The Precambrian Geology of the Tibetan Plateau

Fulai Liu, Yongsheng Dong and Chaohui Liu

Abstract The Tibetan Plateau, which includes all the Tibet and Qinghai Provinces, the southern Xinjiang and Gansu Provinces and the western Sichuan and Yunnan Provinces, is a tectonically active region among the Indian, Yangtze, Tarim, and North China blocks. On the basis of the geological background, it can be divided into the Altyn-Qaidam-West Qinling orogenic system, the Kara Kunlun-Bayan Har-Chamdo-Simao orogenic system, and the Southern Qiang-Gangdise-Himalaya-Baoshan orogenic system from north to south, separated by the Kangxiwa-Southern Kunlun-Madoi-Maqên suture zone and the Longmuco-Two Lake-Lancang River suture zone, respectively. Every orogenic system can be further divided into several terranes by suture zones (melanges) consisting of deep-sea sediment residues, ophiolites (melanges), and high-pressure metamorphic rocks. This chapter describes the distribution, composition, protolith and metamorphic ages, and metamorphic characteristics of the Precambrian geologic units of the terranes and suture zones. Also included are research progress, existing problems, and an overview of different opinions from different researchers on the Precambrian history of the terranes. Additionally, a preliminary summary is given for major geological events and tectonic evolution of every Precambrian orogenic system. The Tibetan Plateau is vast in territory, but the Precambrian geological units distribute scatteredly in tectonic melanges of or between the terranes. Although abundant studies have been made about the Precambrian geology of the Tibetan Plateau, the overall level of geological research is much lower than those of other Precambrian terranes in China. Geochronologic data for each geologic unit is also of confusion, which led

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to divergence on their protolith and metamorphic ages, tectonic attributes, and other aspects, so the crustal evolution studies of the Precambrian Tibetan Plateau need to be further deepened.

Keywords Precambrian rocks · Protolith and metamorphic ages · Orogenic system · Precambrian terrane · Tibetan plateau

1 Distribution of the Precambrian Rocks in the Tibetan Plateau

The Tibetan Plateau is located in the southwest China, including all the Tibet and Xinjiang Provinces, the southern Gansu, and western Sichuan and Yunnan Provinces. It is a tectonically active zone among the Indian, Yangtze, Tarim blocks, and the North China Craton. Its original crustal blocks were formed by accretion, subduction, collision of the margins, or split off pieces of the peripheral continental blocks, and separated by melange belts (suture zones) consisting of deep-sea sedimentary debris, ophiolites (melanges), and high-pressure metamorphic rocks.

According to the current tectonic division scheme, the Tibetan Plateau is divided into the Altyn-Tagh-Qaidam-western Qinling orogenic system, the Karakorum-Bayanhar-Qamdo-Simao orogenic system, and the Southern Qiangtang-Gangdise-Himalaya-Baoshan orogenic system from north to south, in which the southern and western extensions of the South Qiang-Gangdise-Himalaya-Baoshan orogenic system is outside of China. The boundaries are the Kangxiwar-Muztag-Anemaqen suture zone and the Longmu Tso-Shuanghu-Lancang suture zone from north to south (Fig. 1).

The Precambrian rocks in the Tibetan Plateau are scattered and exposed within the blocks or melange belts among the blocks, and the degree of geological research is generally poor. Previous divisions and comparisons of the Precambrian geological units were mostly based on the metamorphic grade or limited and imprecise isotopic geochronology results. In recent years, a number of high precision isotope geochronology data have been achieved, which put more accurate temporal constraints on parts of the Precambrian geologic units. At the same time, some originally defined Precambrian geologic units were also questioned. From the current data, the Precambrian Tibetan Plateau has the following characteristics: (1) there is no unified Precambrian basement in the Tibetan Plateau, and most of the old basement residues have different geologic affinities; (2) the Archean ages only occur in detrital zircons from parametamorphic rocks of different ages and no Archean geological units have been found; (3) Precambrian geological units formed mainly in the Paleoproterozoic to Neoproterozoic (Nanhua). There are still the following problems: (1) due to the lack of geochronology, paleontology, and other aspects of data, parts of the geology units do not have accurate ages, which were

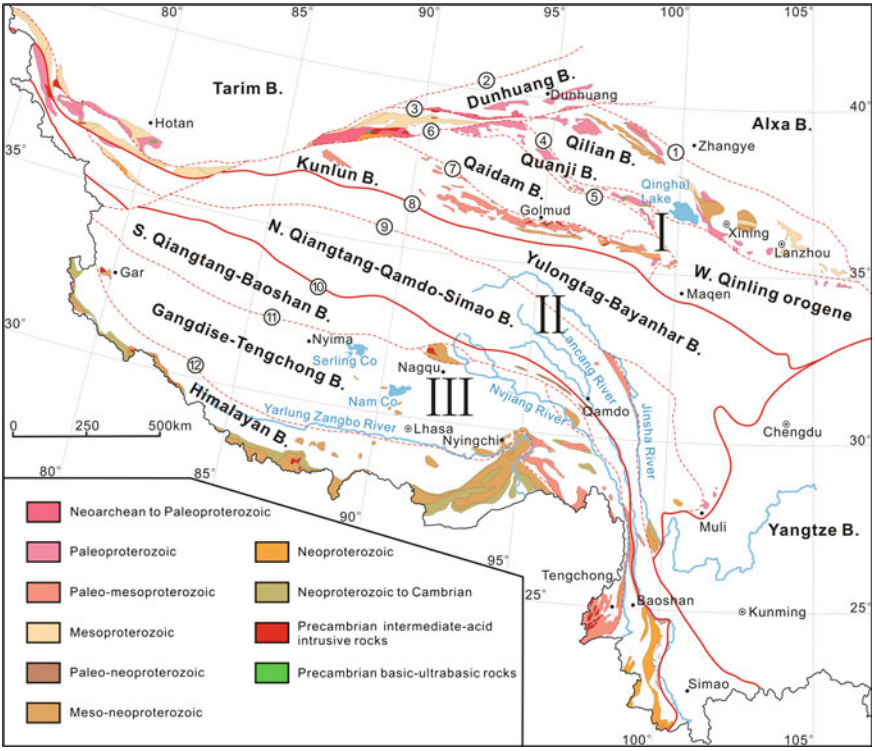

Fig. 1 Geological map showing the distribution of Precambrian rocks in the Tibetan Plateau. *I* Altyn-Tagh-Qaidam-western Qinling orogenic system; *II* Karakorum-Bayanhar-Qamdo-Simao orogenic system; *III* Southern Qiangtang-Gangdise-Himalaya-Baoshan orogenic system. ① Sunan-Tianzhu suture zone; ② Qiemo-Xingxingxia fault; ③ Hongliugou-Lapeiquan suture zone; ④ DaQaidam-Zongwulongshan fault; ⑤ North Qaidam ultrahigh-pressure metamorphic belt; ⑥ Altyn Tagh fault; ⑦ South Qaidam fault; ⑧ Kangxiwar-Muztag-Anemaqen suture zone; ⑨ Yanghu-Jinsha suture zone; ⑩ Longmu Tso-Shuanghu-Lancang suture zone; ⑪ Bangong-Nujiang suture zone; ⑫ Yarlung Zangboe suture zone. *G.* Group, *B.* Block

often placed as Paleo- to Mesoproterozoic, Meso- to Neoproterozoic, Sinian-Cambrian and other general statements, even a broadly temporal constraint as Proterozoic; (2) due to the complexity of tectonic deformation in the orogenic systems, the division is a bit confusing and there are phenomenons of homonym or homonyms; related to this, geochronology data of each geologic unit is also confused, which led to different opinions on its formation age, tectonic characteristics, and other aspects. These issues also restricted the study on the Precambrian crustal evolution of the Tibetan Plateau.

2 Precambrian Rocks in Different Orogenic System

Precambrian geological units in the Tibetan Plateau are distributed scatteredly in the Altyn-Tagh-Qaidam-western Qinling orogenic system, the Karakorum-Bayanhar-Qamdo-Simao orogenic system, and the Southern Qiangtang-Gangdise-Himalaya-Baoshan orogenic system, which have geologic affinities with the Tarim and North China blocks, Yangtze block, and the Indian block, respectively. The Precambrian geological units relatively concentrate in the northern and southern margins of the Tibetan Plateau.

2.1 Precambrian Rocks in the Altyn-Qaidam-West Qinling Orogenic System

The Altyn-Tagh-Qaidam-western Qinling orogenic system includes the Dunhuang, Qilian, Altyn, Quanji, Kunlun Mountain, and the Western Qinling blocks, and the Saishiteng-Xitieshan (North Qaidam), Kangxiwa-Muztagh-Machen suture zones (Fig. 2).

2.1.1 Neoarchean-Paleoproterozoic

Dunhuang Block The oldest metamorphic basement rocks in the Dunhuang block is the Aktas Tagg complex (formerly known as the Milan group), which outcrops EW in the southern Dunhuang block. Its southern boundary is in fault contact with the Hongliugou-Lapeiquan ophiolite melange of the northern Altyn block and unconformably overlied by the Luanshishan Formation of the Xorkol Group (Qingbaikou system) in the Inge Burak.

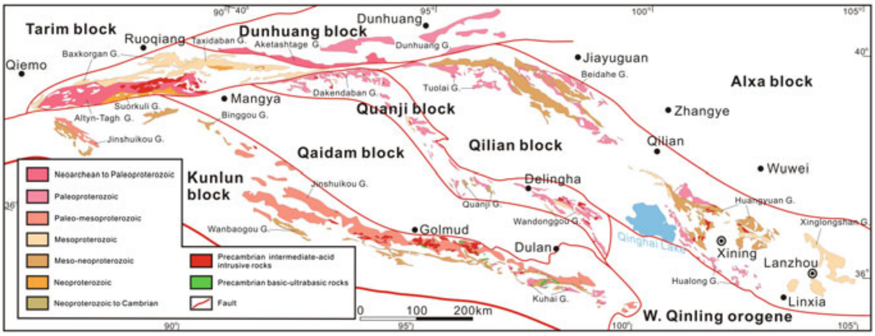

Fig. 2 Geological map showing the distribution of Precambrian rocks in Altyn-Tagh, Qaidam, and Qilian regions. *G.* Group

The Aktas Tagg complex consists of different types of mafic granulites, amphibolites, TTG granitic gneisses, and marbles, as well as charnockites. Different mineral assemblages of supracrustal rocks and charnockite indicate that they have reached the granulite-facies metamorphism (Lu et al. 2008).

Zircon U–Pb and Sm–Nd isochron ages obtained from the Aktas Tagg complex are 2460–2789 Ma (Xinjiang Uygur Autonomous Region Bureau of Geology and Mineral Resources 1993; Che and Sun 1996). Li et al. (2001), Lu et al. (2002a, b, 2006 2008) obtained zircon ages of different rock types from the Aktas Tagg complex by zircon U–Pb TIMS and SHRIMP methods. The age of magmatic zircons from tonalite gneiss is at 2604 ± 102 Ma, magmatic zircon age of adamellite is about 2830 ± 45 Ma, and magmatic zircon age of granitic gneiss is at 2396 ± 36 Ma (Lu et al. 2008), and the inheritance zircons of 3574–3665 Ma are the oldest in the northwestern China so far (Li et al. 2001; Lu et al. 2008). Meanwhile, analysis on the metamorphic zircon rims from the TTGs and metamorphic zircons from the paragneisses gave metamorphic and anatexis ages of 1978 ± 50 and 1986 ± 29 Ma. Xin et al. (2011) obtained SHRIMP U–Pb zircon ages of 2567 ± 32 and 2592 ± 15 Ma from the felsic gneisses and TTGs of the Aktas Tagg complex and suggested them to represent the continental crust accretion of the southern margin of the Tarim craton.

2.1.2 Paleoproterozoic

Dunhuang Block The Paleoproterozoic rocks in the Dunhuang block is called the Dunhuang Group, which mainly outcrops in the north of the Calatayud Alushta Georgia-Kyzy Le Tagg region (Fig. 2). Its rock assemblage has khondalite characteristic and is mainly composed of Al-rich felsic gneisses, including garnet-biotite gneisses, garnet-biotite-hornblende-plagioclase gneisses, leptites and biotite-quartz schists, marbles, graphite-bearing quartzites and garnet-amphibolites, interlayered with a small amount of biotite-plagioclase gneisses and amphibolites. The protoliths are terrigenous clastic and carbonate rocks interbedded with volcanics. The group's stratigraphic features is clear and dominated by amphibolites at the bottom, quartzites and biotite-quartz schists in the middle and marbles at the top, which has been metamorphosed at amphibolite facies.

Xin et al. (2011) obtained SHRIMP U–Pb age of 2140 ± 9 Ma from the volcanic interlayer of the Dunhuang Group and 2135 ± 10 Ma from the diorite pluton, indicating the formation age of Paleoproterozoic.

The Paleoproterozoic intrusions are distributed in the west Kumu Burak-Kalata Shi Tage area, north of the Lapeiquan. Most of the intrusions are distributed in NW or EW trending and mainly amphibolites and dioritic gneiss (gneissic diorite), quartz-dioritic gneiss (gneissic quartz diorite), gneissic hornblende syenite (K-feldspar hornblende gneisses) metamorphosed from mafic dikes. Zircon SHRIMP U–Pb ages are 2135, 2051, and 1873 Ma, respectively, representing the early subduction stage, the syn-collision stage, and post-orogenic stage (Xin et al. 2011). Zhang et al. (2012, 2013a) identified high-pressure granulites in the Dunhuang block and achieved relatively high P/T peak metamorphic conditions and clockwise P-T path, implying that these high-pressure rocks are the product of a collision event. Metamorphic ages were obtained on metamorphic zircons and restricted at 1.83–1.84 Ga, suggesting that the Dunhuang block experienced the late Paleoproterozoic (high pressure) granulite-facies metamorphic event (Zhang et al. 2012, 2013a).

Altyn Block The Neoarchean-Paleoproterozoic rocks are mainly exposed in the western part of the Altyn block and in the small area of the middle part, which are known as the Altyn group. Supracrustal rocks of the group can be divided into two types, in which the first type consists of (garnet) plagioclase amphibolites, (garnet) biotite leptynites, sillimanite-bearing biotite-plagioclase gneisses, biotite-schists, and (graphite) marbles. These rocks have experienced strong deformation and amphibolite-facies metamorphism. The second rock assemblage is high-pressure metamorphic pararocks, including kyanite-biotite-plagioclase gneisses and garnet amphibolites. The two types of rock have no contact relationship in space, but outcrop as different scale of lenticulars in the granitic gneisses. The degree of deformation and metamorphism of the supracrustal rocks are clearly different from the granitic gneisses. Besides intrusive contact, the supracrustal rocks and the granitic gneisses are in tectonic contact (ductile and brittle tectonic belt). Due to the deformation and metamorphism, supracrustal rocks only locally preserve blasto-bedding structures and geochemical composition of mafic volcanic rocks show within-plate and continental margin features.

Hu et al. (2001) obtained U–Pb zircon upper intercept age of 1820 ± 27 Ma and T_{DM} ages of 1.82–1.94 Ga from a gneiss sample of the Altyn group. Mao et al. (2000) got TIMS zircon U–Pb apparent age of 2459 ± 48 Ma from the Keke Sa biotite-feldspar gneiss. Zhang et al. (2000) obtained U–Pb zircon age of 2571 ± 340 Ma (detrital zircon), 1027 ± 10 Ma (upper intercept age), 481 ± 19 Ma (lower intercept age) from the khondalite rocks in the Tula area. Guangxi Institute of Geological Survey obtained U–Pb zircon ages of 1368 ± 49 Ma (upper intercept age) and 566 ± 14 Ma (lower intercept age) from the Qingshuiquan supracrustal rocks. Combined with the metamorphic features, the Altyn is considered as Paleoproterozoic and may experience later metamorphism.

Qilian Block The Paleoproterozoic rocks in the middle Qilian block are called the Tuolai and Beidahe groups, whereas the souther Paleoproterozoic rocks are named as the Hualong group.

The Tuolai and Beidahe groups are exposed in the Tuolaishan and Menyuan areas. The rock association is dominated by biotite-quartz schist, amphibolite, diopside marble, dolomite, quartzite, and leptynite, interbedded with biotite-amphibolite gneiss, which have experienced high amphibolite-facies metamorphism. Zhang et al. (1998) obtained Sm–Nd isochron age of 1980 ± 27 Ma from the plagioclase amphibolite, quartz-actinolitite, plagioclase-biotite schist of the Beidahe group in the north of Diaodaban, and considered it as the formation age.

However, Li et al. (2007) suggeted that the Beidahe group was deposited between 1400 Ma (the minimum detrital zircon age) and 863 Ma (the metamorphic age), not the previously believed Paleoproterozoic, based on the detrital zircon SHRIMP U–Pb results from the muscovite-quartz schist. He et al. (2010) also implied that the group was deposited between 1400 and 724 Ma based on their detrital zircon studies on the Beidahe group in the Danghe area of the Gansu Province.

The Hualong group is mainly exposed on the eastern side of the Qinghai Lake and consists of high amphibolite-facies metamorphic rocks characterized by low-pressure high-temperature metamorphic minerals, including andalusite and sillimanite (Fig. 2). Their protoliths are clastic rocks with a small amount of mafic volcanic rocks and carbonate rocks, similar to the Paleoproterozoic basement rocks in the middle Qilian block. Researcher has different opinions on the age of the Hualong group, including a series of Rb–Sr isochron age of ~1.4 Ga, 2331 ± 215 Ma U–Pb upper intercept age of granitic veins in the gneisses (1:250000 Menyuan 2006), TIMS zircon U–Pb age of 750 ± 30 Ma from the potassic granite intruding the Hualong gneiss (Wan et al. 2003), zircon LA-ICP-MS upper intercept age of 875 ± 8 Ma from weakly gneissic granite vein (Xu et al. 2007). Therefore, the protolith of the Hualong group is generally believed to form at Paleo- to Mesoproterozoic and metamorphised at ~1.0 Ga.

The Xinglongshan group is exposed in the southeastern Qilian block and consists of biotite-plagioclase (monzonite) gneisses, garnet amphibolites, sillimanite-garnet-biotite-quartz schists, biotite-plagioclase leptynites, quartz marbles, graphite marbles, diopside-plagioclase leptynites, and stripped migmatites. Some of the plagioclase amphibolites are mostly massive and display gradual transition relationship with mafic dikes (Chen et al. 2002).

Quanji Block The Paleoproterozoic geologic units in the Quanji block include the Delingha complex and the Dakendaban group, which are associated in space (Fig. 2).

The early Paloeproterozoic Delingha complex is dominated by monzogranitic gneiss, in which amphibolites exist as different sizes and shapes of inclusions. Single zircon U–Pb ages of 2412 ± 14 and 2366 ± 10 Ma have been obtained from the amphibolite and monzogranitic gneiss (Lu et al. 2002a).

The Dakendaban group is distributed along the southern slope of the Altyn Mountain and the northern Qaidam Basin and consists of quartzites, garnet-sillimanite-quartz schists, mica schists, amphibolite schists, and a small amount of granulites. The protoliths are dominated by major clastic rocks and minor volcanics, which suffered high amphibolite to granulite-facies metamorphism. Based on the Sm–Nd isochron age of 1791 ± 37 Ma from the mafic granulite (Zhang et al. 2001), the protoliths are suggested to form in the late Paleoproterozoic.

Kunlun Block The Kunlun block is divided into the West Kunlun and East Kunlun, separated by the Altyn fault.

In the West Kunlun, the Paleoproterozoic Kulangnagu group is well exposed in the Datong city, the Kulangnagu drainage basin and north of the Xaidula city. It is in fault contact with the surrounding stratum and is a set of middle to high metamorphosed rock, which can reach high amphibolite facies. The group can be divided into two formations, A and B. Formation A is composed of various schists (muscovite schists, biotite-quartz schists, two-mica schists, two-mica-quartz schists, amphibolite schists) and quartzites, with a small amount of marbles, gneisses (biotite-plagioclase gneisses, biotite-diopside-plagioclase gneisses) and volcanic layers. Formation B is dominated by marbles, which suffered talc and tremolite alterations. The protoliths of the group are clastic rocks at the bottom, clastic rocks interlayered with carbonate rocks in the middle, and carbonate rocks at the top. Reliable age constraints of the group are absent and the granite intrusion gave zircon U–Pb age of 480–495 Ma (1:250000 Yecheng). The metamorphic and deformation characteristics are similar with those of the Xaidula group in the west, so the group is temporarily assigned to the Paleoproterozoic.

In addition, the Paleoproterozoic Elian Carter group and Hero Stan TTG complex are exposed at the southern edge of the Tarim Basin, northern part of West Kunlun, which do not have direct contact in the region. The Elian Carter group is exposed along the Tikriklamu Ron and Boston rivers and extends south to the Hotan city. It consists of quartz-mica schists, marbles, and garnet-biotite-plagioclase (monzonite) gneisses in the north of Kangxiwar and locally unconformably overlied by the spilite keratophyres and clastic rocks of the Changcheng system Serra Jiazitage group, of which the latter is constrained as 1764 Ma, so the underlying group is placed as the Paleoproterozoic.

The Herro Stan complex scattered outcrops in the Aotulageyer and Ca Rava Schickel areas, south of the Yecheng city. The rock assemblage is TTG series granitic gneisses and unconformably overlied by the Jixian system Borchardt Tagg formation. Zhang et al. (2004) obtained zircon SHRIMP U–Pb ages of 2426 ± 46 Ma from the granitic gneiss.

In the East Kunlun, the Paleoproterozoic Jinshuikou group is exposed in the Baisha River and Jinshuikou areas and composed of various leptynites, gneisses, migmatites, migmatic gneisses, migmatic granites, dolomite marbles, olivine marbles, and amphibolites (Fig. 2). Sillimanite-andalusite schists are found in the western Kaimudu Taseer regions and sillimanite-andalusite-biotite-plagioclase gneisses are recognized in the Ren Su Haitu River and Dahuozao River areas. The metamorphic grade becomes higher in the Tiantai Mountain, where migmatites, two-pyroxene granulites and amphibolite granulites occur. Two-pyroxene granulites and leptynites occur from the Jinshuikou to Jialu River in the east. The protoliths are clastic rocks, mafic volcanic rocks, and magnesium-rich carbonate rocks, reflecting the characteristics of active continental margin tectonic setting. Overall, the group evolved from the volcanic and clastic rocks at the bottom to carbonate rocks at the top. From west to east, terrigenous clastic and volcanic rocks decrease and carbonate rocks increase, combined with decreasing of strata thickness. It is generally believed that the Baishahe group has undergone two stages of metamorphism, including the Luliang and Jinning events.

The Paleoproterozoic Kuhai group in the south section of Burhan Budai Mountain is a set of amphibolite-facies metamorphic rocks, including a variety of gneisses, plagioclase amphibolites, biotite-quartz schists, and diopside marbles. In fact, in addition to the original metamorphic supracrustal rocks (including clastic rocks, intermediate-mafic volcanic rocks, and carbonate rocks), there are a large amount of metamorphic felsic intrusions, which have experienced strong migmatization and have complex features.

The time constraints on the Kuhai group are inconsistent. Previous studies got Sm–Nd whole-rock isochron age of 2213 ± 17 Ma from the intruding mafic dykes, and obtained U–Pb zircon upper intercept age of 2330 ± 50 Ma and lower intercept age of 746 ± 6Ma from hornblende-plagioclase gneiss of the group. Wang et al. (2007) obtained U–Pb zircon age of 1441 Ma from biotite-plagioclase gneiss, Rb–Sr ages of 1167 ± 19 and 1132 ± 69 Ma, respectively, from mica-quartz schist and gneiss, and suggested that the formation age of the complex is at Paleo- to Mesoproterozoic and its final consolidation time should be the end of the Mesoproterozoic.

Western Qinling Block The Paleoproterozoic rocks of the Western Qinling block mainly occur in the Wushan-Gangu area, known as the Qinling group, which is mainly a set of high amphibolite-facies metamorphic rocks. The lower part consists of biotite-plagioclase gneisses, amphibolites, biotite-quartz schists, amphibolite schists and marbles, graphite marbles and the upper part is composed of quartz-biotite schists and quartzites, interbedded with stripped marbles and amphibolites, whose portoliths are terrigenous clastic-carbonate rocks.

Lu et al. (2006) dated the detrital zircon of pararocks of the Qinling group by U–Pb SHRIMP and LA-ICP-MS methods and found that its provenance is mainly 1.5–1.9 Ga granites and the group was most possibly deposited at the end of the Mesoproterozoic.

Saishiteng-Xitieshan Suture Zone (North Qaidam) The Mesoproterozoic rocks in the Saishiteng-Xitieshan suture zone are mainly Shaliuhe group, which mainly consists of various schists, including quartz-mica schists, banded quartz schists, plagioclase-amphibolite schists, and garnet-amphibolite-quartz schists, with eclogite enclaves. Mineral assemblage of different rocks are basically consistent with the Dakendaban group in the north. The protoliths are a set of intermediate-mafic volcanic rocks at active continental margin. The direct isotopic age constaint on the goup is absent for now. The protoliths of eclogites are ocean floor basalts, ocean island basalts, and island arc basalts, and involved continental crust materials in deep subduction (Yang et al. 2003). Based on the rutile inclusions in the kyanite and coesite inclusions in the zircon from the Beishan gneiss in the north of the Yematan (Yang et al. 2002; Song et al. 2003), supracrustal rocks experienced deep subduction and UHP metamorphism.

Single zircon U–Pb upper intercept age of 2017 ± 31 Ma and lower intercept age of 2018 ± 31 Ma have been achieved from mylonitized amphibolite (1:250000 Dulan County 2006). Upper intercept age of 2002 ± 60 Ma and lower intercept age of 219.11 Ma were obtained from the biotite-quartz shicst, showing that it was formed in the Paleoproterozoic and may be equivalent to the Dakendaban group in the north Quanji block.

Kangxiwa-Muztagh-Machen Suture Zone In the western Kangxiwa-Muztagh-Machen suture zone, the Paleoproterozoic Kangxiwa group is sandwiched in the melange as different sizes of tectonic enclaves, which consists of biotite-plagioclase gneisses, garnet-amphibolite-biotite-plagioclase gneisses, garnet-biotite-plagioclase quartzites, granet-plagioclase leptynites, garnet (sillimanite)-biotite-plagioclase leptynites, garnet quartzites, silimanite biotite-quartz schists, garnet (sillimanite)-two-mica (biotite)-quartz schists. The protoliths mainly belong to continental island arc rocks, some of which also have characteristics of oceanic island arc. The peak metamorphism reached to high amphibolite facies.

A set of middle-high metamorphosed stratum was disintegrated from the Triassic Keleqinghe group, which has reached high amphibolite metamorphism and was though to be comparable with the Ailiankete group and higher than those of the Tianshuhe, Sailatu and Sailajiazitage groups in the metamorphic grades (Shaanxi Institute of Geological Survey 2006). The geochemical compositions of metamorphic clastic rocks are similar with the Archean meta-clastic rocks, rather than the Proterozoic meta-clastic rocks. Based on regional stratigraphic correlation, the group was thought to be formed at Paleoproterozoic.

2.1.3 Mesoproterozoic

Qilian Block The Mesoproterozoic strata in the Qilian block include the Changcheng system Xinglongshan, Zhulongguan, Haiyuan groups and the Jixian system Tuolainanshan, Gaolan and Huangyuan groups, whose rock types are complex and metamorphic features change from area to area. The greenschist-facies to low amphibolite-facies metamorphic rocks and the related mineral assemblages have been found. The greenschist rocks (metabasalt) of the Haiyuan group were dated at 800 ± 40, 1002 and 1128 ± 209 Ma by Rb–Sr whole-rock method (1:50000 Nianhaowan and Dalachi 1992). The Neoproterozoic Qingbaikou system is a set of stromatolites and microfossils rich clastic-carbonate rocks, the bottom conglomerates of which unconformably overlies the metamorphic basement rocks.

The Neoproterozoic granites invading the Paleo- to Mesoproterozoic stratum have two age groups, including ~800 and ~900 Ma. ~800 Ma granitic rocks consist mainly of granodiorite and granite, whose geochemical characteristics imply rift environment. In constrast, ~900 Ma granitic rocks include quartz diorite, granodiorite, and granite, which formed in active continental margin (Tung et al. 2013). Amphibolite-facies metamorphosed mafic rocks (gabbro) in the southeastern block have crystallization ages of 905 ± 6 and 919 ± 10 Ma, whose geochemical characteristics indicate continental island arc setting (Tung et al. 2012).

Quanji Block The Mesoproterozoic metamorphic rocks distributed between the Tanjianshan and Wandonggou are called the Wandonggou group, of which the lower part is composed of phyllites, sericite phyllites interlayered with limestones and minor amphibolite schists, the central part consists of dolomites, marbles interbedded with sandstones, and the upper part is limestones, marbles, dolomite marbles sandwiched with sericite quartz schists, plagioclase amphibolite schists, and tuffaceous sandstones. Rb–Sr isochron age of 1022 ± 64 Ma has been obtained from the group (Yu et al. 1994), which represents the metamorphic age, so the group should belong to Mesoproterozoic. The late Neoproterozoic unmetamorphosed Quanji Group unconformably overlies the Wandonggou group.

The Quanji group is located between the Quanji Mountain and the Oulongbuluke Mountain in the north of the Qaidam Basin, unconformably overlies the migmatic gneisses of the Delingha complex, and is unconformable overlied by the Cambrian brachiopods-bearing stratum. The group can be divided into the following assemblagess: the bottom continental sandstones and conglomerates (Mahuanggou formation), whose basal conglomerates are dominated by siliceous gravel and scarce gravels from the underlying migmatites of the Delingha complex, implying the Quanji group was autochthonous rather than allochthonous. Bidirectional oblique beddings or parallel beddings developed in the feldspar quartz sandstones and quartz sandstones of the lower part, representing coastal to tidal flat clastic rocks (Kubaimu and Shiyingliang formations). Several hundreds of meters-thick stromatolite-rich carbonate rocks (Hongzaoshan formation) overlie the sandstones and the transition zone has three layers of volcanics, between which tuffs exist, diaplaying cycle characteristics of volcanic eruptions. Above the carbonate rocks, a set of purple and gray-green variegated sandstone (Heitupo formation) occur. Massive conglomerates (Hongtiegou formation) develop in the upper part, which were treated as tillites and can be comparable with the Hangeerqiaoke tillites of the Kuluketage group in the northern margin of Tarim Basin (Wang et al. 1980). The Cambrian brachiopods fossil-bearing phosphorus clastic rocks parallel unconformably overlie the tillites. The whole stratigraphic sequence of the group display aulacogen or passive continental margin basin characteristics. The group is almost unmetamorphosed and is dominated by brittle fractures, apparently different from the metamorphic basement, so the group should be attributed to the sedimentary cover after cratonization.

The Quanji group is the lowest part of the sedimentary covers preserved in the Oulongbuluke block, whose stratigraphic sequences show the aulacogen-like sedimentary characteristics and have sedimentary cover features. Single zircon U–Pb age of 738 ± 28 Ma has been obtained from basalt of the middle-lower Quanji group, therefore the low boundary of the group was estimated as $\sim$760 Ma. The group is important for exploring the Neoproterozoic geological evolution, the tillites of the Hongtiegou formation is a marker bed for stratigraphic correlation and is the key layer to correlate the late Neoproterozoic stratigraphic correlation of the North China Craton with the Tarim block (Lu et al. 2002b).

Altyn Block The Mesoproterozoic Changcheng System Bashkuergan and Jixian system Taxidaban groups outcrop in the northern, southern, and western margins of the Altyn Mountains, which have experienced low greenschist-facies metamorphism. The protoliths of the Bashkuergan group are basalts, andesite basalts, and dacites, of which most of basalts display tholeiitic features and a few are alkaline, showing within-plate or continental margin rift features. The protoliths of the Taxidaban group are shallow marine carbonate rocks and clastic rocks, which possibly formed by shallowing upward in filling process of rift basins.

The Neoproterozoic Qingbaikou system Xorkol group unconformably overlies the Jixian system or older strata, so its metamorphic age was estimated as ~ 1.0 Ga.

The Xorkol group (Annanba group in the Gansu Province) mainly distributes in the Annanba and Ingebulake areas and is a set of littoral-shallow marine terrigenous clastic and carbonate sedimentary rocks. The lower part (Luanshishan formation) has hundreds of meters-thick purple fluvial glutenite with good roundness at the bottom, displaying characteristics of basal conglomerate. The upper part is a set of coastal-shallow marine clastic-carbonate rocks interlayered with volcanics locally and unconformably overlies the Jixian or older stratum. It is composed of low metamorphic phyllites and greenschists, constituting the initial sedimentary cover on the block.

Kunlun Block In the West Kunlun, the Mesoproterozoic Changcheng system Sailatu group constitutes the main ridge of the western Kunlun Mountains, which consists of biotite-plagioclase gneisses, biotite schists, leptynites, quartzites interbedded with amphibolites, above which the Jixian system Sanju Tagg group unconformably overlies.

The Jixian system Sanju Tagg group is primarily exposed in the Qiaerlongnan, Akto County, and Mututage areas. It is overall a set of low to middle metamorphosed clastic and carbonate rocks, including mica or feldspar-quartz schists, mica-tremolite-calcite schists, biotite leptynites, quartzites, and marbles.

The Sinian-Cambrian Alajiaoyi group is in fault contact with the upper and lower strata, whose lower rock assemblage is biotite-quartz schist, biotite-feldspar-quartz schist, leptynite and polymictic conglomerate and the upper part is composed of dolomitic limestone, crystalline limestone, and quartz greywacke.

In the East Kunlun, the Mesoproterozoic rocks include Xiaomiaoyan formation and Jixian system Langyashan formation.

The Xiaomiaoyan formation is the upper part of the Jinshuikou group and intermittently outcrops in the Xiaojianshan, Gulamulakesayi, Ulu Akzo River, Hatu, Boluositai and Ulasitai-Naomuhunketeli-Haolaterenna around the main ridge of the Burhan Budai Mountain. It is a set of greenschist-facies metamorphic rocks, whose protoliths are coastal-shallow marine clastic-carbonate rocks interbedded with intermediate-mafic volcanics. At the bottom, it is separated from the Baishahe formation by a large amount of quartzitic rocks, but the deformation characteristics is the same with those of the Baishahe formation. At the top, the formation is parallel unconformably overlied by the Mesoproterozoic Jixian System Langyashan formation, which consists of dolomites, dolomitic limestones interlayered with quartz sandstone and mafic volcanic rocks.

The metamorphic (rim) zircon of the gneisse and leptynites from the Xiaomiaoyan formation gave SHRIMP ages of 1097 ± 30 and 969 ± 32 Ma, respectively. The Meso- to Neoproterozoic Qingbaikou system Qiujidonggou formation unconformably overlies the Langyashan formation, indicating that strong metamorphism occurred in the Mesoproterozoic. The detrital zircon evaporation Pb–Pb ages of 1901, 2053 and 2069 Ma have been achieved from garnet-mica-quartzite of the Xiaomiaoyan formation, and intrusions (two-mica plagiogneiss) gave crystallization zircon Pb–Pb ages of 913, 971, and 1011 Ma, implying that the intrusive age should be older than 1000 Ma.

The Neoproterozoic Qingbaikou system Qiujidonggou formation is overall a set of low metamorphic, low maturity terrigenous clastic rocks with mafic volcanic rocks.

The Meso- to Neoproterozoic melanges include the Changliugou-Xiangyangquan ophiolite melange in the Muztag-Xidatan ophiolite belt and the Wanbaogou-Qingshuiquan ophiolite melange in the Burhan Budai ophiolite belt. The Meso- to Neoproterozoic melange are spatially isolated blocks in the Paleozoic ophiolite melange and consist of metamorphic and deformed mafic-ultramafic rocks, mafic volcanics, clastic and carbonate rocks and cherts. The metamorphic rock assemblages are metamorphic mafic volcanic-pyroclastic rocks, sericite phyllites, epidote chlorite schists, chlorite epidote schists, muscovite chlorite schists, dolomite marbles, chlorite marbles, serpentine marbles, phlogopite marbles, and tremolite rocks. The pararocks in the Wanbaogou-Qingshuiquan ophiolite melange are called the Wanbaogou group.

Based on the whole-rock Sm–Nd isochron age of 1004.7–1372 ± 85 Ma of the mafic-ultramafic rocks (Zheng et al. 1992; Xie 1998, 1:250000 Donggicuona 2000; 1:250000 Arak Lake 2003), the Sm–Nd isochron age of 1441 ± 230 Ma of the metabasalt from the Wanbaogou group ($Pt_{2\text{-}3}$), the SHRIMP zircon U–Pb age of 1348 ± 30 Ma (1:200000 Nachitai 1981; Jiang et al. 1992; Ah et al. 2003), the protoliths were formed at the Meso- to Neoproterozoic and metamophsed at the Jinning era. However, Lu et al. (2002b) got TIMS zircon age of 522.3 ± 4.1 Ma from the Qingshuiquan gabbro, implying that the age of the Wanbaogou-Qingshuiquan ophiolite need further study.

2.1.4 The Precambrian Geological Events and Evolution of the Altyn-Qaidam-West Qinling Orogenic System

The Archean geological records are preserved very little in the Altyn-Qaidam-West Qinling orogenic system, so far the relevant age information have only been obtained from the Dunhuang block in the north. The Aketashitage complex is mainly composed of supracrustal rocks and TTG granitic rocks and the existing data suggest that the main formation age is of Archean to Paleoproterozoic (Dong et al. 2007a, b; Mei et al. 1998; Xinjiang Bureau of Geology and Mineral Resources 1993; Che and Sun 1996; Lu et al. 2002b, 2006, 2008) and the Paleoarchean age is also reported locally (Li et al. 2001). 1:25000 regional geological survey of the Xiaomiaoyan group in the eastern Kunlun found 3306 Ma detrital zircon, implying that their provenance should include Archean crust. However, due to the limited research, it is still unable to accurately determine the scope of the Archean continental nuclei.

The widespread Paleoproterozoic TTG gneisses reflect crustal vertical accretion after the initial nucleus formation, which is associated with development of clastic-carbonate rocks interbedded with mafic volcanic rocks at the active continental margin.

The widespread unconformity between the Paleoproterozoic and Mesoproterozoic strata in the Altyn, Kunlun, and the southern edge of the Tarim indicate that the areas have suffered late Paleoproterozoic tectonic events (Luliang movement), so that the Neoarchean and Paleoproterozoic strata were metamorphosed to amphibolite facies (locally granulite facies and even high-pressure granulite facies) and changed to the crystalline basement. Zhang et al. (2012) considered that the 1.85 Ga high-pressure granulite-facies metamorphism in the Tarim Craton is similar to that of the North China Craton, both of which are part of the Paleoproterozoic Columbia supercontinent.

After formation of the Paleoproterozoic crystalline basement, the Neoproterozoic sedimentary cover began to be deposited. The Changcheng system volcanics and shallow water, coastal phase passive continental margin deposition reflect the start of the Mesoproterozoic continental blocks breakup. The typical volcanics include the Sailajiazitage spilite keratophyre in the Tiekelike Mountain of the southern margin of the Tarim Basin, the within-plate basalts of the Xiaomiao group in the eastern Kunlun and the Changcheng system basalts, andesite basalts and dcaites of the Bashikuergan group in the Altyn block. The basalts of the Bashikuergan group are dominated by tholeiitic basalt with subordinate alkaline series and their geochemical characteristics show within-plate or margin rift features. The high maturity of clastic rocks of the Changchengian system represents the sedimentary response in relatively stable areas at the same time or later than the magmatic event.

The Jixianian extensional rifting continued to develop and ophiolite rocks occurred with the intensification of breakup, such as Changliuquan-Xiangyangquan ophiolite melange in the Muzitage-Xidatan of the Kangxiwa-Muztagh-Machen suture zone and the Wanbaogou-Qingshuiquan ophiolite melange in the Burhan Buda Mountain. The accompanying sedimentary response is a large amount of Jixian system passive continental margin shallow water-carbonate platform deposition in the Altyn, Kunlun and other areas, such as the Bochatataga formation in the southern edge of the Tarim, the Taxidaban group in the Altyn region, the Sangzhutage group in the West Kunlun and the Langyashan group in the East Kunlun, all of which are clastic-carbonate rocks.

The blocks gathered in the Qingbaikou area and all the Haiyuan group in the Qilian block, the Suoerkuli group in the Altyn block, and the Qiujidonggou formation in the Kunlun block unconformably overlie the underlying Jixian system or older metamorphic rocks with basal conglomerates. The Qingbaikou system geological units are comparable with the global events related to the Rodinia supercontinent formation in time and should be its response in the western China.

The Qingbaikou system deposition is a set of shallow marine clastic-carbonate rocks, whose sedimentary environments and stromatolites combination are similar to those in the North China Craton at the same period.

After the Rodinia converge event, the tillite occurred in the Nanhua-Sinian Quanji group, which is comparable with the Nantuo tillites in the Yangtze Block. This combination of early North China Craton's affinites and later Yangtze Block's affinites has two possible factors. One possibility is that these blocks were in a transition zone between the North China and Yangtze blocks; another possibility is that the blocks were parts of the North China Craton before the Nanhua era, but separated from it and connected with the Yangtze block, both of which have the Nanhua-Sinian sedimentary covers.

The Nanhua-Sinian sediments marked that the area has begun to enter a new phase of the breakup process and the blocks collaged and collided to form the current structural pattern in the early Paleozoic.

2.2 Precambrian Rocks in the Karakorum-Bayan Har-Chamdo-Simao Orogenic System

The Karakorum-Bayan Har-Chamdo-Simao orogenic system includes the Yulong Tagg-Bayan Har and North Qiang-Qamdo-Simao Blocks and the Yanghu-Jinshajiang suture zone, in which only the Proterozoic geological unit has been found (Fig. 3).

2.2.1 Paleo- to Mesoproterozoic

The Yulong Tagg-Bayan Har Block The metamorphic basement rocks in the Yulong Tagg-Bayan Har block are the Paleoproterozoic Xiacun group, which are exposed as a series of dome cores in the Jiulong-Muli region of the southern block. It is mainly composed of high greenschist to amphibolite-facies metamorphic rocks, including biotite (hornblende) plagioclase gneisses, leptynites, plagioclase amphibolites and various schists, marbles, whose protoliths are argillaceous and volcanic rocks. On the basis of regional stratigraphy and geochronological data, Yao and Ni (1990) suggested that the Xiacun group is younger than the Kangding group and older than the Huili and Yanbia groups, whose formation age is between 2000 and 1700 Ma in the Paleo- to Mesoproterozoic.

The North Qiang-Qamdo-Simao Block The Paleoproterozoic rocks distributed in the west of the Altyn fault, along the Bulunkou-Taxkorgan County, are called the Bulunkuole group, which consists of garnet and sillimanite-rich metamorphic rocks, including garnet (or hornblende)-plagioclase gneisses, garnet-sillimanite-biotite-plagioclase gneisses and marbles, interbedded with meta-felsic volcanic rocks. In the Taheman, Qiaopukalimo, Laobing, and other places also developed a set of iron formation, including layered-banded magnetite, magnetite-quartzite, and so on, forming a huge scale (up to 120 km) of sedimentary-metamorphic magnetite bed.

Zircon LA-ICP-MS U–Pb age of 2481 ± 14 Ma has been obtained from the meta-rhyolite of the Bulunkuole group in the southeastern Budaer, the Tashikuergan

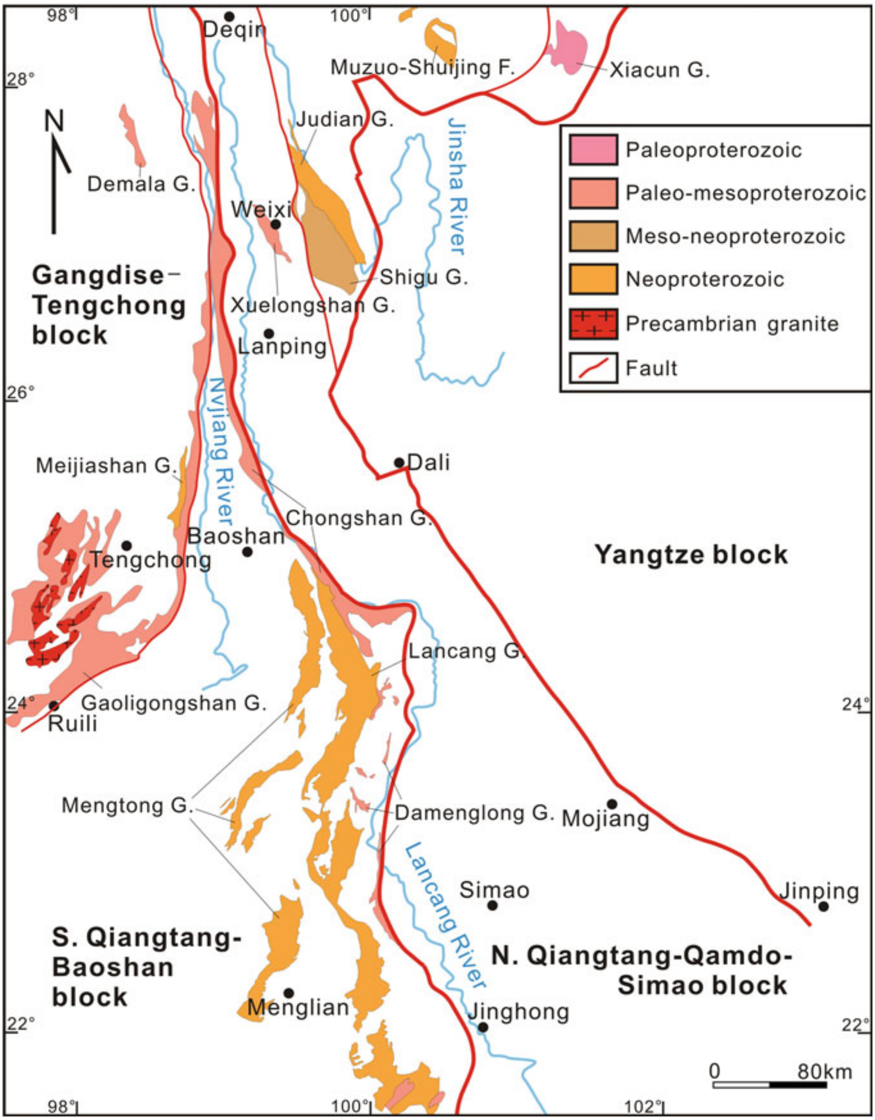

Fig. 3 Geological map showing the distribution of Precambrian rocks in western Yunnan. *F.* Formation, *G.* Group, *B.* Block

County (Ji et al. 2009), which was designated as the Paleoproterozoic.

The Paleo- to Mesoproterozoic rocks outcrop in the Xiaosumang and Jialaiduo areas of the eastern margin of the Chamdo basin and the Yanghu-Jinshajiang suture, called the Ningduo group. The main lithologies include biotite-plagioclase gneiss, quartz schist, quartzite and leptynite interbedded with amphibolite schist, hornblende schist, marble and diopsidite, which are characterized by regional schistosity and gneissosity and suffered amphibolite-facies metamorphism. Based on regional data, the protoliths were formed in the Paleoproterozoic and metamorphosed in the late Mesoproterozoic, but no reliable geochronologic data has been given.

He et al. (2011) used LA-ICP-MS zircon U–Pb method to obtain the oldest detrital zircon age of 3981 ± 9 Ma from the garnet-two-mica-quartz schist of the Ningduo group near the Yushu and also got 3505 ± 18–3127 ± 10 Ma detrital zircon ages, reflecting very old continental nucleus in the source area. Other age groups include 2600–2300, 1700–1400, 1200–850, and 700–530 Ma with peaks at ~2440, ~1532, ~982, and ~618 Ma, respectively. Among them, the main age peak of ~982 Ma is synchronous with the Grenville orogeny of the Rodinia supercontinent and the subordinate age peak of ~618 Ma is roughly simultaneous with the Pan-African movement of the Gondwana supercontinent. Thus, further study is needed for the formation age of the group.

In the Lanping area of the southern block, the Paleo- to Mesoproterozoic rocks located in the eastern side of the Lanping basin and along the Xuelong Mountian are called the Xuelongshan group. Its upper part consists of (hornblende) biotite-plagioclase leptynites, (staurolite kyanite) two-mica-quartz schists and a small amount of quartzites, amphibolite diopside marbles, amphibolite schists; the central part is composed of garnet-two-mica-quartz schists, (garnet) biotite-plagioclase leptynites, garnet-bearing biotite-plagioclase gneisses and a little biotite-quartz schists, amphibolite schists; the lower part includes biotite-plagioclase lepynites, (biotite) amphibolites, two-mica (quartz) schist and minor (amphibolite) biotite-plagioclase gneisses, marbles. The rocks are generally migmatized and metamorphosed to amphibolite facies. According to the regional data, the protolithes were formed in the Paleo- to Mesoproterozoic and metamorphosed in the late Neoproterozoic, but no reliable geochronologic data has been obtained.

2.2.2 Meso- to Neoproterozoic

The Yulong Tagg-Bayan Har Block To the west of the Altyn fault, the Meso- to Neoproterozoic Changcheng System Tianshuihe group, Jixian system Chalukou formation and Qingbaikou system Xiaoerkegudi formation are mainly a set of low metamorphic carbonate and fine-grained clastic rocks interbedded with mudrocks, including sericite (or chlorite) quartz schists, calcite schists, biotite-quartz calcite schists, chlorite-albite schists, quartzites, marbles, and so on. Metamorphic mineral assemblages reflect greenschist-facies metamorphism and the metamorphic age is of Neoproterozoic.

The Xinjiang Bureau of Geology and Mineral Resources suggest that the Tianshuihe group is formed at Changcheng era based on the *Xiayingella, Stratifera, Litia* fossiles collected from the stromatolite and regional comparison. The stromatolite fossils from the dolomites of the Xiaoerkegudi formation are tapered, cylindrical, and the laminae are very rough. According to the identification of

Researcher Feng Tang from the Institute of Geology, Chinese Academy of Sciences, they are *Tekesia* sp. *Turks* stromatolite (undetermined species), *Tungussia* sp. stromatolites (undetermined species) and its era is Qingbaikou era. Combined with the previous collected *Xiayingella, Stratifera, Litia*. Stromatolites from the formation, it is redefined as Qingbaikou system based on comprehensive analysis.

The Qingbaikou system Xiakasha formation is only distributed in the Kasha of Sichuan Muli County in the eastern block and is a set of metavolcanic rocks, pyroclastic-terrigenous clastic strata. The lower part consists of phyllites and carbonaceous slates, metamorphic felsic siltstones tuffs, albite quartz schists; the central part includes albite (quartz) leptynites, albite schists, albite quartz schists, mica schist, and phyllites; the upper part is composed of epidote-actinolite schists, chlorite-albite schists, and albite schists. Single zircon U–Pb ages of 855 ± 8 and 1083 ± 2 Ma have been obtained (Hu 1994). The overlying Nanhua System Muzuo formation is dominated by the tillites, conglomerates, and slates in the upper and lower parts and meta-siltstones and slates in the middle. The Sinian Shuijing formation consists mainly of dolomites containing algae fossils, comparable with the Doushantuo formation in the Yangtze block.

North Qiang-Qamdo-Simao Block The Neoproterozoic rocks in the Qamdo area of the eastern block are called the Caoqu formation and are distributed in the Caoqu area of the Chamdo County, in fault contact with the surrounding Upper Triassic low metamorphic rocks. The upper part consists of sericite-chlorite schists, muscovite-quartz schists, the middle and lower parts are composed of conglomerates, quartz schists, phyllites, quartzites, feldspar-quartzites and sericite-chlorite schists, interbedded with meta-mafic volcanics. The metamorphic grade is greenschist facies and the protoliths were conglomerates, muddy sandstones, calcareous shales, and mafic volcanics. Previous studies has obtained zircon U–Pb ages of 999 and 876 Ma, comparable with the Qingbaikou era.

Metamorphic strata equivalent to the Caoqu formation outcrop as "tectonic blocks" within the Yanghu-Jinshanjiang suture zone, which are known as the Judian formation. It is mainly composed of carbonaceous sericite phyllites, carbonaceous slates, sericite quartz phyllites, sericite phyllites, albite–actinolite schists, and the protoliths are intermediate-mafic volcanic rocks and volcaniclastic rocks.

Exposed in the Tacheng-Shigu area of the Lijiang city, Yunnan Pronvince, of the southern block, the Meso- to Neoproterozoic rocks are called the Shigu goup, divided into the Yangpo, Longba, and Tacheng formation from bottom to top. Among them, the Meso- to Neoproterozoic Yangpo formation ($Pt_{2\text{-}3}$) has suffered strong metamorphism and deformation and consists of biotite schists, amphibolites, sillimanite-garnet-biotite gneisses, etc., which should be basemnet of the Yangtze block. Sm–Nd model ages of 1369.8–1343.8 Ma (Zhai et al. 1990) and Rb–Sr isochron age of 996.1 ± 33.2 Ma (Zhai and Cong 1993) have been obtained from amphibolite of the Yangpo formation and the Shigui formation, respectively. The Neoproterozoic Longba and Tacheng formations (Pt_3) have low metamorphic grade, strong deformation and the metamorphic rocks are biotite schist, biotite-quartz schist, albite schist, actinolite schist, chlorite quartz schist, chlorite schist, sericite-chlorite interbedded with meta-mafic volcanic.

2.2.3 The Precambrian Geological Events and Evolution of the Karakorum-Bayan Har-Chamdo-Simao Orogenic System

The Karakorum-Bayan Har-Chamdo-Simao orogenic system is part of the Pan-Cathaysia and Yangtz blocks, but the exposed Precambrian geological units are extremely limited, so it is difficult to recover the geological evolution. This section only simply describes clues of the Neoproterozoic tectonic events.

The folded basement was formed in the early Paleo- to Neoproterozoic, including the Bulunkuole, Ningduo, Xiacun groups and the Xiakasha formation in the Muli area. The Jinning event made the fold reture and the Neoproterozoic Caoqu group may belong to molasse when the craton returns. With the regional dynamic metamorphism of greenschist facies, the crust thickened, matureded, and stabilized.

In the Nanhua-Sinian period, the system went into a stable stage of development, and fine-grained clastic rocks containing tillites comparable with those in the Yangtz block were formed.

2.3 Precambrian Rocks in the South Qiang-Gangdise-Himalaya-Baoshan Orogenic System

The South Qiang-Gangdise-Himalaya-Baoshan orogenic system includes the South Qiang-Baoshan, Gangdise-Tengchong and Himalayan blocks and Longmucuo-Shuanghu-Lancang River, Bangong-Nujiang and Yarlung Zangbo suture zones, and so on (Figs. 3 and 4).

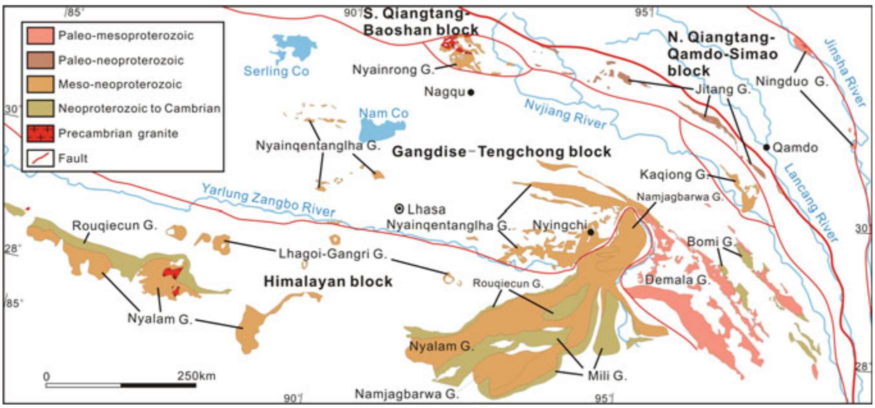

Fig. 4 Geological map showing the distribution of Precambrian rocks in Southern Qiangtang, Gangdise, and Himalayan region. *G.* Group

2.3.1 Paleo- to Mesoproterozoic

The Paleo- to Mesoproterozoic rocks in the block outcrop in the southeast, including the Chongshan and Demala groups.

South Qiang-Baoshan Block The Paleo- to Mesoproterozoic strata in the western Yunnan Province of the South Qiang-Baoshan block is called the Chongshan group, which is distributed along the Biluo and Chong Mountains. The lower part consists of the garnet-sillimanite-biotite-plagioclase gneisses, garnet-bearing sillimanite-biotite schists, quartzites interlayered with biotite-plagioclase leptynites, amphibolites, and marbles, which have generally strong migmatization. The upper part consists of biotite-quartz schists, plagioclase leptynites and hornblende leptynites, marbles, whose mineral assemblages reflect amphibolite-facies metamorphism.

Concordant U–Pb zircon age of 922 Ma has been obtained from the biotite-plagioclase leptynite of the group, the isotope model ages of amphibolites and gneiss focused on 1100–1000 and 1900–1600 Ma, respectively. The model ages of gneisses are roughly equivalent with those of the Damenglong group. Taking into account the basically same rock assemblage, deformation and metamorphism features with those of the Gaoligongshan group, both of them are crystalline basement rocks in the region. The age of 922 Ma is deemed as the metamorphisic age and the formation age is considered as the Paleo- to Mesoproterozoic.

Gangdise-Tengchong Block The Paleo- to Mesoproterozoic rocks in the block are called the De Mala group, which is exposed in the Chayu area, east of the east structural knot and is a set of high metamorphic rocks, including gneisses, schists, leptynites, migmatites and a small amount of marbles, all of which suffered amphibolite-facies metamorphism.

Sm–Nd ages of 2146–2264 and 1524–1598 Ma have been obtained from the De Mala group (1:200000 Songleng and Zhuwagen 1995), and also Sm–Nd isochron age of 2138 Ma has been obtained. Dong et al. (2011a, b) used zircon LA-ICP-MS U–Pb dating method for the orthometamorphic rocks (biotite-hornblende schist) and parametamorphic rock (biotite-quartz schist). The biotite-hornblende schist gave the age of 217 Ma, representing the crystallization age and mafic magmatism during the Late Triassic. The biotite-hornblende schist gave detrital zircon ages ranging from 188–1902 Ma, mainly in the 200–210, 520–600 and 900–1100 Ma, reflecting ages of the source area. Above data indicate that some areas of the De Mala group in the southeastern Tibet were the Paleozoic sedimentary rocks, which have undergone alteration of late Mesozoic magmatism. Although this result can not completely deny the existence of Precambrian basement metamorphic rocks, but at least reflects that the De Mala group should be determined as a set of metamorphic rocks.

2.3.2 Meso- to Neoproterozoic

South Qiang-Baoshan Block The Meso- to Neoproterozoic rocks in the eastern Tibet are mainly exposed in the Dêngqên-Riwoqe-Jitong-Bitu area and named the Jitong group in the west of the north Lancang River fault zone. The lower part consists of gneisses and migmatites, and the upper part is dominated by various schists, including the lower Enda formation and the upper Youxi formation.

Based on the current geological data, the Jitang group mainly consists of amphibolite facies biotite-plagioclase gneisses, biotite leptynites, hornblende-plagioclase gneisses, banded migmatites interbedded with quartz schists, sillimanite-garnet schist plagioclase schists, biotite-feldspar schists, and marbles. The protoliths are quartz sandstones, greywackes and argillites with a small amount of carbonate rocks and mafic volcanic rocks. Based on the metamorphic mineral assemblages, the metamorphic degree was determined as amphibolite facies.

The Jitang group was originally classified as Paleo- to Mesoproterozoic. However, He et al. (2012) used LA-ICP-MS zircon U–Pb method to date quartz chlorite schist (formerly intermediate volcanic rock) from the Youxi formation of the Jitang group along the Taniantaweng Mountain and got the formation age of 965 ± 55 Ma. Additionally, the greenschist (original intermediate-mafic volcanic rocks) was dated at 1048.2 ± 3.3 Ma, implying that the Youxi formation of the Jitamg group was formed in the Neoproterozoic and the metamorphic age is tentatively constrained in the late Neoproterozoic.

In the western Yunnan, the Meso- to Neoproterozoic rocks include the Mesoproterozoic Damenglong group and the Neoproterozoic Lancang group, which mainly outcrop in the Lincang-Lancang block and scatter as enclaves in the intrusions. The Damenglong group mainly consists of biotite-plagioclase leptynites with biotite-plagioclase gneisses; the Lancang group is dominated by quartz-mica-bearing tectonic schists with minor leptynites, phyllites, marbles and metamorphic mafic lenses.

The Gangdise-Tengchong Block The Neoproterozoic rocks in the Gangdise block are called the Nianqingtanggula group, mainly along the main ridge of the Nianqingtangula Mountain in the north of Dangxiong and in the west and north of the eastern structure knot. It is mainly composed of biotite monzonite gneisses, quartz gneisses, granitic gneisses, hornblende-plagioclase leptynites, amphibolites, magnetite quartzites, schists, marbles, and others.

About rock formation age of the group, Hu et al. (2005) have got the protolith ages of 748–787 Ma (orthometamorphic gneiss) and 782 Ma (meta-mafic rocks) from the group in the Namucuo area. Zhang et al. (2010) obtained metamorphic ages of 678–759 Ma (average age of 718 Ma) from the marbles in the Naguo area, west of Namucuo. Zhang et al. (2013b) used zircon U–Pb LA-ICP-MS method to obtain the protolith age of 742–758 Ma (Fig. 5), 666 Ma metamorphic age (Fig. 6) and 660 Ma anatexis age (Fig. 7) from the garnet amphibolites in the Yongzhu area.

Dong et al. (2009) dated detrital zircons of the group in the Nyingchi area, west of the eastern structure knot and found their age peaks mainly at around 500–600 Ma. The protoliths were formed at early Paleozoic and metamorphosed at

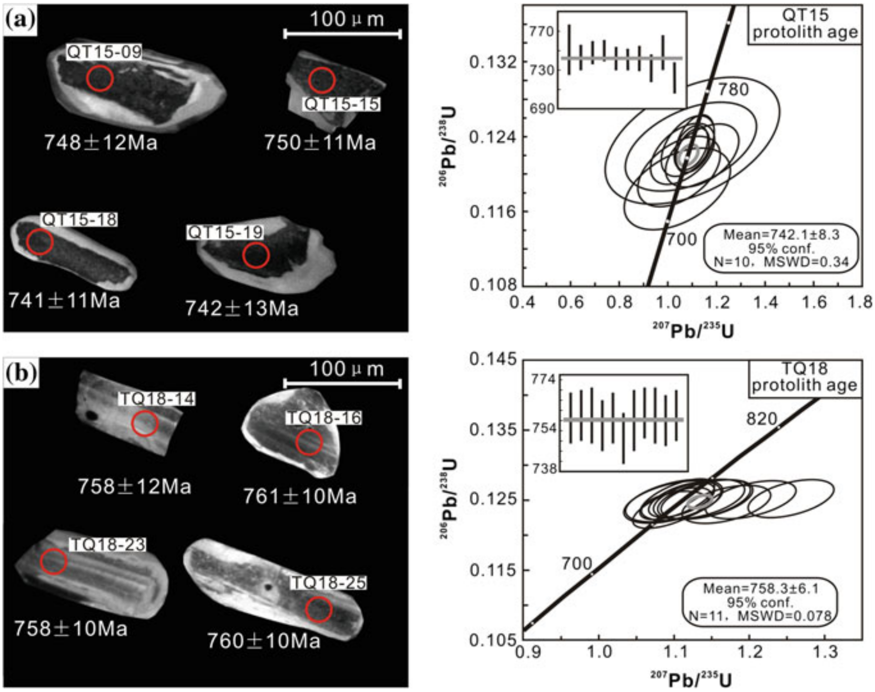

Fig. 5 Cathodoluminescence (CL) images and U–Pb concordia diagram of zircons in garnet plagioclase-amphibole gneisses (cited from Zhang et al. 2013b)

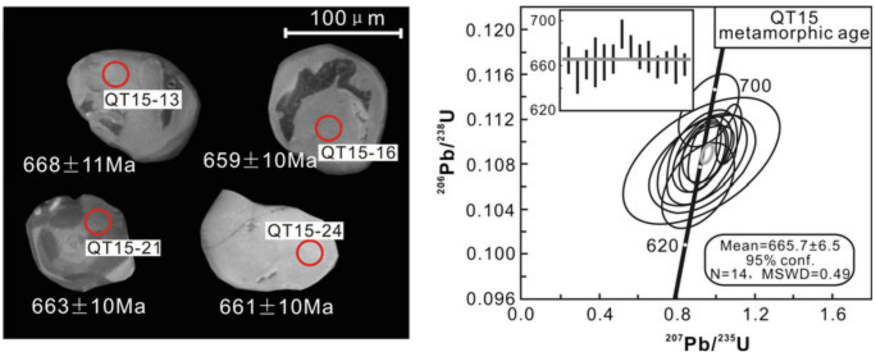

Fig. 6 Cathodoluminescence (CL) images and U–Pb concordia diagram of zircons in garnet plagioclase-amphibole gneiss (cited from Zhang et al. 2013b)

Cenozoic (about 35 Ma). Although this result cannot completely deny the existence of the original Nianqingtanggula group, but at least it should be a metamorphic complex.

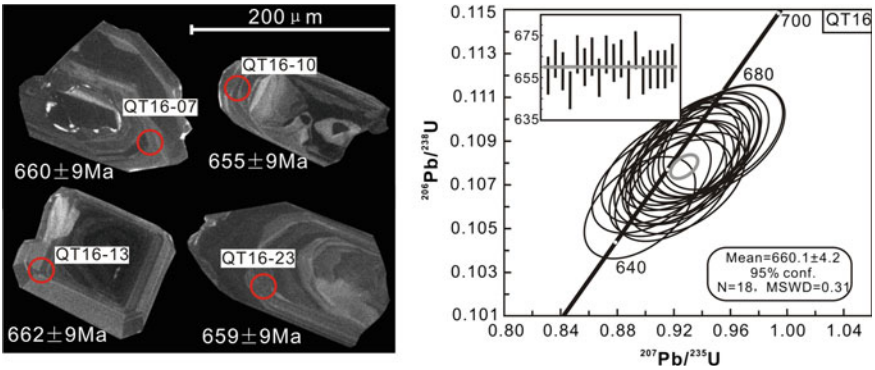

Fig. 7 Cathodoluminescence (CL) images and U–Pb concordia diagram of zircons in felsic veins within garnet plagioclase-amphibole gneiss (cited from Zhang et al. 2013b)

Small amounts of Neoproterozoic strata are exposed in the Bomi-Tongmai area of the southeastern block and called the Bomi group. It is mainly composed of two-mica-quartz schists, meta-sandstones, siltstones, intermediate-felsic volcanic rocks with minor marbles, slates, phyllites, etc. Based on the U–Pb zircon age of 564 Ma Bureau of Geology and Mineral Resources of Xizang Autonomous Region (BGMR 1993) of the quartz-mica schist in the southern Tongmai, the group was placed in the Neoproterozoic era.

The Neoproterozoic rocks in the Tengchong area of the souther block are called the Gaoligongshan group, which consists of biotite-plagioclase gneisses, diopside-hornblende-plagioclase leptynites, sillimanite-biotite schists and amphibolites and suffered amphibolite-facies metamorphism. Li et al. (2012) got magmatic zircon SHRIMP and LA-ICP-MS U–Pb ages of 497.8±7.2 and 500±14 Ma from the orthogneiss with the maximum age of 622 Ma. Therefore, the formation age of the sedimentary Gaoligongshan group should be earlier than 500 Ma. The results also show that the Gaoligongshan group suffered the Pan-African tectonic-magmatic events.

The Himalaya Block The Meso- to Neoproterozoic units in the Himalaya block include the Meso- to Neoproterozoic Laguigangri, Nanjiabarwa, and Nyalam groups and the Neoproterozoic Rouqiecun and Miri groups.

The Laguigangri group is intermittently exposed in the Laguigangri-Kangma-Lhünzê County area of the northern block as intermittent dome-shaped (structure window) outcrops. The main rock types include mica schist or mica-quartz schist with metamorphic minerals of garnet, kyanite, staurolite, biotite-plagioclase (monzonite) gneiss, staurolite-garnet-biotite-plagioclase gneiss, amphibolite plagioclase gneiss, garnet-amphibolite, marble, and quartzite. The protoliths are mainly claystone, muddy sandstone (siltstone), feldspathic sandstones, intermediate-mafic volcanic rocks, tuff, which is a set of terrigenous clastic-carbonate rocks interbedded with volcanics.

The Laguigangri and Nyalam groups are comparable in the rock assemblage and metamorphic and deformation characteristics. The orthogneiss from the Laguigangri group gave SHRIMP zircon age of 1812 ± 7 Ma (Liao et al. 2007). Xu et al. (2005) obtained SHRIMP zircon age of 528–504 Ma (the average age of 515.4 ± 9.3 Ma) in the Kangma area and considered that the metamorphic basement rocks were involved in the early Paleozoic Pan-African orogenic events; Liu et al. (2002) and Zhou et al. (2004) found the lower Ordovician basal conglomerates in the Kangma dome and suggested them as geological markers of the Pan-African event.

Given the SHRIMP age of 1812 ± 7 Ma of the orthogneiss (ancient intrusions) from the Laguigangri group, the possibility that the group extended to the Paleoproterozoic era can not be ruled out.

The Nanjiabarwa group is distributed in the Nanjiabarwa area and the Yarlung Zangbo Great bend, whose periphery was surrounded by zonal distribution of the Yarlung Zangbo suture zone ophiolite, separated by ductile shear zone. The group is divided into the Zhibaiyan formation, Duoxiongla complex and Paixiang formation, divided by two tectonic interfaces. The Zhibaiyan formation mainly consists of high-pressure granulites, garnet amphibolites, Al-rich gneisses interbedded with kyanite-garnet monzogneiss lenses and granitic gneisses. The Duoxiongla complex is composed of banded migmatites, augen migmatites, intestinal-like migmatites and leptynites, gneisses and calc-silicate rocks are locally remained. The Paixiang formation includes biotite leptynites, biotite schists, marbles, calc-silicate rocks. Except some high-pressure granulite lens in the Zhibaiyan formation, the main lithologies of the three formations are similar.

Zhang et al. (2008) accomplished petrologic and geochronological studies on the widespread felsic gneisses of the group. Except individual rocks preserving high-pressure pelitic granulite-facies mineral assemblage of garnet + kyanite + three ternary felspar, most of the gneisses have amphibolite-facies metamorphic mineral assemblages, and their protoliths include diorite and granodiorite with geochemical composition of magmatic arc granites. Zircons from the gneiss commonly have core–rim structures, and SHRIMP and LA-ICP-MS in situ analysis showed that the zircon rims gave multi-Pan-African to Cenezoic metamorphic and magmatic ages (500–10 Ma), and the Precambrian zircon cores gave ages of ~2500, ~1600, and ~1000 Ma. The analyzed zircon region has apparent magmatic oscillatory structures and high Th/U ratios, suggesting magmatic origins. The age peaks are comparable with those of the Precambrian tectonic events in the high Himalayan crystalline complex and Indian block.

The Nyalam group is distributed EW in the southern block and extend southward out of the country. The group is mainly composed of gneisses, schists, quartzites, marbles, amphibolites, and other low to intermediate metamorphic rocks, whose protoliths are mainly muddy-sandy continental margin clastic rocks with carbonates and intermediate to mafic volcanic rock, equivalent to flysch-like containing volcanics. Some of the protoliths should be granitic intrusions and (ultra) mafic intrusions.

Predecessors have obtained a lot of isotopic ages from the Nyalam group (Institute of Geochemistry, Guiyang 1973; Xu et al. 1985; Wei et al. 1989; Liu et al 1990; Hebei District Investigation Team 2004). The ages can be roughly divided into four groups: 1250–2450, 792–950, 458–664, and 42–10 Ma. The 1250–2450 Ma age should represent the formation age of the protoliths, the 792–950 Ma are representative of the Neoproterozoic (before the Pan-African) tectono-thermal events, the 458–664 Ma are coincide with the Pan-African movement; the 42–10 Ma are representative of the Himalayan tectono-thermal event. Limited to the testing methods and accuracy, further study is needed for the precise formation and metamorphic ages of the group.

The Neoproterozoic low metamorphic units adjacent to the north Nyalam group include Lower Cambrian strata at the top, which are called the Rouqiecun formation, which suffered deformation transformation and is dominated by ductile shear zone mylonite including biotite mylonites, marble mylonites, muscovite granitic mylonites and other mylonites. The upper part is composed of mica schists, quartz-mica schists, chlorite schists, slates and phyllites with crystalline limestones, meta-sandstone. The protoliths are pelitic-claystones, shale sandstones, greywackes, and carbonate rocks with a small amount of basic or acidic volcanic rocks, displaying low greenschist-facies metamorphism features. Liu et al. (1990) obtained U–Pb isochron age of 640 and 686 Ma, and Zhao et al. (2001) obtained U–Pb age of 410–515 Ma. Accordingly, the group may be formed in the Sinian-Cambrian, experienced the Pan-African orogeny main metamorphic event and the metamorphic grade is low greenschist facies (locally high greenschist facies).

The Neoproterozoic-Cambrian strata exposed in the Cona-Medog area are called the Miri group, which is composed of fine clastic rocks, dolomite, dolomitic limestone in the lower part, intermediate-mafic volcanic rocks in the middle and quartzites, feldspar sandstones, conglomerates with slates and marls in the upper part.

The Bangong-Nujiang Suture Zone The Bangong-Nujiang suture zone separates the South Qiang-Baoshan and Gangdise-Tengchong blocks and has two micro-blocks containing Precambrian geological units, called the Nierong and Kaqiong micro-blocks. The Meso- to Neoproterozoic units in the Nierong micro-block are called the Nierong group, which mainly consists of gneisses and amphibolites and the distribution range of the latter is far greater than the former. Specific rock types are biotite-plagioclase (monzonite) gneiss, hornblende-plagioclase gneiss, garnet-amphibolite diopside-plagioclase gneiss, amphibolites and pyroxene amphibolites with the metamorphic garde up to amphibolite facies.

The granitic rocks intruding the Nierong group have SHRIMP U–Pb zircon ages of 491 ± 1.15, 492 ± 111, 814 ± 18, 515 ± 14 Ma (1:250000 Anduo 2004). Their emplacement age may be the Neoproterozoic and the metamorphic age is late Neoproterozoic. The 491–530 Ma may be the geological record of the Pan-African orogeny thermal event.

The Carqiong group is located in the eastern part of the Basu County and mainly consists of sillimanite-garnet-biotite-kyanite schists, kyanite-garnet-sillimanite-biotite-monzonite gneisses, amphibolites, eclogites, granulites, and marbles, a set of medium-high metamorphic rocks. SHRIMP U–Pb zircon age of 507 ± 10 Ma has been obtained from the granitic gneiss of the Basu group in the Tongka area, which may be the geological record of the Pan-African orogeny thermal event (Li et al. 2008). In addition, retrograde eclogite xenoliths have been recognized in the group and outcropped as NW-SE beaded enclaves in the kyanite-garnet-biotite-sillimanite-monzonite gneisses. The gneissosity of the enclaves and country rocks are the same, but the age is unknown (Dong et al. 2007a, b).

2.3.3 The Precambrian Geological Events and Evolution of the South Qiang-Gangdise-Himalaya-Baoshan Orogenic System

The South Qiang-Gangdise-Himalaya-Baoshan orogenic system is distributed in the northern margin of the Indian block, whose basement metamorphic rocks are composed of metamorphic supracrustal rocks and plutons. The meta-supracrustal rocks are mainly pelitic-sandy continental margin clastic rocks with carbonates and intermediate-mafic volcanics, probably formed in the Neoproterozoic or earlier, but reliable formation or metamorphic ages of each Precambrian units are scarce.

In contrast, the Paleozoic strata in the Gangdise block to the south of the Longmucuo-Shuanghu suture zone have a large number of Precambrian detrital zircons. The early to middle Ordovician Wenquan quartzites in the south of the Longmuco-Shuanghu suture zone contain detrital zircons of 520–700, ~800, 900–1100, 1800–1900, and 2400–2500 Ma, of which the 625 and 950 Ma age peaks are most obvious. The reliable youngest detrital zircon age is 525 Ma and the oldest detrital zircon age is 3180 Ma. Therefore the source area of the Wenquan quartzites has experienced the Pan-African tectonic and magmatic events and Grenville-Jinning tectonic and magmatic events. The study of detrital zircons in the Carboniferous strata in the central Lhasa block (Leier et al. 2007) showed ages mainly in 2500, 1950–1700 Ma (peak of 1850 Ma), 1300–1050 Ma (peak of 1120 Ma), and 600–500 Ma (peak of 540 Ma).

The currently considered Precambrian strata also have such age information, such as the 1200–900 and 600–500 Ma detrital zircons from the Nianqingtanggula group in the Linzhi area (Dong et al. 2009), the 600–520 and 1100–900 Ma detrital zircons from the Demala group in the Chayu area and the 600–500 and 1100–900 Ma detrital zircon ages in the Tethyan Himalayan belt (DeCelles et al. 2000; Gehrels et al. 2003; Myrow et al. 2003).

Above age information reflects that some Precambrian geological units should be redetermined and the existence of a long-term stable source areas recording Grenville movement (~1100 Ma) and the Pan-African orogeny (~550 Ma) until the late Carboniferous in the entire South Qiang-Gangdise block.

The traditional view suggests that the Lhasa, South Qiang, and Himalaya blocks originate in the northern margin of the Indian craton before the Carboniferous-Permian era (Allègre et al. 1984; Yin and Harrison 2000). Zhang et al. (2008) implied that the Nanjiabarwa group and the high Himalayan crystalline rocks are composed of multi-episodes Archean to Neoproterozoic magmatic rocks, and experienced Rodinia and Columbia supercontinent formation and breakup process as a part of the India craton.

Another view is that the Lhasa block originated from the northern Australia (Audley-Charles 1983, 1984; Zhu et al. 2011). LA-ICP-MS dating results of the Nianqingtanggula block in the Yongzhu area indicate that the protoliths of the orthometamorphic rocks are a set of E-MORB rocks and oceanic island arc magmatic rocks and the oceanic crust was formed at 758 Ma (Zhang et al. 2013b), roughly consistent with the Rodinia supercontinent breakup, which may be a part of the nascent Neoproterozoic oceanic basin in this period of global breakup events. The 665 Ma metamorphic age and 660 Ma anatexis veins are difficult to be regionally comparable in the large range with those in the India craton (Cawood et al. 2007; Chatterjee et al. 2007a, b; Simmat and Raith 2008). However, this phase of tectonic events were recorded in the northwestern Australia (Miles orogeny, 646–671 Ma; Durocher et al. 2003; Bagas 2004), which seem to have affinities (Zhang et al. 2013b).

Combined with the regional geology and geochronology data, the South Qiang-Gangdise-Himalaya-Dianxi orogenic system suffered amphibolite-facies metamorphic at least before the formation of Neoproterozoic Rouqiecun and Miri groups, but the detailed sequence of geological events, especially in the parametamorphic rocks, are not recorded clearly.

The 590–480 Ma Pan-African tectono-thermal event made the Neoproterozoic-Cambrian strata suffered greenschist-facies metamorphism, forming the Pan-African metamorphic basement. The metamorphic strata were the Rouqiecun and Miri groups (Pt3-∈), etc., and the ancient metamorphic basement were superposed metamorphosed. The existence of a large number of the aforementioned “Pan-African” isotopic age data (664–458 Ma) in the basement metamorphic rocks may represent a period of metamorphism and the corresponding tectonic-magmatic event. Xu et al. (2005) got SHRIMP zircon ages of 530–500 Ma in the Geelong, Yadong, Nyalam, etc., and suggested that the metamorphic basement rocks were involved in the Pan-African event and continued until the early Paleozoic. The early Ordovician basal conglomerates found in the Niemula of the high Himalaya and the Kangma dome of the Tethyan Himalayan are considered as a geological mark of the Pan-African events (Zhou et al. 2004).

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