaque mineral (pyrite and Fe-Ti oxides), chlorite (less than 5%) and sericite (less than 5%) ([Fig. 4i](#)). Locations of the samples from the Kangxiwa Group and the Tianshuihai Group are given in [Supplementary Table 1](#).

4. Analytical procedures

Zircon and monazite separations were carried out using conventional magnetic and density techniques to concentrate non-magnetic, heavy fractions. Zircon and monazite grains were then hand-picked under a binocular microscope. For the zircon U-Pb dating, the grains and zircon standard 91500 were mounted in epoxy mounts that were subsequently polished to section the crystals in half for analysis. All zircons were documented with transmitted and reflected light micrographs as well as Cathodoluminescence (CL) images to reveal their internal structures. Zircon U-Pb ages were analyzed using the LA-ICPMS method at the Tianjin Institute of Geology and Mineral Resources, Chinese Geology Survey (CGS). A Neptune MC-ICP-MS coupled with a 193 nm excimer laser ablation system was used to determine zircon U-Pb ages. The laser beam diameter was 35 μm and it was operated with a frequency of 10 Hz. Every set of five sample analyses was followed by analysis of the zircon standards 91500 and eight sample analyses followed by the zircon standard GJ-1 ([Jackson et al., 2004](#)), and the glass standard NIST610 ([Hou et al., 2009](#); [Geng et al., 2011](#)). Common Pb was corrected using the method proposed by [Andersen \(2002\)](#). The U-Pb concordia plots were processed with ISOPLLOT 3.0 and data are presented with 1σ errors and 95% confidence limits ([Ludwig, 2003](#)). The zircon U-Pb age data are reported in [Supplementary Table 2](#).

For the monazite U-Pb dating, monazite grains and the monazite standard 44069 ([Wan et al., 2004](#)) were mounted in epoxy mounts. The mounts were subsequently polished to section the crystals almost in half. All the monazite grains were documented with BSE images to reveal their inner structures. Monazite U-Pb ages were determined using the LA-ICPMS method at the same laboratory with the same instrument at the Tianjin Institute of Geology and Mineral Resources. Detailed analytical procedures have been reported in [Cui et al. \(2012\)](#). Monazite U-Pb analytical results are given in [Supplementary Table 3](#).

The zircon Lu-Hf isotope measurements were performed at the Tianjin Institute of Geology and Mineral Resources, mostly on the ablated spots where U-Pb analysis was made. The analytical procedure has been documented in [Wu et al. \(2006\)](#) and [Geng et al. \(2011\)](#). The isotope data are presented in [Supplementary Table 4](#).

5. Analytical results

5.1. Zircon and monazite U-Pb ages of the Saitula Group

Zircons from the two paragneiss samples (2015D008, 2015D012-2) are similar in size and shape. These zircons are 50–150 μm long with length/width ratios of 1–3, and some zircons are rounded or ovoid in shape. Zircon CL images show distinctive features ([Fig. 5](#)). Some zircons exhibit oscillatory zoning, similar to that of the zircons crystallized from silicic magma, whereas others show homogenous or wide striped inner structure, sharing some features of the zircons crystallized from mafic magma. The distinct features of the detrital zircons suggest that they were derived from different sources. Core-mantle structure is commonly seen in CL images but some mantles are too thin for a spot analysis. Most mantles are homogeneous and dark grayish in CL images ([Fig. 5](#)), indicating their high Th and U contents and their possible rapid crystallization in a relatively short time ([Vavra et al., 1999](#); [Whitehouse and Kamber, 2002](#)). Twenty-six and forty-one analyses were conducted for sample 2015D008 and 2015D012-2, respectively. The results show variable Th and U contents and Th/U ratios (mostly higher than 0.4, [Supplementary Table 1](#)). Most analyses on detrital zircons yield concordant ages ranging from 2500 Ma to 600 Ma whereas others show variable degrees of loss of radiogenic Pb ([Fig. 6a](#)). Eight analyses were conducted on the mantle parts of the zircons showing core-mantle structure. Though we tried to carefully avoid the cores during laser ablation, some analyses could be affected by the cores (see following discussions).

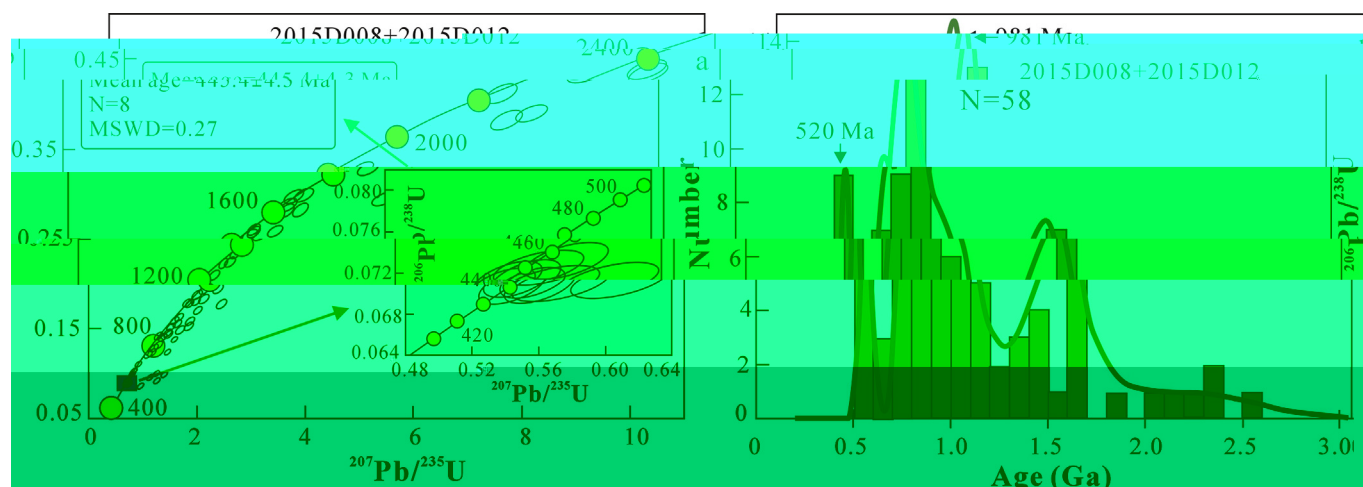


Figure 6. Concordia and the histogram of $^{206}\text{Pb}/^{238}\text{U}$ ages of the detrital zircons of the paragneiss samples from the Saitula Group (see details in the text).

Nevertheless, the eight analyses yield concordant ages with a weighted mean age of 445 ± 6.3 Ma (MSWD = 0.27) (see inset of Fig. 6a). Excluding the spots showing significant radiogenic lead loss, as shown in Fig. 6b, the $^{206}\text{Pb}/^{238}\text{U}$ ages of the detrital zircons from the two paragneiss samples exhibit major age peaks at ca. 520 Ma, 980 Ma and 1600 Ma.

Zircons from the altered gabbro sample (2015D018, Fig. 4b) are subhedral to anhedral and are 80–150 μm long with length to width ratios of 1–2. They are colorless and transparent. In CL images, most zircons show homogeneous, patchy, stripe or zoning texture and lack core-mantle structure, sharing most features of the zircons crystallized from mafic magma (Fig. 5). Twenty-two analyses were obtained and the age results are consistent within analytical errors. These zircons have variable Th and U contents with Th/U ratios ranging from 0.4 to 0.6. The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 481.4 ± 2.1 Ma ($N = 22$, MSWD = 0.68) (Fig. 7a) is interpreted as the crystallization age of the gabbros.

Zircons from the meta-rhyolite sample 2015D017 are of columnar forms, transparent and colorless, ranging from 80 μm to 150 μm in length with length/width ratios of 2–3. According to CL image features, almost all zircon grains display oscillatory zoning, sharing features of the zircons crystallized from silicic magmas. Some of them have core-mantle structure but the mantle part is too thin for a spot analysis (Fig. 5). Thirty-nine analyses were performed on zircons from this sample. They have Th ranging from 180 ppm to 852 ppm and U from 203 ppm to 1185 ppm with Th/U ratios between 0.6 and 0.9. All the analyses yield consistent $^{206}\text{Pb}/^{238}\text{U}$ ages with a weighted mean age of 480.7 ± 1.6 Ma (MSWD = 0.81) (Fig. 7b).

Zircons from the granodiorite sample 2015D016-1 are of columnar forms, transparent and colorless, ranging from 100 μm to 180 μm in length with length/width ratios of 2–3. Almost all zircon grains display oscillatory zoning in CL images. Cracks and metamictization can be seen in some zircons due to their high U contents and such zircons are avoided in analysis. Twenty analyses performed on this sample show that they have Th ranging from 180 ppm to 852 ppm and U from 203 ppm to 1185 ppm with Th/U ratios between 0.6 and 0.9. All the analyses yield consistent $^{206}\text{Pb}/^{238}\text{U}$ ages with a weighted mean age of 470.2 ± 2.2 Ma (MSWD = 0.36) (Fig. 7c). This age is interpreted as the crystallization age of the granodiorite.

Zircons from the gneissic granodiorite samples (2015D014) and the gneissic granite dyke sample (2015D015) have similar features. Most of the crystals are euhedral and range from 80 μm to 150 μm in length with length to width ratios of 1–3. They are transparent and colorless. Euhedral concentric zoning texture is commonly seen, sharing the typical features of the zircons crystallized from granitic magma. Some zircon grains show very thin bright rim in CL image possibly due to the overprinting of the tectonothermal event after their crystallization. Twenty-four and thirty-two analyses were conducted on 2015D014 and 2015D015, respectively. Both samples have comparable Th/U ratios ranging from 0.3 to 0.7 (mostly ~ 0.5) and yield concordant $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages. The mean $^{206}\text{Pb}/^{238}\text{U}$ age of the sample 2015D014 and 2015D015 are 445.0 ± 1.9 Ma (MSWD = 0.68) and 446.0 ± 1.6 Ma (MSWD = 0.93) (Fig. 8A and B), respectively, indicating coeval emplacement of the gneissic granodiorite and the gneissic granite dyke.

Most zircons grains from the amphibolite sample 2015D012-3 are round, transparent and colorless and are 50–120 μm long. Most of them are homogeneous and show relatively bright CL image, sharing features of metamorphic zircons and different from those of the zircons crystallized from mafic magma (Hoskin and Schaltegger, 2001). Thirty-two analyses were conducted on this sample. Their Th content ranges from 13 ppm to 196 ppm, U from



Figure 7. Concordia of the zircon U-Pb data of the gneissic granodiorite, granofels and altered gabbros from the Saitula Group (see details in the text).

110 ppm to 1351 ppm with Th/U ratios from 0.08 to 0.3 (mostly between 0.1 and 0.2). All the analyses yield concordant $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 442.8 ± 1.6 Ma (MSWD = 0.34) (Fig. 8C). This age was interpreted as the amphibolite-facies metamorphic age of the amphibolite.

Monazite grains from the biotite schist sample 2015D013 have anhedral morphology and are 100–150 μm long. In BSE images, most grains are homogenous with some showing patchy patterns with swirling bright and dark domains. The bright and dark domains are carefully avoided for analysis. Thirty analyses were conducted on this sample and almost all the analyses yield concordant $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages. Three spots (13.6, 13.9, 13.19) yield relatively juvenile concordant ages possibly due to

variable involvement of the overgrowth monazites formed after the main metamorphic event. The other 27 analyses yield a mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 440.4 ± 1.8 Ma (MSWD = 1.07) (Fig. 8D).

5.2. Zircon and monazite U-Pb ages of the Kangxiwa Group

Most zircons from the biotite plagioclase gneiss sample 2015D005-2 are generally colorless and some are slight pinkish. They are euhedral to sub-euhedral and are 80–150 μm long with length to width ratios of 1

(ca. 752 Ma) have significantly high $\varepsilon_{\text{Hf}}(t)$ and their $\varepsilon_{\text{Hf}}(t)$ values increase gradually from old population to young population (Fig. 11d). This scenario resembles that of the Neoproterozoic detrital zircons from South China (Li et al., 2014).

the Precambrian metamorphic rocks in NKT, such as the Heluositan Group, Kalakashi Group and Ailiankate Group (Fig. 2; Zhang et al., 2003, 2016b

6. Discussions

6.1. Age of the Saitula Group

In the earlier Chinese geological maps, most high-grade metamorphic rocks were regarded as Precambrian basement due to the lack of reliable fossils or isotopic ages. For example, in South China, the amphibolite-(leptynite)-facies metamorphic rocks in Cathaysia were mapped as the Paleoproterozoic basement. As more and more in-situ zircon U-Pb ages are obtained, geologists have come to realize that the so-called Paleoproterozoic basement actually was deposited during the late Neoproterozoic to early Paleozoic. The amphibolite-(leptynite)-facies metamorphism took place at ca. 440–430 Ma because of the presence of abundant zircons of Pan-African ages (Wan et al., 2007, 2010; Li et al., 2014 and references therein).

Similar to the scenario in South China, the Saitula Group was considered as the Precambrian basement of the SKT drifted from the southern margin of the Tarim Block, on the basis of their amphibolite-facies metamorphism (e.g., Xinjiang BGMR, 1993; Han et al., 2004; Cui et al., 2006a, 2006b). According to field observations, the rock association of the Saitula Group differs from those of

and the deformed leucogranite dyke revealed that the high-grade greenschist- to amphibolite-facies metamorphism of the Kangxiwa Group took place at ca. 210–200 Ma. The youngest detrital zircon group yields a concordant age of ca. 450 Ma. Thus, the Kangxiwa Group was deposited after 450 Ma, possibly during the late Carboniferous to late Permian (Zhang et al., 2017a, b), rather than Mesoproterozoic as previously thought.

6.3. The age of the Tianshuihai Group

The deposition age of the Tianshuihai Group could be tightly constrained by the age of the youngest detrital zircon group and the age of the early Paleozoic gabbroic intrusion, i.e., it should be younger than 743 Ma and older than 530 Ma (Hu et al., 2016). Thus, the Tianshuihai Group was deposited most likely during the late Neoproterozoic. Rock association of the Tianshuihai Group display the typical features of sedimentary sequences at passive continental margins, and the low-grade metamorphism of the Tianshuihai Group suggest that it had not been deeply buried during the evolution of the Tethys due to the possible presence of a basement beneath it (Zhang et al., 2018b).

6.4. Tectonic attribution of the Saitula Group and Kangxiwa Group

In line with the mineral compositions and textures, the precursors of some plagioclase-rich gneiss from the Saitula Group were likely volcanoclastic rocks. The common occurrence of amphibolite (meta-basalt), granofels (meta-rhyolite) interlayered within metamorphic immature clastic rocks (including volcanoclastic rocks) display typical features of the accretionary complex in the southern margin of the Altai orogenic belt (Xiao et al., 2009). On the other hand, we note that voluminous early Paleozoic granite-granodiorites and minor gabbros intruded the Saitula Group. Some of these granitic intrusions emplaced before 440 Ma exhibit gneissic structure and all of them show features typical of

magmatic arc I-type granites (Pan, 1993, 1996; Yuan, 1999; Yuan et al., 2002; Cui et al., 2007a). Thus, the volcanic-sedimentary sequence of the Saitula Group and the intrusions constitute a typical early Paleozoic magmatic arc system.

In line with the rock association and its deposition age (late Paleozoic to early Mesozoic), the Kangxiwa Group most likely represents an overlying clastic sequence deposited after the amalgamation between NKT and TSHT. It was deeply buried during the early Mesozoic accretion process (210–200 Ma) and was exhumed possibly during the sinistral strike-slip motion of the Kangxiwa fault.

6.5. Tectonic attribution of the Tianshuihai terrane

The tectonic attribution of the Precambrian terranes distributed in the Tibet Plateau is unclear. Geologists have agreed that the Lhasa terrane, possibly including the South Qiangtang terrane, was drifted from the northern margin of the Gondwana due to their overprint by the Pan-African metamorphism (Zhu et al., 2011; Zhang et al., 2012). As for other terranes, studies in recent years revealed that most of them, such as the Qilian and Qaidam, share most Precambrian features with those of the Tarim and Yangtze (Song et al., 2010; Chen et al., 2012, 2013; Tung et al., 2012, 2013; Zhang et al., 2013). The age spectra of the detrital zircons and rock association of the Tianshuihai Group are similar to those of the late Neoproterozoic rocks in South China (Banxi Group and its equivalents, Meng et al., 2013; Song et al., 2017; Zhang et al., 2017). The lack of the Pan-African metamorphism in these terranes indicates that they were likely located at the northern fringe of the Gondwana and had never drifted far away from the India-Australia during the breakup of the Rodinia, which is entirely consistent with paleontology evidence (Metcalf, 2011, 2013; Zhang et al., 2015; Metcalf et al., 2017; Li et al., 2018). Thus, we suggest that the Tarim-Yangtze affinity type terranes (including the Qilian, Qaidam, Northern Qianling, Tianshuihai) could be located at the northern

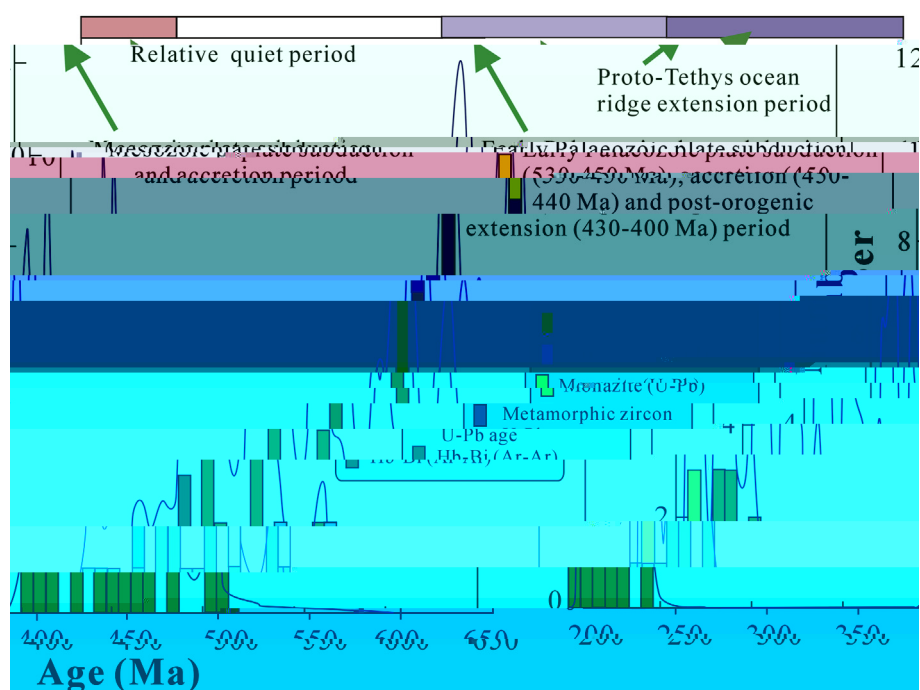


Figure 12. Histogram of the zircon U-Pb ages of the intrusive rocks, the metamorphic zircon and monazite U-Pb ages and mineral (hornblende, biotite) Ar-Ar ages for amphibolite-facies metamorphic rocks in SKT (data are from Cui et al., 2006a, 2007a,b; Zhang C.L. et al., 2007a; Zhang Y. et al., 2016a and references therein and this study).

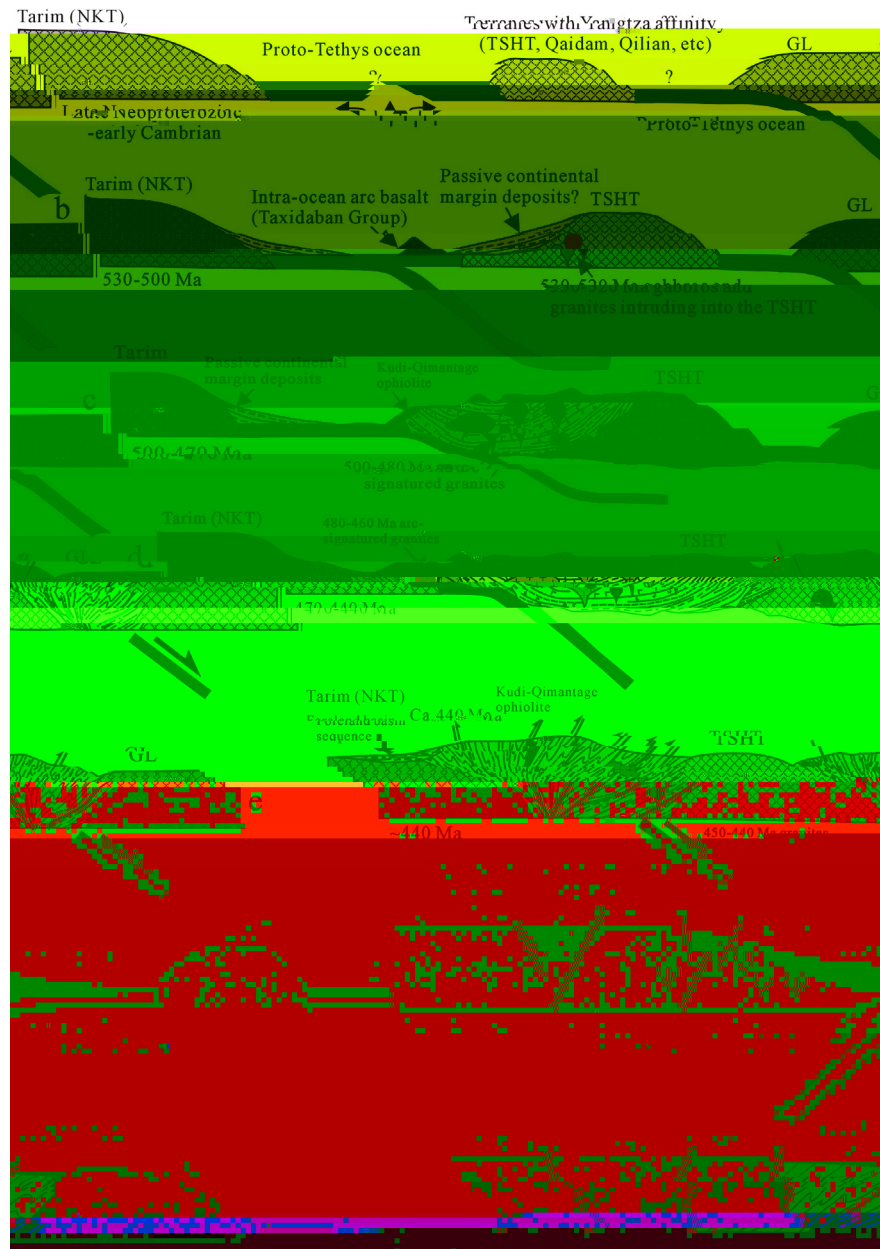


Figure 13. A schematic diagram to illustrate the tectonic evolution of the eastern section of WKOB (see details in text). Abbreviations: NKT—the North Kunlun terrane, SKT—the South Kunlun terrane, TSHT—the Tianshuihai terrane, KAT—the Karakorum terrane, GL—Gondwanaland.

margin of the Gondwana (Metcalf, 2011, 2013; Metcalfe et al., 2017). This conclusion could well account for the commonly seen Pan-African detrital zircons from the Saitula Group.

6.6. Tectonic evolution of the WKOB

Geochronological data of the voluminous granites intruding the Saitula Group (Fig. 1b) (including minor mafic intrusions) revealed that the igneous activities in the eastern section of the WKOB could be divided into two distinct phases, i.e., 530–400 Ma and 240–200 Ma, which is consistent with metamorphic ages of the gneiss-schists in SKT (Fig. 12). According to the geochemical characteristics of the early Paleozoic granites, the 500–450 Ma granites show typical I-type features whereas the 430–400 Ma granites evolve from high Ba-Sr granite to A-type granite (Yuan, 1999; Yuan et al., 2002, 2005; Ye et al., 2008). Taken

together, the plate subduction began slightly before 500 Ma and lasted till 450 Ma (Zhang et al., 2018a), and the accretion finished at ca. 440 Ma, according to the ca. 440 Ma amphibolite-facies metamorphism of the Saitula Group. This process was geodynamically related to the assemblage of the blocks in northern Tibet and eastern Asia (including the Tarim, Qaidam, South Qiangtang, Yangtze, Indochina, Sibumasu, etc.) to the northern margin of the Eastern Gondwana (Metcalf, 2011, 2013; Diwu et al., 2014; Metcalfe et al., 2017; Li et al., 2018). In combination with the commonly seen early Paleozoic orogenic events along the northern Qaidam, Qilian, Qinling, Cathaysia and terranes in Southeast Asia (Domeier and Torsvik, 2014; see details in Li et al., 2018), we suggest that the final assemblage of the above blocks to the Eastern Gondwana finished at 440–430 Ma.

We construct a cartoon model to illustrate the tectonic evolution of the eastern section of the WKOB. The prerequisite of this model is

that the Yangtze, Tarim, Qaidam, Qilian and TSHT were nearby the India-Australia during breakup of the Rodinia, and that shallow marine or limited ocean basin, *i.e.*, the Proto-Tethys ocean, was developed between the India-Australia and these terranes. Such a spatial pattern could guarantee the transport of the Pan-Africa detritus from Gondwana to the Tarim-Yangtze terranes (Fig. 13a). The southward Proto-Tethys ocean intra-ocean subduction possibly began at ca. 530 Ma, in line with the late Sinian to early Cambrian Taxidaban Group intra-ocean arc basalts and the ca. 530 Ma gabbro intruded into the Tianshuihai Group (Fig. 13b; Guo et al., 2002; Gao et al., 2015; Hu et al., 2016). This process also incubated the volcanic arc at the northern margin of the THST and this long-term subduction induced the large accretionary wedge at the northern margin of the THST (Fig. 13c and d). The ca. 510–490 Ma SSZ-type Kudi-Qimanyute ophiolite belt, mainly distributed at the northern margin of this accretionary wedge, most likely formed at a fore-arc environment, according to the geochemistry of the basalts that evolves from typical MORB to island-arc features (Han et al., 2002; Ji et al., 2004; Yuan et al., 2005). At ca. 440–450 Ma, NKT collided with TSHT, leading to the amalgamation between NKT and TSHT (Fig. 13e). Slab delamination induced the ca. 430–400 Ma post-orogenic igneous activities in the collision zone and the southern margin of the NKT (Ye et al., 2008). The orogenic events at this time were also well documented in Qilian, Qingling and Cathaysia, indicating the final assemblage of the Tarim, Qaidam, Qilian, North Qinling and Yangtze to the northern margin of the Gondwana (Fig. 13e; Domeier and Torsvik, 2014; Cao et al., 2017; Metcalfe et al., 2017; Li et al., 2018).

We notice a relatively quiet period between 400 Ma and 250 Ma in the eastern section of WKOB as demonstrated by the absence of igneous activities and metamorphism (Fig. 12). The Devonian red molasse transformed into late Carboniferous - Permian passive continental margin sedimentary sequence. Since the late Paleozoic to early Mesozoic, the northward subduction of the Paleo-Tethys Ocean along the southern margin of TSHT generated the magmatic arc along the southern margin of SKT-TSHT and the back-arc volcanic sequence along the northern side of SKT (Fig. 13f, *e.g.*, Domeier and Torsvik, 2014; Cao et al., 2017; Metcalfe et al., 2017; Li et al., 2018). The accretion of the Karakorum terrane to the NKT-SKT finished at ca. 200 Ma, according to the metamorphic ages of the Kangxiwa Group and the common Jurassic molasse unconformably in the SKT and the TSHT (Fig. 13g).

7. Conclusions

(1) The Saitula Group in NKT and the Tianshuihai Group in TSHT were deposited during the late Neoproterozoic to early Paleozoic, rather than Mesoproterozoic or Paleoproterozoic. The Kangxiwa Group was deposited during the late Paleozoic rather than Mesoproterozoic. Thus, our study does not favor the existence of a Precambrian basement in SKT.

(2) The s46arw4edimea8(46ar)1lher(2(igneThe)-505.8(ac-268(45c,-)we6(og)2dr(2)-259period bin TSHTearish39.3(H),3lime9.7(o)i-sQila-256.93ti3Bh

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