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The genesis of Archean supracrustal rocks in the western Shandong Province of North China Craton: Constraints on regional crustal evolution

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Abstract Archean greenstone belts are supracrustal sequences, the lower part of which is usually composed of voluminous ultramafic-mafic volcanics. Intermediate and acid volcanic rocks increase in abundance towards the upper domains. Greenstone belts constitute ~30% of the total volume of Archean cratons, and preserve significant information on the surface environment and magmatism in the early earth, which are useful in unraveling the nature of crustal formation and evolution. The western Shandong Province (WSP) is located at the eastern part of the North China Craton (NCC), where greenstone sequences formed at ~2.7 and ~2.5 Ga were well preserved. The early Neoarchean supracrustal rocks include komatiite-basalt sequence, some meta-sediments of the lower part of the Taishan Group and the Mengjiatun Formation. The volcanism had been correlated to mantle plume, which resulted in vertical crustal accretion. The late Neoarchean supracrustal rocks were composed of metamorphosed felsic volcano-sedimentary sequences and BIFs of the upper part of the Taishan Group and the Jining Group. The geochemical features of the meta-volcanics show calc-alkaline affinities, similar to modern arc-related magmatism, suggesting that the continental crust in the western Shandong Province witnessed horizontal plate movements at ~2.5 Ga. The metasediments and leucosomes in the Qixingtai area display regional upper amphibolite facies metamorphism and anatexis at 2.53–2.50 Ga, coeval with formation of large volumes of crustally-derived granites. These tectono-thermal events suggest that a unified continental crust was formed in the western Shandong Province at the end of Neoarchean.

Keywords Supracrustal rocks, Greenstone belts, Taishan Group, Western Shandong Province, North China Craton

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1. Introduction

Supracrustal rocks are generally composed of the volcanics and sedimentary rocks which were subjected to regional metamorphism. Most of the original stratigraphy and structure of early Precambrian supracrustal rocks were obliterated due to subsequent tectono-thermal regimes and deformation. Since the protolith of supracrustal rocks formed at or near the surface of the crust, they provide useful information on the surface environment, volcanism and tectonic-sedimentary framework of the early earth. Therefore, supracrustal rocks have been central to investigations in the crustal evolution. Greenstone belts, mainly formed in Archean (3.8–2.5 Ga), are typical Archean supracrustal rocks, which were engulfed in a sea of granitic rocks (Condie,

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1981). They appear in linear shape and define shallow basin-like geometry in transverse section, with exposed stratigraphic thicknesses ranging from 10–20 km (Gorman, 1978). The greenstone sequences dominantly composed of ultramafic-mafic volcanics in lower successions. Komatiite with spinifex texture is one of the important hallmarks of Archean greenstone belts. Intermediate and acid volcanic rocks increase in abundance with stratigraphic height. The volcanic units of greenstone belts might be composed of low-K calc-alkaline or bimodal series with the later probably formed in a different tectonic setting from the former (Jackson et al., 1994; Nelson, 1997; Wyman, 1999; Samsonov et al., 2005). Sediments comprise an important unit in the upper part of greenstone belts, and are mainly terrigenous detritus with smaller amounts of cherts, carbonates or banded iron formations (BIFs). The volcanic and sedimentary succession consists of a whole volcano-sedimentary cycle, which is another diagnostic feature of greenstone belt (Jackson et al., 1994; Cao, 1996; Nesbitt et al., 2009). In addition, small-scale cycles can probably develop in different levels of the greenstone succession, for instance thin layers of ultramafic and felsic volcanics could be interlayered with the lower and upper part of mafic volcanics, respectively. Greenstone belts were usually subjected to low or medium grade metamorphism. Although original structures can be preserved locally, most greenstone belts were deformed intensely. In some cases greenstone belts with different ages were bundled, resulting in the contacts between the supracrustal rocks and associated granitoids becoming obscure (Barnes, 1985; Jackson et al., 1994; Swager, 1997; Swager and Nelson, 1997; Ayer et al., 2002; Trofimovs et al., 2004). Isotopic studies show that the origin of the associated granitoids is related to the formation of greenstone belts. Therefore, geologists often consider the supracrustal rocks and associated granitoids as a unified entirety. As early as 1969, Viljoen and Viljoen used "granite-greenstone belt/terrain" in their publications related to the Barberton greenstone belt in South Africa to emphasize this important tectonic unit, composed of supracrustal sequences and surrounding granitoids, in the Archean basement.

Modern continental crust consists of cratons and orogens. Cratons are the continental parts of the earth's crust which has attained stability for a prolonged period. Most cratons were formed in Archean and gradually stabilized at the end of Neoarchean (Zhai, 2011). Cratons are dominated by TTGs (tonalite, trondhjemite and granodiorite) which are characterized by relatively higher Na and lower K contents. Greenstone belts, with the peak of formation time at 2.8–2.5 Ga, compose only ~30% parts of the total volume of cratons. However, the formations of greenstone belts match the global crustal growth and the significant geological events in Neoarchean (Pidgeon and Wilde, 1990; Nutman et al., 1996; Nelson, 1997; Nelson et al., 1999; Condie, 2000). Most greenstone belts contain important metallic mineral resources and preserve useful information on the magmatism, surface environment and mineralization processes of the early earth. On the other hand, Archean cratons are composed of high grade terranes and greenstone belts. High grade terranes often show domal structure with multiple tight folds. However, the greenstone belts, surrounding high grade terranes, are linear in shape and subjected to relatively low grade metamorphism. These features are markedly different from modern crustal structure. Controlled by plate tectonics, the weakly deformed plates are surrounded by high grade metamorphosed collision zones or orogens.

Geochronological studies show that, the peak of Archean magmatism took place at 2.8–2.7 Ga (Condie et al., 2009). The North China Craton (NCC) is one of the oldest cratons in the world (Liu et al., 1992; Song et al., 1996; Wan et al., 2005b; Wu et al., 2008). Compared to North America, Western Austrilia and South Africa, the NCC is characterized by extensive ~2.5 Ga tectono-thermal events (Kröner et al., 1998; Zhao et al., 2002, 2008; Wilde et al., 2005; Shen et al., 2005; Wan et al., 2005a, 2010, 2012a; Yang et al., 2008; Wang et al., 2009b, 2010a, 2013b; Nutman et al., 2011; Liu et al., 2012; Peng et al., 2012). The TTGs and granites formed at ~2.5 Ga compose near 80% of the Archean basement of the NCC (Zhao and Cawood, 2013). In addition to those in the western and eastern Shandong Province, rocks formed at ~2.7 Ga were also identified from Taihang, Zhongtiao and Inner Mongolia (Jahn et al., 2008; Lu et al., 2008; Wan et al., 2011; Ma et al., 2013; Yang et al., 2013; Zhu et al., 2013). But they ocupied much less volume of the basement relavite to rocks formed at ~2.5 Ga. Moreover, the original stratigraphy and structure of the Archean supracrustal rocks in the NCC were obliterated because of strong deformation. Also, komatiites are not widespreaded in the NCC.

The western Shandong Province (WSP), with total area >10000 km^2, is located at the eastern part of the NCC. A typical greenstone succession, known as "Taishan Group", is preserved in this terrane. Thus, the Archean basement of the WSP is also named as "WSP granite-greenstone belt" (Xu, 1992). Geochronological and petrogenetic studies on the supracrustal and plutonic rocks in this region suggest that the contintal crust of the WSP was mainly formed at ~2.7 Ga (Jahn et al., 1988; Cao, 1996; Zhuang et al., 1997; Wan et al., 2011). However, studies on the relationship between ~2.7 and ~2.5 Ga tectono-thermal events and the evolution of the contintal crust of the WSP during the Neoarchean are rare. The Archean supracrustal rocks of the WSP include the Taishan Group, the Mengjiatun Formation, the Jining Group and the Yishui Group (Figure 1). Because the formation age is controversial (Shen et al., 1993; Zhao et al., 2009), we do not further discuss the Yishui Group, which is exposed near the Tanlu Fault. We combine data from various geolocial events, the protolith of supracrustal rocks and their geochronology, geochemistry and degree of meta-

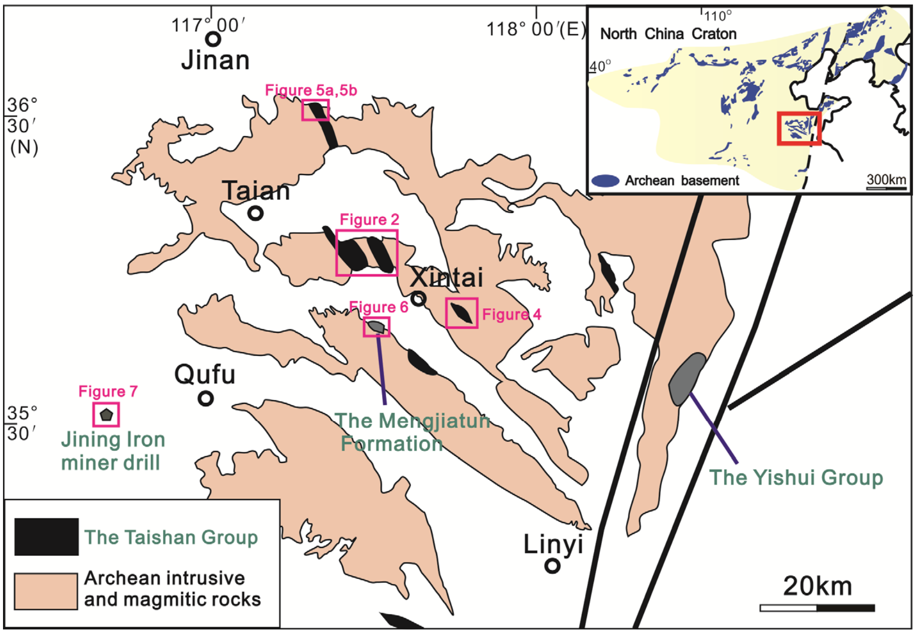

Figure 1 The distributions of Archean supracrustal rocks of the western Shandong Province (modified after Cao (1996)).

morphism in this study. Based on these, we attempt to reveal the Neoarchean volcano-sedimentary stratigraphy and nature of crustal evolution of the WSP.

2. Lithology of Archean supracrustal rocks of the WSP

2.1 The Taishan Group

The Taishan Group, roughly oriented in a northwest-southeast direction, is widely exposed in the central part of the WSP and well-preserved at Yanlingguan-Liuhang and Qixingtai areas. In previous published literatures, the Taishan Group is divided into Yanlingguan, Shancaoyu and Liuhang Formations (Cao, 1996 and references therein), although the subdivisions of each formation are controversial. Different nomenclature including "subformation" and "member" were both adopted in different studies (Song et al., 1994 and references therein).

2.1.1 The Yanlingguan Formation

The Yanlingguan Formation, with an exposed thickness of ~1.2 km in the Yanlingguan area, is composed of amphibolite, tremolite actinolite schist, some leptite and banded iron formation (BIF) (Figure 2). The protoliths are dominated by ultramafic-mafic lavas. Cheng et al. (1982) considered that the Yanlingguan Formation is composed of two subformations, which represents two ultramafic-mafic volcanic cycles. Some amphibolites have spot-like structures. We consider the protolith of the spot-like amphibolite as pillow basalt with amygdaloidal structure. And the quartz and carbonate fillings with banded structure in the pillows are strong deformed eyebrows (Figure 3a and b). Around Tianjingyu village, the stratigraphic height of ultramafic rocks is up to 300 m. Data from nearly one hundred samples show high MgO (12–28%), low SiO_2 (41–50%) and ΣREE contents (Cheng and Xu, 1991). Based on the nature of occurrence, petrologic characteristics and geochemistry, these ultramafic rocks were considered as komatiites, although no spinifex texture has been noted (Cheng et al., 1982; Cheng and Xu, 1991). Some komatiites with well-preserved spinifex textures were identified in the Sujiagou area (Zhang et al., 2001; Cheng and Kusky, 2007). They were subdivided the Yanlingguan Formation into two members (Zhang et al., 2001). The first member contains abundant metamorphosed ultramafic rocks and some andesitic-basaltic rocks. Komatiites, ranging in thickness from 20 to 50 m, show interlayered massive, brecciated and layered structures (Figures 3c and 4). Their geochemical features show marked affinities to the Al-depleted komatiites in other cratons (Polat et al., 2006). The second member of the Yanlingguan Formation is dominated by amphibolites, which have similar occurrences to those in the Yanlingguan area. Wan et al. (2011) obtained a zircon SHRIMP U-Pb age of 2747±7 Ma from andesitic basalts interlayered with ultramafic-mafic sequence in the Yanlingguan area, indicating that the ultramafic-mafic lavas formed close to 2.75 Ga.

In the Qixingtai area, the Yanlingguan Formation is 100–200 m in thick and occurs within the ~2.5 Ga monzogranites and migmatites as lenses or relicts (Figure 5a). The major rock types are amphibolite interlayered with tremolite schist in the lower part and hornblende leptite at the top. The protolith contains ultramafic-mafic rocks and some andesitic volcanic sedimentary rocks. Near the contact between amphibolite and hornblende leptite, the leptite was deformed intensively (Figure 3d). Wan et al. (2012b) ob-

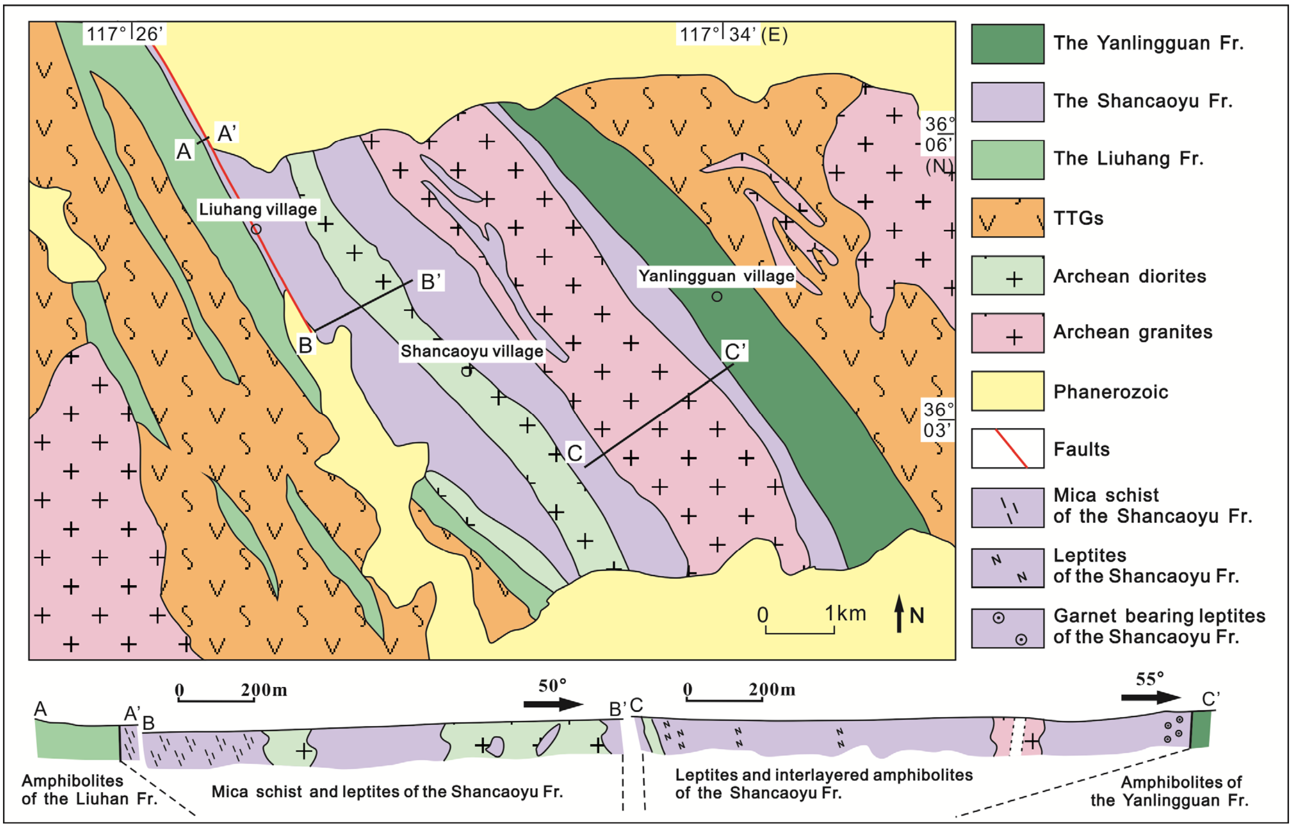

Figure 2 Geological sketch map of the Yanlingguan area (modified after Wan et al. (2012b)). Fr., Formation.

tained the formation age of 2534±9 Ma for the hornblende leptite. Combined with the geological and geochronological studies, we propose that the 2.53 Ga leptite in the top is tectonically in contact with the 2.75 Ga ultramafic-mafic rocks in the lower part of the Yanlingguan Formation.

2.1.2 The Liuhang Formation

The lower part of the Liuhang Formation is composed of amphibolite, hornblendite and some leptite with the protolith dominated by basaltic lavas. The basaltic lavas are more than 1.5 km thick locally (Figure 5a and b). They show massive, layered and pillow structures in the Qixingtai area (Figure 3e–h). Some basaltic rocks with schistose structure are 1–3 m in thickness and are interlayered with pillow lavas (Figure 3i). They usually contain relatively more sulphides than other basalts. It was proposed that the protolith of these schistose basalts might have originated from fine-grained pyroclasts, which were deposited in a relative stable environment at the interval of submarine eruptions (Wang et al., 2013a). Generally, the rock assemblage of the lower Liuhang Formation is similar to the upper part of the Yanlingguan Formation. Dong Yijie equated the Liuhang Formation to the Yanlingguan Formation as two synclinal limbs (Cao, 1996). Compared to the Yanlingguan Formation, the eyebrows and amygdaloidal structures are not well developed in the pillow basalts of the Liuhang Formation. Accordingly, it is inferred that the Liuhang mafic lavas were erupted in deeper water environment relative to the Yanlingguan Formation (personal communications with J Ayer and G Stott). Wang et al. (2009a, 2013a) obtained crystallization ages of 2707±9 and 2706±9 Ma for the TTG rocks, which intruded into the layered and pillow basalts of the Liuhang Formation, respectively. These studies constrain the Liuhang basaltic sequence to have formed before 2.71 Ga.

The upper part of the Liuhang Formation, distinctly different from the lower part, consists of hornblende and biotite leptite interlayered with a few of amphibolite, some metamorphic conglomerate and felsic schist. In the Qixingtai area, the upper part of the Liuhang Formation is dominated by hornblende leptite, which is also intensely deformed near the contact with the lower basaltic sequence. Wang et al. (2013b) proposed that the protolith of the hornblende-biotite leptite is related to andesitic-rhyolitic volcanics. The correlations of major elements of hornblende-biotite leptite indicate that they originated from a calc-alkaline series of pyroclasts. Considering other geological studies, we suggest that the contact between 2.54–2.53 Ga meta-felsic volcano-sedimentary rocks and the >2.71 Ga basaltic sequence are also tectonic as similar as the Yanlingguan Formation. The metamorphic conglomerates, interlayered with leptite, in the upper part of the Liuhang Formation exposed around the Liuhang village. These metasediments are several centimeters to several meters in

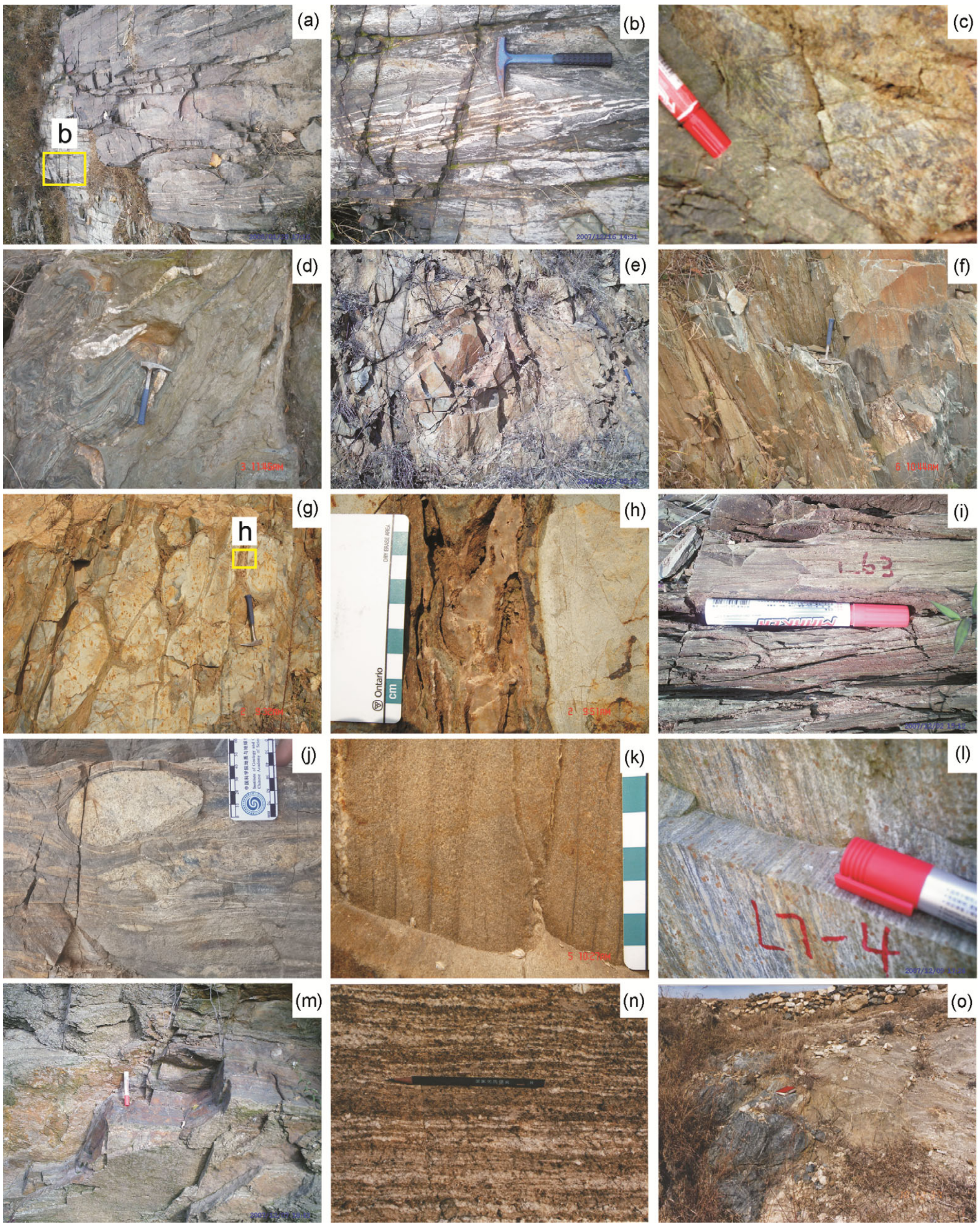

Figure 3 Photographs of the Archean supracrustal rocks of the WSP. (a), (b) Metamorphosed pillow basalts with amygdaloidal and eyebrow structures in the Yanlingguan area; (c) komatiite with spinifex texture in the Sujiagou area; (d) strong deformed hornblende leptites and associated amphibolites in the Qixingtai area; (e) metamorphosed massive basalts of the Liuhang Formation in the Qixingtai area; (f) metamorphosed layered basalts of the Liuhang Formation in the Qixingtai area; (g) metamorphosed pillow basalts of the Liuhang Formation in the Qixingtai area; (h) carbonates between the pillow basalts of the Liuhang Formation; (i) schistose basaltic rocks of the Liuhang Formation; (j) meta-conglomerates of the upper Liuhang Formation in the Yanlingguan area; (k) biotite leptite in the Qixingtai area; (l) garnet biotite gneiss in the Qixingtai area; (m) the BIF relict in migmatites of the Qixingtai area; (n) garnet quartzite of the Mengjiatun Formation; (o) staurolite bearing mica schist of the Mengjiatun Formation intruded by coarse-grained metagabbro.

thickness. The gravels of the conglomerates include TTG gneiss, amphibolite, quartzite and meta-sedimentary rocks. The matrix has similar mineral composition as the biotite leptite (Figure 3j). Geochronological study of the detrital zircons from the metamorphic conglomerate of the Liuhang Formation show an age peak at 2.59–2.58 Ga, and their depositional time is not earlier than 2.53 Ga (Wan et al., 2012b).

2.1.3 The Shancaoyu Formation

The Shancaoyu Formation is composed of hornblende-biotite leptite interlayered with amphibolite, garnet-sillimanite gneiss, together with some mica schist and BIFs. The protolith is dominated by felsic volcano-sedimentary rocks, which is similar to the upper part of the Liuhang Formation. The Shancaoyu Formation is 1–2 km thick and mainly contains biotite leptite in the Qixingtai area (Figure

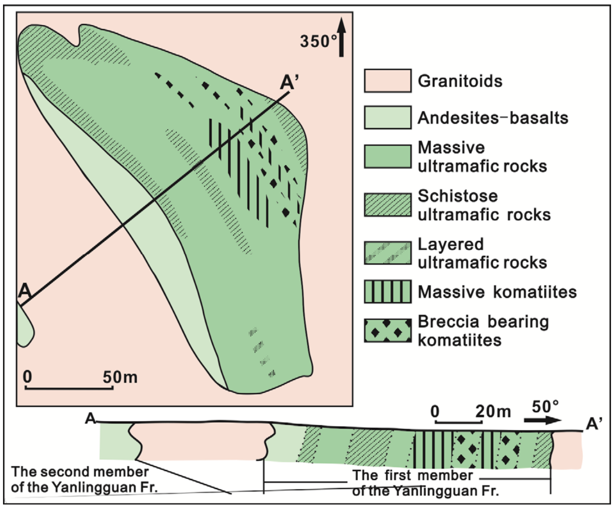

Figure 4 The distribution of komatiites in the Sujiagou area (modified after Zhang et al. (2001)).

3k). The biotite leptite shows same occurrence as the hornblende leptite of upper Liuhang Formation and no sharp contact with the latter (Wang et al, 2013b). Following anatexis, the leucosome-rich biotite leptite progressively increases from west to east, and the metamorphic rocks show a marked coarsening of grain size. Biotite plagioclase gneiss and migmatite replace biotite leptites in the east. The distributions of leptite, gneiss and migmatite show regular changes from west to east (Figure 5a). Some relicts, including biotite schist, garnet-sillimanite gneiss and BIF can be identified in the migmatite zone (Figure 3l and m). In the Yanlingguan-Liuhang area, the Shancaoyu Formation becomes more than 3 km thick. However, the textures of the metamorphic rocks do not show regular change, although they were also influenced by anatexis. Similar to the Qixingtai area, there is no sharp contact between the Shancaoyu leptite and the mica schist of the Liuhang Formation in the west (Figure 2).

Geochronological studies have revealed relatively younger peak age for zircons in the leptite of the Shancaoyu Formation at 2.55–2.53 Ga, which is identical to age from hornblende leptite in the top of the Yanlingguan and Liuhang Formations (Wan et al., 2012b). The dominant population of detrital zircons from the garnet gneiss of the Shancaoyu Formation shows an age of 2.58 Ga, similar to the one from the matrix of metamorphic conglomerates of the Liuhang Formation. The age dating of detrital zircons shows that the clastic rocks of the Shancaoyu Formation deposited after 2.53 Ga (Wang et al., 2014). In the upper part of the Shancaoyu Formation, some BIFs are associated with leptite or metapelite. The volume of BIFs varies in different places of the WSP and becames large-scale in the Hanwang area. Regional geology and associated rocks constrain that the Shancaoyu BIFs formed at 2.53–2.50 Ga.

2.2 The Mengjiatun Formation

The Mengjiatun Formation, mainly exposed at the southeast of the Mengjiatun village, extends in a northwest-southeast direction (Figure 6). It is composed of garnet quartzite, staurolite bearing garnet biotite gneiss and moderate to fine-grained amphibolite. The garnet quartzite is widespread regionally and extends for more than 2 km along the strike. It shows massive, gneissic or banded structures and mainly consists of quartz (65–75%) and garnet (20–25%) with few plagioclase and biotite (Figure 3n). The age populations of the detrital and metamorphic zircons from the garnet quartzite are 2.72 and 2.62 Ga, respectively. The staurolite garnet biotite gneiss, interlayered with the garnet quartzite, is composed of quartz (50%±), biotite (35%±), garent (10%±) and staurolite (5%±) and shows banded structure (Figure 3o). The age peaks of the detrital and metamorphic zircons from the staurolite garnet biotite gneiss are 2.74 and 2.64 Ga, respectively (Du et al., 2003). The amphibolite, locally interlayered with the garnet quartzite, display massive and banded structures. It is dominantly composed of hornblende (65%±) and plagioclase (35%±) with minor quartz. The zircons from the Mengjiatun amphibolite record ~2.6 Ga metamorphism. Regional geology and intrusive contacts suggest that the age of the Mengjiatun Formation should be older than 2.7 Ga (Du et al., 2005; Wan et al., 2012b).

2.3 The Jining Group

The Jining Group shows angular unconformity with the overlying Phanerozoic cover at the depth of ~1000 m. A large-scale magnetic anomaly extends along northeast-southwest direction at Yandian area, testifying to the occurrence of BIFs (Figure 7) (Han et al., 2008). Geophysical studies and drill core data indicated that the upper part of the Jining Group is mainly composed of calcic, siliceous and ferriferous sericite phyllite, chlorite phyllite, slate and BIFs within several centimeters to ten meters thick. Calcite is widely present in various rock-types. Some meta-felsic volcanics occur in the middle and lower parts of the Jining Group (Figure 8). Mineral assemblage suggests that the Jining Group was subjected greenschist facies metamorphism. The protolith of the Jining Group are siliceous and ferriferous sedimentary rocks, calcic pelite, volcanic debris-bearing siltstone/pelite and minor intermediate/felsic lava and tuff. The depositional environment is thought to be the transition between neritic and pelagic facies. SHRIMP zircon U-Pb dating suggest that the meta-felsic volcanics, interlayered with the sericite phyllite in the lower part of the Jining Group, erupted at 2.55–2.52 Ga, indicating the Jining Group formed in the Neoarchean (Wang et al., 2010b; Wan et al., 2012a).

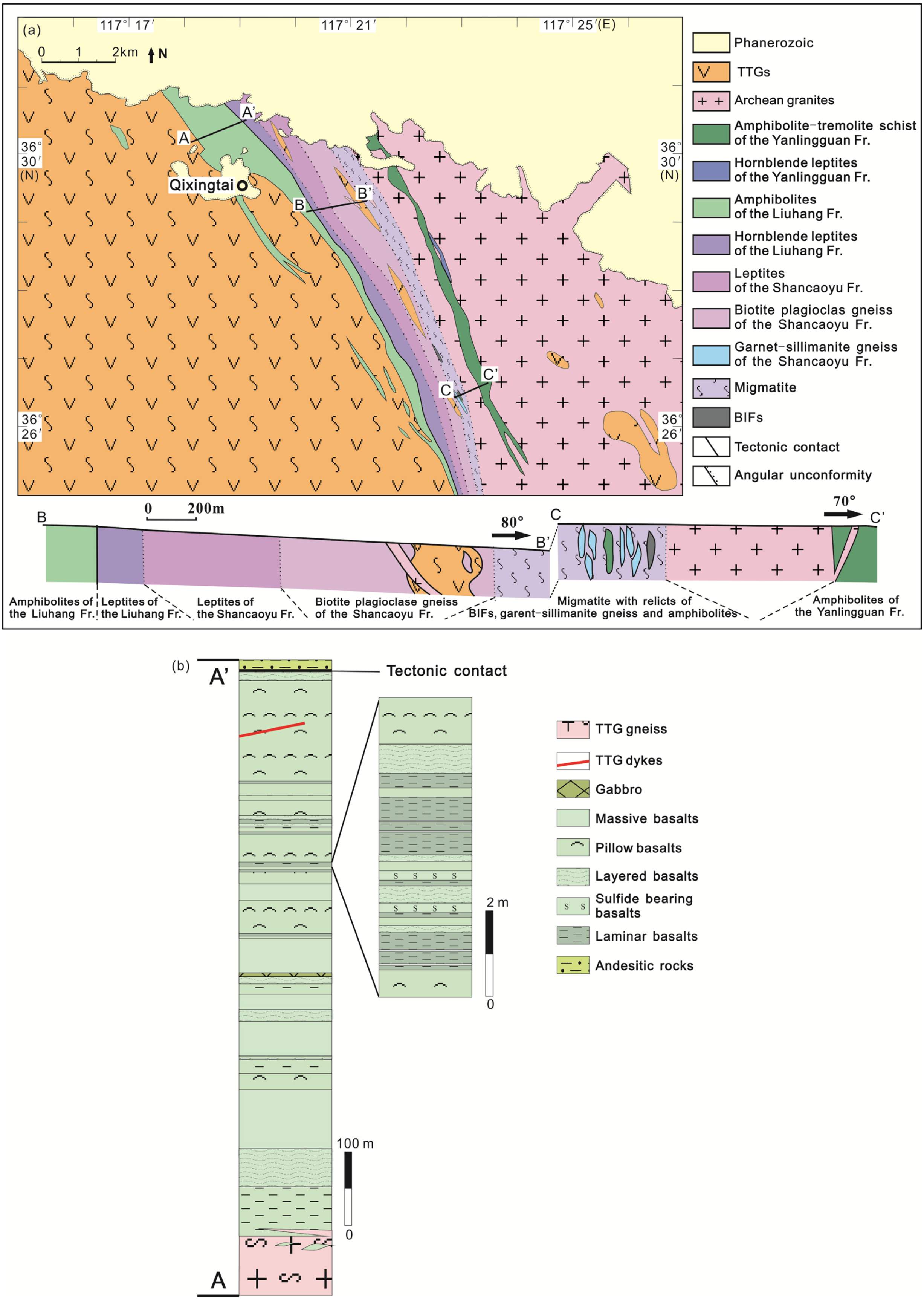

Figure 5 Geological sketch map of the Qixingtai area of the WSP (a) and lithological section of the lower part of the Liuhang Formation in the Qixingtai area (b) (modified after Wang et al. (2013a)).

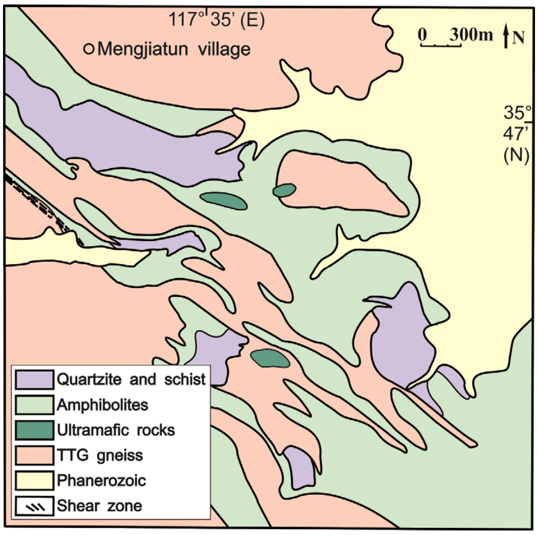

Figure 6 Geological sketch map of the Mengjiatun area (modified after Du et al. (2003)).

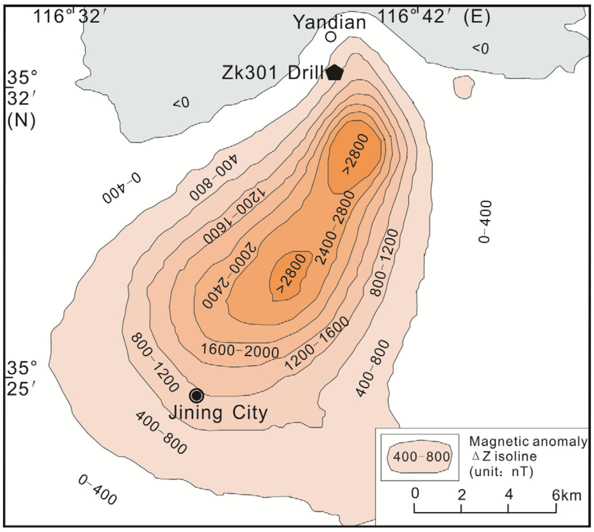

Figure 7 Magnetic anomaly caused by the iron deposit of the Jining Group (after Han et al. (2008)).

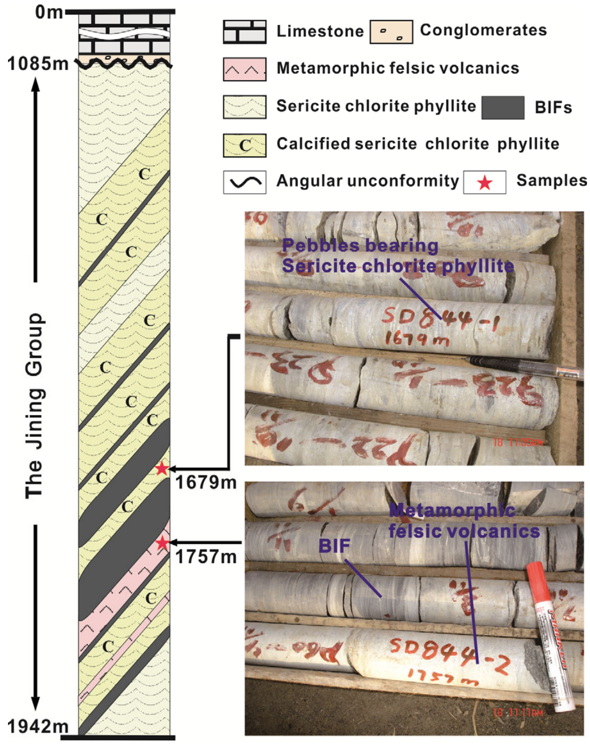

Figure 8 Simplified lithological column and photographs of Jining Iron Deposit drill core (modified after Han et al. (2008) and our observation).

3. Geochronology

The various formations of the Taishan Group were considered to have formed at 2.7 Ga. The Yanlingguan and Shancaoyu Formations represent the initial volcano-sedimentary cycle of the greenstone belt, and the Liuhang Formation represents the second and third incomplete cycles (Cao, 1996). However, recent geochronological studies reveal that the Taishan Group was formed during two periods of 2.75–2.71 and 2.53–2.50 Ga in Neoarchean. The contacts between these two are tectonic as suggested by regional geology and zircon age dating. The supracrustal rocks, formed at 2.75–2.71 Ga, contain komatiite-basalt sequence, some metamorphosed andesitic basalts and meta-sediments of the Yanglingguan Formation and the basaltic lavas of the Liuhang Formation. The younger supracrustal rocks, formed at 2.53–2.50 Ga, are composed of hornblende leptite in the top of the Yanlingguan Formation, the leptite and meta-conglomerate in the upper part of the Liuhang Formation and the metamorphosed volcano-sedimentary rocks and BIFs of the Shancaoyu Formation. These two assemblages distinctly differ from each other with regard to the formation age, rock type and petrogenesis. These observations are in conflict with the definition of "Group" in Chinese literatures. However, appropriate nomenclature for the Taishan supracrustal rocks has not yet been proposed.

The Mengjiatun Formation in the WSP greenstone belt constitutes the supracrustal rocks coeval with the 2.75–2.71 Ga komatiite-basalt sequence of the Taishan Group. The provenance of the metasediments of the Mengjiatun Formation is intermediate to acid magmatic rocks, which is close to the depositional basin. Zircon age dating revealed that the source materials of the sediments formed at 2.74–2.72 Ga and were deposited at 2.72–2.70 Ga (Du et al., 2003). Based on metamorphic history and deformation, some geologists suggested that the Mengjiatun Formation formed earlier than the Taishan Group, although no contacts between the two can be observed (Du et al., 2003). The andesitic basalt of the Taishan Group, interlayered with the komatiite-basalt sequence, formed at 2747 Ma (Wan et al., 2011). This is older than the depositional time of the metasediments of the Mengjiatun Formation, even if we take into consideration of the analytical error. We suggest that the Mengjiatun rocks formed after the komatiite-basalt sequence of the Taishan Group and its depositional environment was a relatively stable continental margin basin. The Jining Group is a coeval supracrustal sequence with the ~2.5 Ga meta-felsic volcano-sedimentary rocks of the Taishan Group. However, the Jining Group was subjected to greenschist facies metamorphism and was oriented in a northeast-southwest direction, which indicates that the Jining Group was controlled by a different tectonic realm as compared to that of the western Shandong Province after its deposition. The Jining Group is dominated by sericite-chlorite schist and seems to be the lower grade metamorphic equivalents of the garnet-sillimanite gneiss in the Taishan Group. The similar rock assemblage, composed of meta-pelite and BIF, was also indentified in east Hebei and Inner Mongolia locally. It is prospected that this sedimentary rock assemblage probably played an important role in the WSP or even on a regional scale in the NCC at the end of Neoarchean.

4. Volcano-sedimentary sequences and crustal evolution

Most greenstone belts are dominated by two volcano-sedimentary successions. The first is komatiite-tholeiitic basalt sequences, associated with mafic pelite, turbidite, deep water shale and chert. The geochemical features of the volcanicsare characterized by near-flat or minor LREE-depleted patterns, comparable to those of Phanerozoic oceanic plateaus. These sequences were thought to be derived from mantle plumes (Condie, 2000; Condie et al., 2001) and are widespread in the Archean basements of North America, Western Australia, Greenland, southern India and South Africa (Hollings et al., 1999; Wyman, 1999; Bateman et al., 2001; Ayer et al., 2002; Hofmann et al., 2004; Manikyamba et al., 2004; Polat, 2009; Said et al., 2010). The second class is tholeiitic to calc-alkaline basalt, andesite, dacite and rhyolite sequences associated with intermediate-acid turbidite. Some geologists believed that this volcano-sedimentary succession can be compared to trench-arc system controlled by plate tectonics. These volcanics show fractionated REE with negative Nb, Ti and P anomalies, which are typical geochemical features of modern arc magmas (Jachson et al., 1994; Hollings et al., 1999; Polat and Kerrich, 2001; Ayer et al., 2002). Studies on greenstone belts showed that these two volcano-sedimentary successions are often spatially bundled within the same terrane (Manikyamba et al., 2004; Polat, 2009), or even exposed in a single supracrustal sequence within different stratigraphic height (Said and Kerrich, 2010). This lithological feature was attributed to mantle-related activities developed at the convergent margins (Wyman, 1999; Polat, 2009; Wyman and Kerrich, 2009) or heterogeneous mantle source (Said and Kerrich, 2010; Said et al., 2010).

The supracrustal associations in the Archean basement of the WSP, represented by the Taishan Group, are the products of ~2.7 and ~2.5 Ga volcano-sedimentary events. In the early Neoarchean, the meta-volcanics are dominated by komatiite-basalt sequences. Komatiites are geochemically characterized by Al depletion (Polat et al., 2006), and the basalts are composed of tholeiites and enriched basalts (Wang et al., 2013a). The rock assemblages and their geochemical features suggest a mantle plume origin. Although some 2.75 Ga basalts with calc-alkaline geochemical affinities were identified in the Qixingtai area, these are relatively minor in volume (Wang, 2015). Thus, the early Neoarchean meta-volcanics of the WSP are comparable to the first type of volcano-sedimentary successions occurring coeval greenstone belts globally. The supracrustal associations formed in the late Neoarchean (~2.5 Ga) contain significant metamorphosed intermediate to acid volcano-sedimentary rocks, some clastic rocks and BIFs. According to published geochronological data and regional geology, it can be inferred that the terrigenous clastics and ferriferous sediments were deposited after or coevally with the felsic volcanic materials, although it is hard to recover the original stratigraphy of the ~2.5 Ga supracrustal rocks. It seems that the ~2.5 Ga supracrustal rocks recorded a changing process from magmatism to sedimentation in a stable basin of the WSP in the late of Neoarchean. Distinct from the high temperature magmas originated from mantle plume in the early Neoarchean, the ~2.5 Ga volcanics display negative anomalies in Nb, Ta and Ti contents and other geochemical affinities of calc-alkaline series (Wang et al., 2013b). It is known that the development of the calc-alkaline volcanism is associated with fluids, which could decrease the temperature of partial melting. Moreover, the magmas originated from mantle plume and mantle wedge partial melting usually generate garnet and olivine residue in the sources. The ~2.5 Ga meta-volcanics of the Taishan Group show linear extension and the andesitic rocks show geochemical affinities of sanukitoids (Wang et al., 2013b). Although the calc-alkaline rocks could be generated from partial melting of mafic rocks of lower crust without arc system, the geological and geochemical features of the ~2.5 Ga Taishan volcanics can be better explained by arc-like magmatism. Although no ~2.5 Ga calc-alkaline basalts have been identified in the Qixingtai and Yanlingguan areas of the WSP, the nature of magmatism during the late Neoarchean (~2.5 Ga) is distinctly different from the early Neoarchean (~2.7 Ga), with a general variation from komatiite-tholeiite to calc-alkaline.

The geochemistry and Nd isotopic composition of the Taishan komatiite-tholeiite sequence indicate the role of crustal contamination (Polat et al., 2006; Wang et al., 2013a). Some >3.0 Ga detrital and inherited zircons were identified from meta-clastic rocks of the Taishan Group and ~2.5 Ga granite in the Archean basement of WSP (Lu et al., 2008). It is believed that the ancient nuclei of continental crust were formed before the Neoarchean. But these could be in small scale or as micro continents, because >2.8 Ga rocks are not found in WSP. The 2.8–2.7 Ga window in the Neoarchean is an important period for crustal growth of the WSP. Accompanied with komatiites and basalts, large volumes of coeval TTGs were formed in the early Neoarchean (Lu et al., 2008; Wang et al., 2008; Wang et al., 2009a; Wan et al., 2011), similar to other granite-greenstone belts such as in North America, Western Australia, Greenland, South Africa and Baltic shield. The mantle plume related magmatism in the WSP greenstone belt suggests that the NCC was also important records of the global crustal growth event at ~2.7 Ga. During the early Neoarchean, the crustal growth was mainly by vertical accretion. The calc-alkaline volcanics and sanukitoids developed at ~2.5 Ga in the WSP greenstone belt. This late Neoarchean rock assemblage, probably products of partial melting of oceanic crust and mantle wedge, suggests plate movements and growth of continental crust by horizontal accretion at ~2.5 Ga, similar to modern plate tectonics. Because of partial melting of pre-existing oceanic crust and mantle wedge, the ~2.5 Ga magmatism is characterized by both juvenile crust formation and recycling. In addition to those in the WSP, ~2.5 Ga calc-alkaline volcanics also developed in Wutai, Dengfeng and other domains of the NCC (Wang et al., 2004; Diwu et al., 2011). The similar volcano-sedimentary sequences can be best explained by relative movement of blocks, marking the amalgamation of the NCC at the end of Neoarchean (Zhai and Santosh, 2011; Zhai, 2014; Yang et al., 2015).

5. ~2.5 Ga metamorphism-anatexis and crustal stablization

The supracrustal rocks were subjected to ~2.5 Ga regional metamorphism and anatexis. Migmatites developed at the Qixingtai, Longting and Mengliangu areas in the WSP. A lithological section, displaying continuous change from supracrustal rock to migmatite, is preserved in the Qixingtai area. Some BIFs, garnet-sillimanite gneiss and amphibolites occur as relicts in migmatites, suggesting the degree of anatexis related to the protolith of supracrustal rocks. Field investigations show that the leucosomes of the migmatites are monzonitic or K-rich in composition. Na-rich leucosomes are rare or occur in small scale. K-feldspar, quartz and plagioclase in leucosomes often display medium to coarse grained textures. Melanosomes are mainly felsic gneiss with abundance of biotite and amphibolite. Two types of leucosomes can be identified according to their occurrences. The first type shows selvage texture with irregular shape and size, indicating in-situ crystallization of the melt with minor movement. The second is vein-like in occurrence and parallel with the melanosome. They were thought to be the product of segregation and movement of the melt (Sawyer, 1998, 2001). Because of intense deformation, the leucosome, melanosome and associated gneiss usually show banded structures.

Based on geochronological studies, the regional metamorphic-anatectic age of the WSP greenstone belt can be constrained at 2.53–2.50 Ga. The *P-T* estimates obtained from the garnet gneiss relict in the Qixingtai area by garnet + biotite thermometer and GBPQ barometer show P= 550–570 MPa and T=670–680°C (Wang et al., 2014). These conditions correspond to low-medium pressure upper amphibolite facies metamorphism, representing the *P-T* conditions of solidus during anatexis (communications with Prof. C J Wei). Some anatectic case studies show that most pelitic rocks will be dehydrated when they are subjected to medium-upper amphibolite facies metamorphism. The fluids, originated from dehydration of protolith sediments, are favorable to anatexis, through which the spatially associated clastic rocks and volcanics could be fertilized, thereby decreasing the melting temperature (White et al., 2005; Brown, 2007). In the Qixingtai area, the leptites of the Taishan Group show a marked coarsening of grain size along with leucosome-rich domains which progressively increases from west to east. Leptites were replaced by biotite plagioclase gneiss and migmatite in the east. In the migmatitic zone close to the exposures of garnet-sillimanite gneiss, the parallel banded structures are composed of coarse grained leucosomes and foliated biotite gneiss. These geological characteristics suggest that the fluid-induced metasomatism and fertilization played important roles for regional anatexis. The fluids, released by the pelitic rocks under upper amphibolite facies, triggered melting in the surrounding Na-rich volcanics and clastics at relatively lower temperature, and resulted in the formation of biotite rich melanosomes and monzonitic or K-rich leucosomes. Farther from the pelitic rocks, the minerals in the leptites were recrystallized and became coarser grained during metamorphism and anatexis. The horizontal changes in lithology of the supracrustal rocks in the Qixingtai area reflected the vertical variation of the WSP Archean metamorphic basement that formed at ~2.5 Ga.

The age distributions of felsic intrusions, calc-alkaline volcanics and regional metamorphism and anatexis are compiled in Figure 9. Before the formation of the calc-alkaline volcanics (>2.53 Ga), the felsic intrusions were dominated by TTGs. The eruption of calc-alkaline volcanics was followed by regional metamorphism and anatexis. Large volumes of crustally derived granites developed coeval to the anatexis (2.52–2.50 Ga). The earlier Na-rich magmatism transformed to relatively K-rich granitic magmatism from 2.53–2.52 Ga. Regardless the mechanism of origin of TTGs as to subduction-related or not, the development of calc-alkaline magmatism indicates that the Archean basement of the WSP witnessed an arc-like tectonic regime with nature of magmatism changing from

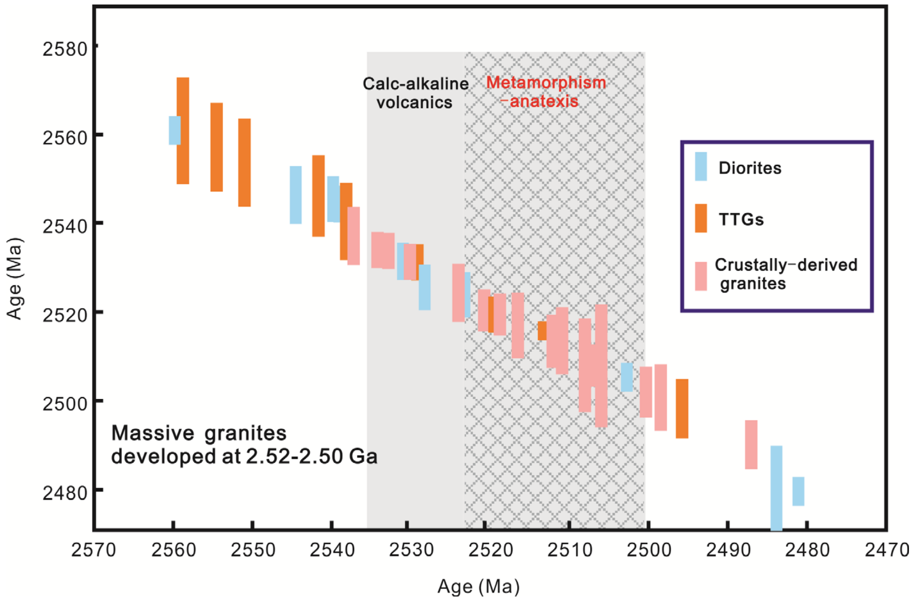

Figure 9 Age distribution of the Neoarchean felsic intrusions of the WSP (data from Lu et al. (2008), Wang et al. (2009b), Wan et al. (2010), Wang et al. (2013a, 2013b)).

Na-rich to relatively K-rich in composition. After the arc-like tectonic regime (2.52–2.50 Ga), the Archean basement of the WSP was subjected to extensive regional metamorphism, anatexis and crustally-derived magmatism. However, the tectonic setting related to regional crustal re-working events is not clear yet. In the migmatitic zone of the Qixingtai area, the relicts contains metamorphic pelitic rocks and BIFs, suggesting the existence of a relatively stable depositional environment after (or before?) the formation of the calc-alkaline volcanics. We infer that 2.53–2.50 Ga metamorphism and anatexis in the WSP recorded by the paragneiss could be related to the amalgamation of arc and micro blocks. Voluminous crustally-derived magmas indicate that a unified continental crust was formed in the WSP at the end of Neoarchean.

6. Conclusions

The greenstone belts, as the representative of the Archean supracrustal rocks, preserve important records of the evolutionary history of continental crust in the early earth. The identification of Neoarchean supracrustal rocks, formed at ~2.7 and ~2.5 Ga in the WSP greenstone belt, offer opportunities for understanding the crustal evolution of the NCC. The magmatism, sedimentation, regional metamorphism and anatexis recorded by these supracrustal rocks suggest that the crust formation and stabilization in the WSP witnessed three major processes as follows. (1) Differentiation of crustal materials from mantle and vertical accretion controlled by plume at ~2.7 Ga. (2) Horizontal plate movements resulting in calc-alkaline magmatism and the amalgamation of micro blocks at 2.53–2.50 Ga. (3) Regional metamorphism, anatexis and crustal re-working at the end of Neoarchean. The geochemical characteristics of the ~2.7 Ga komatiite-basalt sequence of the WSP are comparable to those in coeval greenstone belts globally, suggesting that the crustal evolution of the NCC could probably be similar to other cratons at the early Neoarchean. On the other hand, the ~2.5 Ga meta-volcanics in the WSP show geochemical affinities of modern arc-related series. Similar coeval volcanic sequences also developed in other parts of the NCC, suggesting horizontal movements and amalgamation of micro blocks. Another significant achievement is the identification of the ~2.5 Ga Al-rich rocks in the WSP greenstone belt. The *P-T* estimates by mineral chemistry and assemblage of these Al-rich rocks yielded 550–570 MPa and 670–680°C, suggesting that the WSP greenstone belt subjected to upper amphibolite facies metamorphism and anatexis at ~2.5 Ga. At the same time, the basement of the WSP experienced widespread crustal remelting and emplacement of voluminous K-rich and monzonitic granites. Thus, the continental crust of the WSP attained considerable thickness at the end of Neoarchean.

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