2 Geological Background[*]

The Qilian-Qaidam Mountain system, situated in the northern Qinghai-Tibet Plateau of NW China, was formed by convergence and collision of the Alxa and Qaidam blocks and documents an excellent record of early to middle Paleozoic subduction-accretion (Yin and Harrison, 2000; Song et al., 2006; Yin et al., 2007; Xiao et al., 2009). It is bounded by the Sino-Korean craton to the east, the Qaidam basin to the south, and Tarim basin to the west (Figure 2.1a).

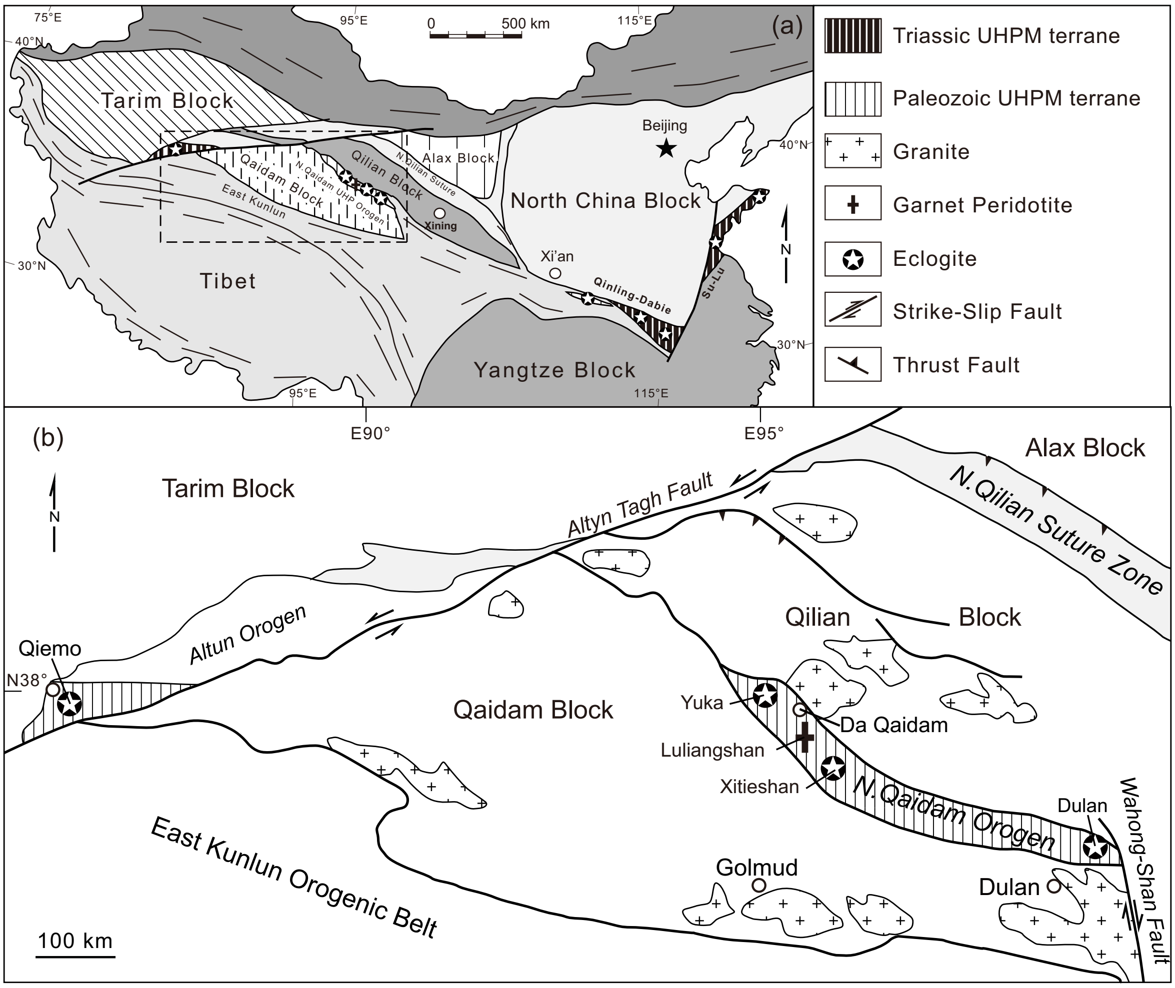

Figure 2.1 (a) Geological sketch map showing the locality of North Qaidam Orogen in China; (b) distribution of UHP metamorphic terranes in the North Qaidam Orogenic belt (modified after Song et al., 2006).

As a classic and broad orogenic belt, the Qilian-Qaidam Mountain system contains a significant number of island arcs, accretionary prisms, ophiolites (mélange), seamounts, and HP/UHP metamorphic rocks that developed during subduction- and collision-related

[*] This chapter was part of the Chinese version of the thesis.

processes (Xiao et al., 1978; Wu et al., 1993; Yang et al., 1994; Yang et al., 2001; 2002b; Song et al., 2004b; 2006; Xu et al., 2006; Mattinson et al., 2007; Yin et al., 2007; Xiao et al., 2009; Zhang et al., 2010). From north to south, the Qilian-Qaidam Mountain system can be divided into five tectonic sub-units (Figure 2.1a and b), they are (1) the Alxa block, or Alashan, once considered part of the North China Craton, (2) the North Qilian suture zone, (3) the Qilian block, (4) the North Qaidam UHP metamorphic orogenic belt and (5) the Qaidam block. These units are cut by a large NE-striking sinistral fault system in the west: the Altyn Tagh Fault. The tectonic features of interest for this study will be discussed in more detail below.

2.1 The Alxa Block

The Alxa block is a desert-covered area with fault-bounded massifs located at the western margin of the North China Craton (Figure 2.1a). The block is predominately comprised of early Proterozoic basement with 1.9 – 2.3 Ga granitic gneisses and is overlain by Cambrian to middle Ordovician strata (NBGMR., 1990; Zhou, 1992; 1995). In the southern part of the block, a *ca.* 827 Ma sulfide-bearing ultramafic intrusion and associated dolerite dykes have been found to in the Paleoproterozoic gneisses (Wan et al., 2001; Li et al., 2004; 2005), which are possibly related to superplume emplacement that triggered the breakup of the supercontinent Rodinia in the Neoproterozoic around 830-750 Ma (Li et al., 2005; Song et al., 2013). Traditionally, this triangular block was considered to be the westernmost part of the North China Craton (NBGMR., 1990). However, recent studies reveal that the Alxa block and the North China Craton actually have a significantly different tectonic history in the Neoproterozoic and early Paleozoic eras (Song et al., 2013). Therefore, the Alxa Block is unlikely to be the western part of the North China Craton.

2.2 The North Qilian Suture Zone

The North Qilian suture zone is located between the Qilian block in the south and the Alxa block to the north and represents the northernmost part of the Tibetan Plateau (Figure 2.1b). To the west, it is cut by the Altyn-Tagh Fault. The suture zone is about 80 to 100 km wide, 500 km long and extends in NW direction parallel to the North Qaidam orogenic belt in the south (Wu et al., 1993; Song et al., 2004b; 2006). Existing studies show that the belt has features typical of Pacific-type subduction zones (Xiao et al., 1978; Song et al., 2007; Yang et al., 2012; Song et al., 2013). It is predominantly comprised of ophiolite suites, calc-alkaline volcanic, granitoid plutons, Silurian flysch formations, Devonian molasses, Carboniferous to Triassic sedimentary cover sequences, and subduction-zone complexes including high-pressure low-temperature (HPLT) rocks and mélange (Xiao et al., 1978; Feng and Wu, 1992; Wu et al., 1993).

Ophiolitic rocks are well preserved in this suture zone and are interpreted to represent the remnants of ancient oceanic lithosphere. The basaltic rocks geochemically resemble present-day N-type and E-type mid-ocean ridge basalt (MORB) (Feng and He, 1995). In general, HPLT rocks in the suture zone can be subdivided into a low-grade blueschist belt and a high-grade blueschist belt based on spatial features, styles of metamorphism and deformation (Wu et al., 1993). High-grade blueschist belt eclogite zircons dated using the SHRIMP U-Pb method gave what was interpreted to be an eclogite-facies metamorphic age of 463 – 468 Ma (Song et al., 2004b). In contrast, published $^{40}Ar/^{39}Ar$ measurements on glaucophane and phengite from the high-grade blueschist belt reveal two stages of metamorphism at 460 – 440 and 400 – 380 Ma, that were interpreted as the time of subduction and orogeny (Liou et al., 1989; Wu et al., 1993). More recently, $^{40}Ar/^{39}Ar$ analysis on glaucophane and phengite from the low-grade blueschist belt yielded isochron ages of around 413 Ma and 415 Ma, respectively (Lin et al., 2010). The results were interpreted as the final closing time of the northern Qilian remnant oceanic basin and the age of convergence between the north China Craton and the Qaidam block.

2.3 The Qilian Block

The Qilian block, about 600 km long and 240 km wide, is located between the North Qilian Suture Zone and the North Qaidam UHP orogenic belt (Figure 2.1b). It is considered an imbricate thrust slice of Precambrian basement overlain by Paleozoic sedimentary sequences, comprising granitic gneiss, marble, amphibolite, phyllite and minor granulite (BGMQ., 1991). Spatially, the block can further be divided into (1) the Huangyuan metamorphic basement, (2) the South Qilian Caledonian fold belt, and (3) the Oulongbuluk block, on the basis of mineral assemblages, metamorphism and deformation features (Xu et al., 2006). Geochronological studies on zircons with various methods give ages of 940 – 880 Ma for garnet-bearing granite intrusions (Guo et al., 1999; Wan et al., 2001; Tung et al., 2007) and of around 2470 Ma for granitic gneiss from this block (Chen et al., 2009b). These ages were interpreted as protolith formation ages and are consistent with the ages of granitic gneisses from the north Qaidam UHP metamorphic belt.

2.4 The North Qaidam UHP metamorphic belt

The North Qaidam Orogenic belt, parallel to the North Qilian Suture Zone, is located at the northern margin of the Qaidam block of NW China (Figure 2.1a). This UHP metamorphic belt is the second known occurrence of coesite/diamond in deep crustal rocks in China besides the Dabie-Sulu in central-eastern China (Yang et al., 2001), and records a complete history of the evolution of a continental orogen from initial oceanic subduction, through continental collision and subduction, to ultimate orogenic collapse in the time period from the Neoproterozoic to the Paleozoic (Song et al., 2006; Zhang et al., 2013; Song et al., 2014). Geographically, it is bounded by the Qilian block (microplate) to the northeast, the Qaidam block to the southwest, and it extends for around 400 km along a NWW-strike long from the Altyn-Tagh fault in the west to the Wahong-Shan fault in the east (Figure 2.1b). The belt comprises a Cambrian-Ordovician ophiolite complex and island-arc volcanic rocks and is intruded by Caledonian granites (Wang et al., 2005; Xu et al., 2006). Ultrahigh pressure metamorphic rock types in this unit are coesite- or diamond-bearing eclogite, para- or orthogneiss and garnet peridotite.

Based on field occurrences, petrology and rock association, the North Qaidam UHP metamorphic belt can be subdivided into four sub-units. From east to west they are: the Dulan eclogite-gneiss terrane (DLT), the Xitieshan eclogite-gneiss terrane (XTT), the Luliangshan (garnet) peridotite-gneiss terrane (LLT), and the Yuka eclogite-gneiss terrane (YKT), which are separated by Paleozoic to Cenozoic sediments (Figure 2.1b). Moreover, the presence of diamond, oriented SiO_2 lamellae in omphacitic clinopyroxene and coesite in garnet peridotite (Song et al., 2005a; 2005b; 2009), eclogite (or amphibolite) and pelitic gneiss (Yang et al., 2001; Song et al., 2003; Mattinson et al., 2006; Zhang et al., 2009a; Zhang et al., 2010; Liu et al., 2012), provide critical evidence that they were subducted to upper mantle depth (~95 km) and equilibrated at pressures within the diamond/coesite *P-T* stability field. The Yuka eclogite-gneiss terrane and the Xitieshan eclogite-gneiss terrane are the two main objects of this study.

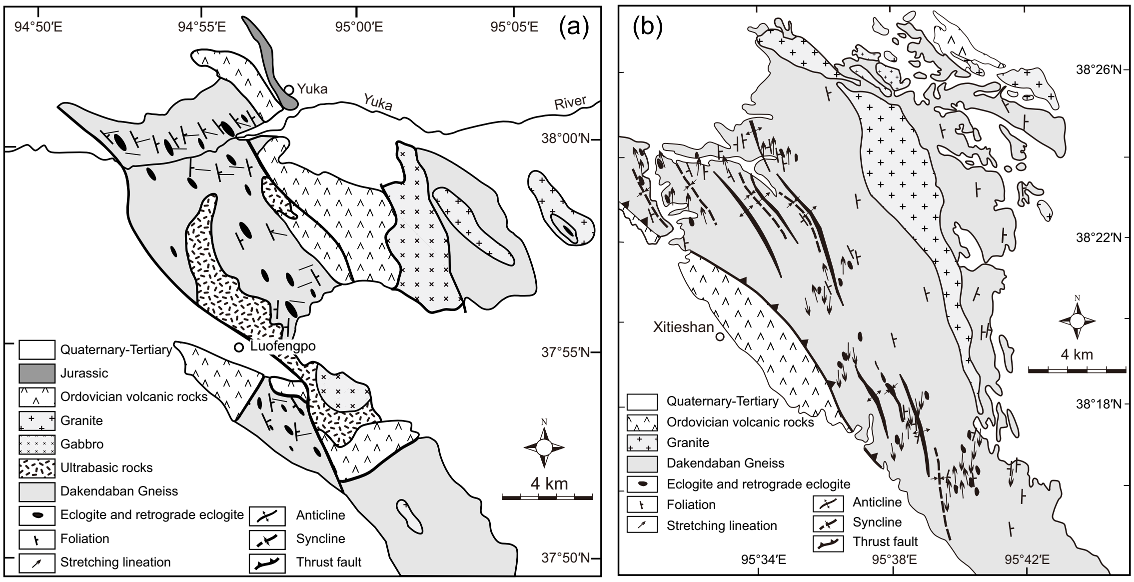

Figure 2.2 Geological sketch maps of the Yuka (a) and Xitieshan (b) terranes of the north Qaidam Orogen, Western China (modified after Zhang et al., 2005a)

2.4.1 The Yuka eclogite-gneiss terrane

The Yuka eclogite-gneiss terrane is located in the westernmost segment of the North Qaidam UHP metamorphic belt, at the northern flank of the Lüliang Mountains and 40 km north of Da Qaidam town (Figure 2.1b). This terrane is covered by Tertiary sediments in the west and in fault contact with the Ordovician volcanics in the east. It consists of various types of amphibolite-facies lithologies, including gneiss, pelitic schist, amphibolite and migmatite. Coesite-bearing eclogite and its retrogressed products occur as lenses or blocks cropping out along the Yuka River (Figure 2.2a).

2.4.1.1 Yuka eclogite

Two main types of eclogite have been distinguished in this region based upon mineral assemblages and grain size: coarse-grained phengite eclogite and fine-grained massive eclogite (Chen et al., 2005; 2007a; Zhang et al., 2009a). Coarse-grained phengite eclogite has a granoblastic texture and is composed mainly of garnet, omphacite, phengite, amphibolite, zoisite and rutile, and minor plagioclase and quartz. Fine-grained massive eclogite is more compact with smaller minerals than the phengite eclogite, and is composed mainly of garnet, omphacite, amphibole, clinopyroxene-plagioclase symplectites, as well as minor phengite, rutile and quartz. Rutile and phengite contents are usually higher than in eclogites from Xitieshan and Dulan. A *P-T* loop has been determined for eclogites in the Yuka area, with peak metamorphic conditions of P = 23 – 34 kbar and T = 600 – 750 °C (Chen et al., 2005; Zhang et al., 2005a; Song et al., 2006; Zhang et al., 2009a).

Major and trace element analyses indicate that the Yuka eclogitic rocks can be subdivided into high-Ti, medium-Ti and low-Ti types based on their TiO_2 contents (Yang et al., 2006). The geochemical features indicate that the protoliths of the Yuka eclogite were basaltic rocks from different tectonic environments, in which the coarse-grained phengite eclogite is similar to ocean island basalt (OIB) whereas the fine-grained massive eclogite is more like mid-ocean ridge basalt (MORB) (Yang et al., 2006; Chen et al., 2007a). The Nd isotopic signatures of these rocks are characterized by positive εNd (0) values (0.76 – 7.85), providing evidence that the eclogite protoliths were ocean floor basalts to which minor crustal components were added during subduction (Song et al., 2006; Yang et al., 2006; Song et al., 2014). The protolith age (>750 Ma) of Yuka eclogites is older than their metamorphic age by 250 Ma (Zhang et al., 2005a; Chen et al., 2007a; Song et al., 2010; Xiong et al., 2012). This indicates that the time interval between the formation and deep subduction is much longer than the present-day maximum interval (ca. 200 Ma) between the formation of oceanic crust at a mid-oceanic ridge and its subduction. Thus, the protolith may not represent subducted oceanic crust even though it had the geochemical signature of oceanic crust. Alternative and much more likely interpretations are that the Yuka eclogite was not formed by the deep subduction of oceanic crust but was the product of the continental deep subduction (Chen, 2007; Chen et al., 2007a). Even if the protoliths of the Yukahe eclogite was indeed the oceanic basalts, it was unlikely the subducted oceanic crust of Paleozoic but the previous oceanic crust which emplaced to the continental crust before Paleozoic, to say the least (Chen et al., 2009b).

Most previous geochronological data obtained by various methods have concentrated on constraining the age of peak eclogite-facies metamorphism of the UHP rocks. Eclogite zircon dated using the TIMS U-Pb method gave what was interpreted to be an eclogite-facies metamorphic age of 488 – 495 Ma (Zhang et al., 2005a). In contrast, zircon in situ LA-ICP-MS U-Pb dating of the eclogite yielded a mean weighted $^{206}Pb/^{238}U$ age of 436 ± 3 Ma (Chen et al., 2009a) and 443 ± 4 Ma (Xiong et al., 2012) for eclogite-facies metamorphism. $^{40}Ar/^{39}Ar$ measurements on amphiboles and phengites from the eclogites yielded isochron ages of 477

± 8 Ma and 466 ± 5 Ma for cooling ages, respectively, and their isotope correlation diagrams preclude the existing of extraneous ^{40}Ar (Zhang et al., 2000; 2005a). Applying the ^{40}Ar/^{39}Ar incremental heating method, Menold (2006) determined that all the eclogite phengites gave anomalously old apparent ages ranging from 611 to 750 Ma, indicating the presence of extraneous, i.e. inherited or excess ^{40}Ar.

2.4.1.2 Yuka gneiss/schist

The Yuka country rocks consist of about 80 volume-percent of quarto-feldspathic granitic gneiss with subordinate paragneiss and marble (Yang et al., 2001; Zhang et al., 2005a; Chen et al., 2009a; Menold et al., 2009). No UHP index minerals (e.g., coesite, diamond) have been recognized thus far in the matrix or in zircon inclusions in the country rocks, which is partly due to the higher degree of recrystallization in felsic versus mafic rocks. Field and petrographic observations show that the gneiss does not contain a uniform abundance of phases throughout the terrane. Most of the strongly foliated granitic gneiss is composed of albite, K-feldspar, white mica and quartz. Minor phases observed are epidote, apatite, zircon, kyanite and garnet. They have varying protoliths and compositions (Lu et al., 2002a). They are characterized by containing relatively high SiO_2, Al_2O_3, K_2O and Na_2O, but lower TiO_2, FeO_{total}, MgO, MnO and CaO contents, with a Rittman index of 1.92 – 2.36 and an alumina saturation index ACNK of 1.07 – 1.17, which are compatible with the characteristics of S-type granites (Lin et al., 2006). High-pressure relicts and predicted conditions of garnet growth suggest that the garnet-bearing granitic gneiss followed a metamorphic *P-T* path comparable to the eclogite it encloses, with peak pressure at ~26 kbar and temperature at ~630 °C based on *P-T* pseudosection calculations (Menold et al., 2009). Zircons from granitic gneisses analyzed by SHRIMP and LA-ICPMS U-Pb methods yielded protolith ages ranging from 900 to 1000 Ma (Wang et al., 2004; Lin et al., 2006; Chen et al., 2009a; Song et al., 2012).

Paragneiss are off-white to dust-color with a mineral assemblage of white mica, quartz, plagioclase, garnet, chloritoid and minor kyanite and allanite/zoisite. They show two field relations with eclogite blocks: some contain lenticular eclogite blocks and some interbed with layered eclogite blocks as well as granitic gneiss. Garnet from the metapelites generally shows strong growth zoning, and phengite contains up to 3.4 Si per formula units. Utilizing the THERMOCALC program for garnet-phengite and garnet-kyanite-phengite-quartz barometry, (Zhang et al., 2004) obtained peak *P-T* conditions of *P* = 23 – 31 kbar and *T* = 615 – 700 °C on a hairpin-shaped *P-T* path similar to that of adjacent eclogite. This indicates that the relationship between eclogite and country rocks is "*in situ*" rather than "tectonic emplacement". Zircons from the psammitic paragneiss usually show complex core-mantle-rim structures in CL images, and the cores are detrital of various origins, with ^{207}Pb/^{206}Pb ages in a range of 1300 – 2400 Ma (Song et al., 2012). Zircons from the pelitic gneiss are usually uniform in CL and display metamorphic origin with only a few detrital cores observed, giving weighted mean age in a range of 427 – 431 Ma by LA-ICPMS analysis (Chen et al., 2009a; Song et al., 2014).

2.4.2 The Xitieshan eclogite-gneiss terrane

The Xitieshan terrane, located in the central part of the North Qaidam UHP metamorphic belt, consists mainly of granitic and pelitic gneisses intercalated with variably-sized blocks of eclogite and its retrogressed products (Figure 2.1 and Figure 2.2b). It is overlain by Cambrian-Ordovician volcanic sedimentary rocks of the Tanjianshan Group and intruded by granitic rocks dated at 428 ± 1 Ma (TIMS zircon U-Pb, Meng et al., 2005).

2.4.2.1 Xitieshan Eclogite

Xitieshan eclogites generally occur as lenses or boudins encased within both granitic and pelitic gneisses. They were retrogressed to a variable extent with symplectite and amphibolite overprinting, and show evidence for successive transition from eclogite in the center to amphibole in the margin in some well-preserved large eclogite boudins (Yang et al., 2002b; Zhang et al., 2005a).

Based on detailed mineralogical and petrographical studies, two types of eclogites have been recognized: bi-mineralic and phengite eclogite (Zhang et al., 2009b; Zhang et al., 2011a). Bi-mineralic eclogites are widely distributed and consist mainly of garnet, omphacite, amphibole and minor rutile and quartz. Most of them are strongly retrogressed to garnet-amphibolite or amphibolite without garnet that occur as dark-colored blocks in the field. Coesite pseudomorphs have been found in omphacite within the eclogite (Zhang et al., 2009b). Phengite eclogite was found in the Huangyanggou area and shows a coarse-grained, granular texture, with mineral assemblages of garnet, omphacite, phengite, quartz, rutile and zircon. The phengite eclogite is commonly extensively retrograded to garnet amphibolite and/or amphibolite. Recently, coesite inclusions have been found in zircon within the phengite eclogite retrograded product garnet amphibolite (Liu et al., 2012).

The origin of the Xitieshan eclogite protoliths is poorly constrained thus far, although some reported whole-rock major and trace element and Sr-Nd isotopic data suggest that these rocks are similar in composition to MORB (Zhang et al., 2013).

Thermobarometric studies based on intersection of the garnet-phengite-clinopyroxene barometer and the garnet-clinopyroxene thermometer curves suggest that the peak eclogite-facies *P-T* conditions were P = 27.1 – 31.7 kbar, T = 730 – 830 °C (Zhang et al., 2009b). No prograde assemblage for the eclogite has been reported in this locality thus far.

Zircon from retrograde eclogite yields metamorphic ages by TIMS and SHRIMP U-Pb dating methods of 452 – 486 Ma and protolith ages of 750 – 800 Ma (Chen et al., 2005; Song et al., 2006; Zhang et al., 2006). Zircon from the bi-mineralic eclogite yields metamorphic U-Pb SHRIMP ages of 439 – 461 Ma and a magmatic protolith age of ~887 Ma (Zhang et al., 2011a). Zircon from eclogite yielded a by U-Pb SIMS age of 433 Ma, which was interpreted to represent the eclogite facies metamorphic age (Song et al., 2011). More recently, combined SIMS and LA-ICPMS methods applied on metamorphic zircon resulted in U-Pb weighted mean ages of 432 ± 14 and 441 ± 9 Ma from a coesite-bearing amphibolite (Liu et al., 2012). An imprecise Sm-Nd isochron age (whole rock-omphacite-garnet) of 436 ± 49 Ma was obtained for eclogite by Zhang et al. (2005a). Since these authors concluded that all the analyzed minerals recrystallized during post-peak high pressure metamorphism, this result was interpreted as dating a late eclogite facies metamorphism. A cooling age of 407 ± 4 Ma was derived by $^{40}Ar/^{39}Ar$ analyses on pargasitic amphibole from a retrograde eclogite (Zhang et al., 2005a), and the saddle shaped age spectrum indicates that the sample was contaminated by excess ^{40}Ar.

2.4.2.2 Xitieshan gneiss/schist

The Xitieshan terrane consists of more than 80 vol.% of granitic and pelitic gneiss and the field relationship between them is still a controversial issue. The granitic gneiss is composed mainly of plagioclase, K-feldspar, quartz, biotite and muscovite and without evidence of high-pressure metamorphism. The mineral assemblage of the pelitic gneisses is garnet, biotite, muscovite, plagioclase, quartz, kyanite, sillimanite with some accessory phases: rutile, zircon and monazite (Zhang et al., 2006; Chen, 2007; Zhang et al., 2009c; Zhang et al., 2012). Using the compositions of garnet cores, plagioclase cores and the presence of kyanite and quartz, GASP barometry (Grs + 2Ky + Qz = 3An) gave pressure of 9.5 – 11 kbar at 880 °C, and the garnet-biotite thermometer yielded temperatures of 719 – 835 °C at 10 kbar for the pelitic gneisses (Zhang et al., 2009c). For garnet rims and adjacent biotite analyses, garnet-biotite thermometry and GASP geobarometry yield *P-T* conditions of 6.0 – 8.2 kbar and 675 – 785 °C (Zhang et al., 2009c).

Zircon TIMS dating on granitic gneiss enclosing retrogressed eclogite yielded a granitic protolith age of 952 ± 13 Ma and a metamorphic age of 478 ± 44 Ma (Zhang et al., 2006). Because the metamorphic age is in agreement with the age of metamorphic zircons from the eclogite within the margin of error, Zhang et al. (2006) proposed that the gneisses and their enclosed eclogites underwent HP/UHP metamorphism together during an early Paleozoic orogeny and form part of the North Qaidam HP/UHP metamorphic belt. The deposition age of the paragneiss in the Xitieshan terrane remains unknown thus for but the paragneiss experienced high pressure granulite facies metamorphism around 437 – 441 Ma (SHRIMP U-Pb method, Zhang et al., 2008a). More recently, U-Pb SHRIMP dating of monazite from kyanite-bearing biotite gneisses yielded a Neoproterozoic age of ~938 Ma, Paleozoic ages of 455 – 460 Ma and 422 – 425 Ma, which are regarded as corresponding to the protolith age, ages of prograde metamorphism and amphibolite-facies metamorphism (Zhang et al., 2012), respectively.

2.5 The Qaidam block

The triangular Qaidam block is bounded by the Kunzhong fault to the southwest, the Altyn-Tagh fault to the northwest, the North Qaidam UHP Orogenic belt to the northeast and the Zongwulong fault to the east (Wan and Ma, 1984; Lu et al., 2002b). The Qaidam terrane is a Mesozoic to Cenozoic intracontinental basin with strata deposited on the Precambrian crystalline basement. It is mainly composed of Jinshuikou Group and Binggou Group, which are described in more detail below (Wan and Chen, 1984; BGMQ.,1991; Hao et al., 2004).

The Jinshuikou Group on the southern margin of the Qaidam block consists predominately of high-grade metamorphic rocks including marble, granulite and felsic gneisses, and is intruded by late Paleozoic granitoid plutons. Zircon U-Pb dating from granulite-facies gneiss and granitic rocks revealed that the Jinshuikou Group underwent an early Paleozoic tectonothermal event with a metamorphic age of ~460 Ma and it produced inherited provenance (detrital) ages of 1800–1600 Ma (Zhang et al., 2003a).

The Binggou Group is composed of the Langyashan Formation and Qiujidonggou Formation, which are composed mainly of banded marble, dolomite, dolomitic limestone with slate, silty slate and siltstone with marble (BGMQ., 1991).