2 Archean Continental Crust in the Southern North China Craton

Chunrong Diwu, Chengli Zhang, and Yong Sun

Abstract

The Archean-Paleoproterozoic metamorphic basement is well exposed in the southern North China Craton (NCC), and can be divided into three distinct tectonic complexes, naming, the Sushui, Dengfeng and Taihua complexes. Their equivalents probably extend into the Huoqiu and Bengbu areas of Anhui Province in the southeastern margin of the NCC, and the Longshan area of Gansu Province in the southwestern margin. In the last decade, a large number of the Mesoarchean–Neoarchean (ca. 2.85–2.50 Ga) rocks have been widely recognized in those complexes, which provides important insights into the formation and evolution of NCC during this period. Based on the available isotopic data, the Archean continental crust of the southern NCC can be divided into the 2.85–2.70 Ga and ca. 2.50 Ga rock associations. Most of zircons in the 2.85–2.70 Ga rocks that consist predominantly of TTG gneisses have variable but positive $\varepsilon_{Hf}(t)$ values, and their magmatic zircon domains that are characterized by oscillatory zoning in CL images present mantle-like O isotopes, reflecting a somewhat geochemically heterogeneous but depleted mantle Hf isotope reservoir dominates the source of these rocks. The whole-rock Nd isotopic data show similar geochemical characteristics, confirming juvenile sources for their provenance. Although majority of Chinese Precambrian geologists suggested that the ca. 2.50 Ga tectonothermal events were mainly involved in crustal reworking or partial melting of the early Neoarchean mafic crust formed at 2.85–2.70 Ga, we emphasize that ca. 2.50 Ga is another major period of continental crust growth in the southern NCC as well as the whole NCC based on the following lines of evidence: (1) a variable proportion of metabasaltic rocks with ca. 2.50 Ga zircon U–Pb ages exposed in both the high-grade gneissic complexes and the low-grade granite-greenstone terrenes. (2) the metabasaltic rocks present mixed MORB- and/or arc-like geochemical affinities, suggesting that they were derived from mantle source with minor continental crust contamination. (3) most of the ca. 2.50 Ga magmatic zircons from TTG gneisses, amphibolites and related rocks have positive $\varepsilon_{Hf}(t)$ values that are similar to those of the contemporaneous depleted mantle, and their Hf model ages of 2.85–2.49 Ga are close to corresponding U–Pb ages, suggesting that these rocks originated from the juvenile crust at ca. 2.50 Ga. (4) the whole-rock Nd isotopic data of the ca. 2.50 Ga rocks show similar geochemical characteristics, confirming juvenile sources for their provenance. In summary, we suggeste that the southern NCC underwent two marked episodes of continental crust growth at 2.85–2.70 Ga and ca. 2.50 Ga during the Archean, and all the complexes in the southern NCC were welded together to form a coherent ancient terrane at the end of the Neoarchean, we named it the “Southern Archean Block (SAB)”. The SAB show an east–west trending belt from Gansu across Shaanxi and

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Henan into Anhui Province, stretching over 1000 km long, it may has experienced a long geological history which can be traced back to the Hadean. The ca. 2.50 Ga K-rich granitoid rocks were recognized from the southern NCC, which are commonly considered as the proxy of the final stabilization of the block lithosphere.

Keywords
Precambrian • Archean • North China Craton • Continental crust growth • Zircon

2.1 Introduction

Compared with the oceanic crust, the continental crust is stable, thick, and ancient. Although it constitutes only 0.6 % mass of the silicate earth and 40 % of the surface area of the Earth (Rudnick and Gao 2014), it is the archive of the geological history of the Earth. The Archean era (4.5–2.5 billion years) covers more than half of the entire history of the Earth. Models based on the U–Pb, Hf and O isotopic compositions of detrital zircons suggested that at least 60–70 % of the present volume of continental crust had been generated at the end of the Neoarchean, and there was a marked decrease in the rate of crustal growth at ca. 3.0 Ga in global scale (Belousova et al. 2010; Cawood et al. 2013; Hawkesworth et al. 2013). However, a large volume of Archean continental crust have been destroyed by weathering/erosion, crustal reworking or recycled back into the mantle, it was documented that less than 5 % of the current volume at that time was preserved today (Cawood et al. 2013), most of old remnants Archean crust are within craton now presently character by thick lithospheric mantle roots (Bowring and Housh 1995).

The database of global zircon ages from both granitoids and detrital sediments show two major age peaks or peak clusters at 2.70 and 1.90 Ga during the early Precambrian period (Condie et al. 2009a; Condie and Aster 2010), only the 2.70 Ga cluster is prominent and unique, it registers a global event on the continents, thus some researchers suggested that the first supercontinent named Kenorland was as far back as 2700–2650 Ma with a corresponding age cluster of 2.7 Ga (Bleeker 2003). However, the North China Craton (NCC) is one of the oldest cratons in the world preserving continental rocks up to 3.80 Ga old (Liu et al. 1992, 2008; Wan et al. 2005, 2012; Wu et al. 2008). It presents a younger U–Pb age peaks at ca. 2.50 Ga in the period of the Archean, and a large volume of Tonalitic–trondhjemitic–granodioritic (TTG) gneisses, mantle-derived granites and minor supracrustal rocks were formed during this time (Zhai et al. 2003; Zhai and Santosh 2011, 2013), thus some researchers emphasized that the ca. 2.50 Ga tectonothermal event represents a major period of continental crust growth in the NCC (Diwu et al. 2011; Liu et al. 2009b), which is one of the characteristics of the NCC, and markedly different from most other cratons worldwide. Recently, 2.85–2.70 Ga rocks were also recognized in several regions in the NCC (Wan et al. 2014), such as Wuchuan, Hengshan, Fuping, Zanhuang, Shandong, Zhongtiao, Lushan, Xiaoqinling, and Huoqiu. The whole-rock Sm–Nd isotopic data and zircon Hf isotopic compositions indicate that the major continental crust growth event in the NCC occur at 2.85–2.70 Ga, similar to many other cratons in the world, whereas the 2.50 Ga tectonothermal event was mainly involved in crustal reworking or partial melting of the early Neoarchean mafic crust formed at 2.85–2.70 Ga (Wu et al. 2005; Geng et al. 2012; Zhao 2014). The Archean basement rocks are well exposed in the southern NCC, therefore, it is an excellent area for understanding the formation and evolution of NCC at this period. In this contribution, we review the spatial and temporal distribution of the Archean rocks, and present an integrated available whole-rock Nd and Hf-in-zircon isotopic data with a principal aim to provide a comprehensive scenario for the Archean continental crust growth and evolution of the southern NCC.

2.2 Major Archean Lithotectonic Units

The early Precambrian (>1.80 Ga) rocks in the southern NCC show an east–west trending belt from the Gansu across Shaanxi and Henan into Anhui Province, stretching over 1000 km long, which are mainly occurred as high-grade gneissic complexes or low-grade granite-greenstone terranes in Zhongtiaoshan, Dengfeng, Lushan, and Xiaoqinling areas (Fig. 2.1), they were named Sushui, Dengfeng, and Taihua complexes, respectively. Moreover, their equivalents probably extend into the Longshan area of Gansu Province in the most southwestern margin and the Huoqiu area of Anhui Province in the most southeastern margin of the NCC.

2.2.1 Sushui Complex

The Sushui Complex chiefly occurred along the northwestern area of the Zhongtiaoshan, Shanxi Province, it presents a

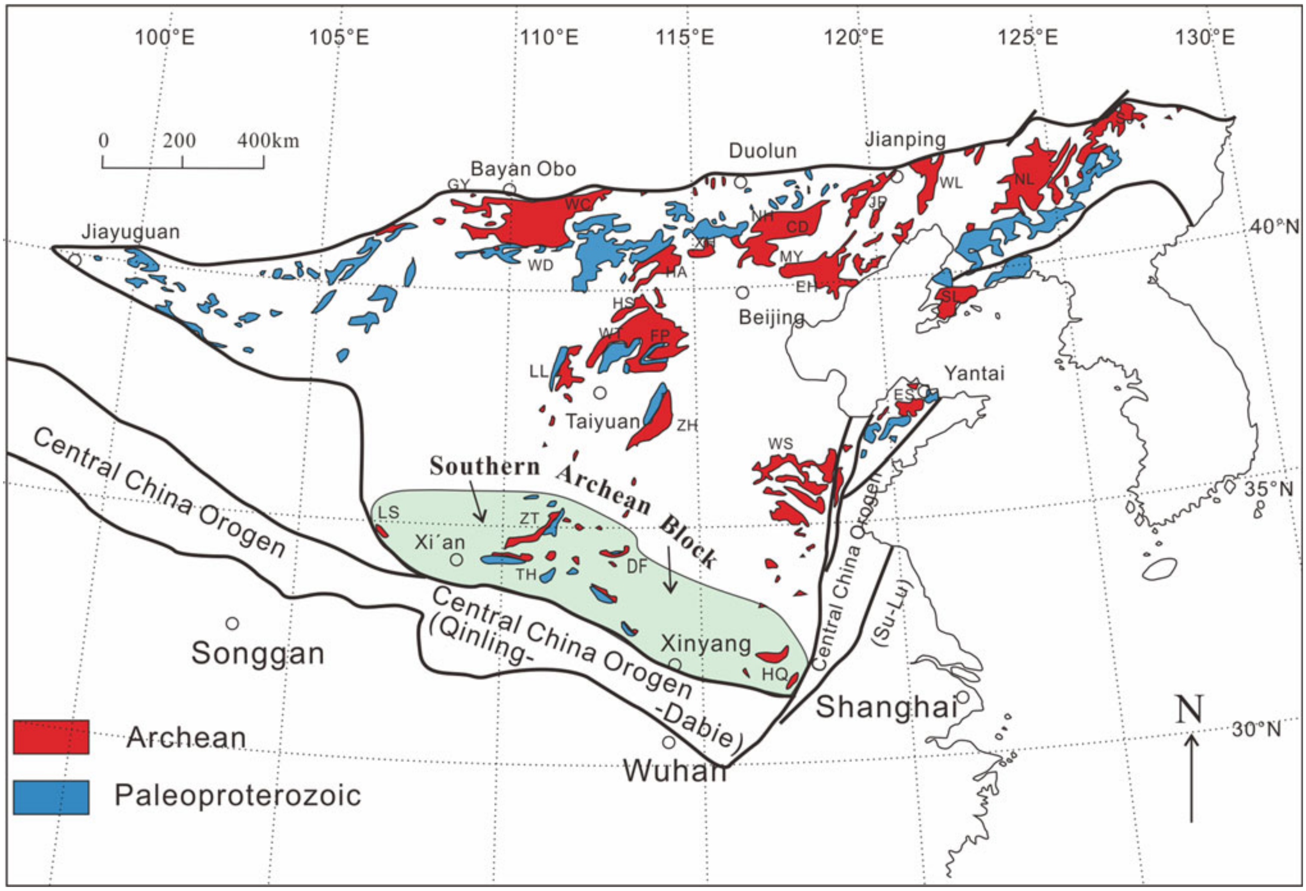


Fig. 2.1 Simplified geological map showing the distribution of metamorphic complexes in the NCC (revised after Zhao et al. 2005). Abbreviations for metamorphic complexes: *CD* Chengde; *D* Dengfeng; *EH* Eastern Hebei; *ES* Eastern Shandong; *FP* Fuping; *GY* Guyang; *HA* Huai'an; *HL* Helanshan; *HQ* Huoqiu; *HS* Hengshan; *JN* Jining; *LG* Langrim; *LL* Lüliang; *LS* Longshan; *MY* Miyun; *NH* Northern Hebei; *NL* Northern Liaoning; *QL* Qianlishan; *SJ* Southern Jilin; *SL* Southern Liaoning; *TH* Taihua; WD Wulashan-Daqingshan; *WL* Western Liaoning; *WS* Western Shandong; *WT* Wutai; *XH* Xuanhua; *ZH* Zanhuang; *ZT* Zhongtiao

northeast–southwest trending zone, extending 200 km long. The complex also scarcely exposed in Yumenkou area of the northern Hancheng, Shaanxi Province.

The Sushui Complex in the Zhongtiaoshan is unconformably overlain by Paleoproterozoic Jiangxian, Zhongtiao, and Danshanshi groups and Mesoproterozoic Xiyanghe and Ruyang groups (Sun et al. 1990; Sun and Hu 1993; Bai et al. 1997) (Fig. 2.2). It consists principally of the Neoarchean granitoid plutons and supracrustal rocks. The former can be subdivided into the Neoarchean (ca. 2.75–2.50 Ga) Xiyao, Zhaizi, and Beiyu TTG gneisses, Neoarchean (Ca. 2.60 Ga) Henglingguan and Haizhou monzogranitic gneisses, and Paleoproterozoic (ca. 2.30 Ga) Yanzhuang potassic granitoid rocks. The latter make up of Lengkou and Chaijiayao supracrustal rocks.

The Xiyao gneisses are mainly exposed in Xiaxian and Haizhou areas in the southwestern part of the Zhongtiaoshan. They are composed predominantly of medium-grained TTG gneisses with minor dioritic gneisses, enclosing amphibolite gneisses, most of which have been strongly deformed with fine banded structures and the migmatized zones, suggesting evidence of in situ melting and advanced anatexis. The Xiyao gneisses were previously considered to have been formed at Mesoarchean. However, recent U–Pb zircon ages reveal that they were mainly emplaced at late Neoarchean (ca. 2.50 Ga) (Tian et al. 2006; Guo et al. 2008; Zhang 2015); it is noteworthy that sparse ca. 2.70 Ga trondhjemitic and dioritic gneisses were also recognized from the Xiyao gneisses (Zhu et al. 2013), confirming the existence of ca. 2.70 Ga crustal components in the Zhongtiaoshan.

The Neoarchean (ca. 2.50 Ga) Zhaizi gneisses are distributed in the areas of Lengkou-Yanzhuang and Caojiagou-Xipingchun with an outcrop area of 35 km^2 in the Northwestern part of the Zhongtiaoshan. Whereas the Neoarchean Beiyu gneisses are composed of orthogneisses with trondhjemitic composition and have coarse-grained texture and massive to gneissic structure, which only

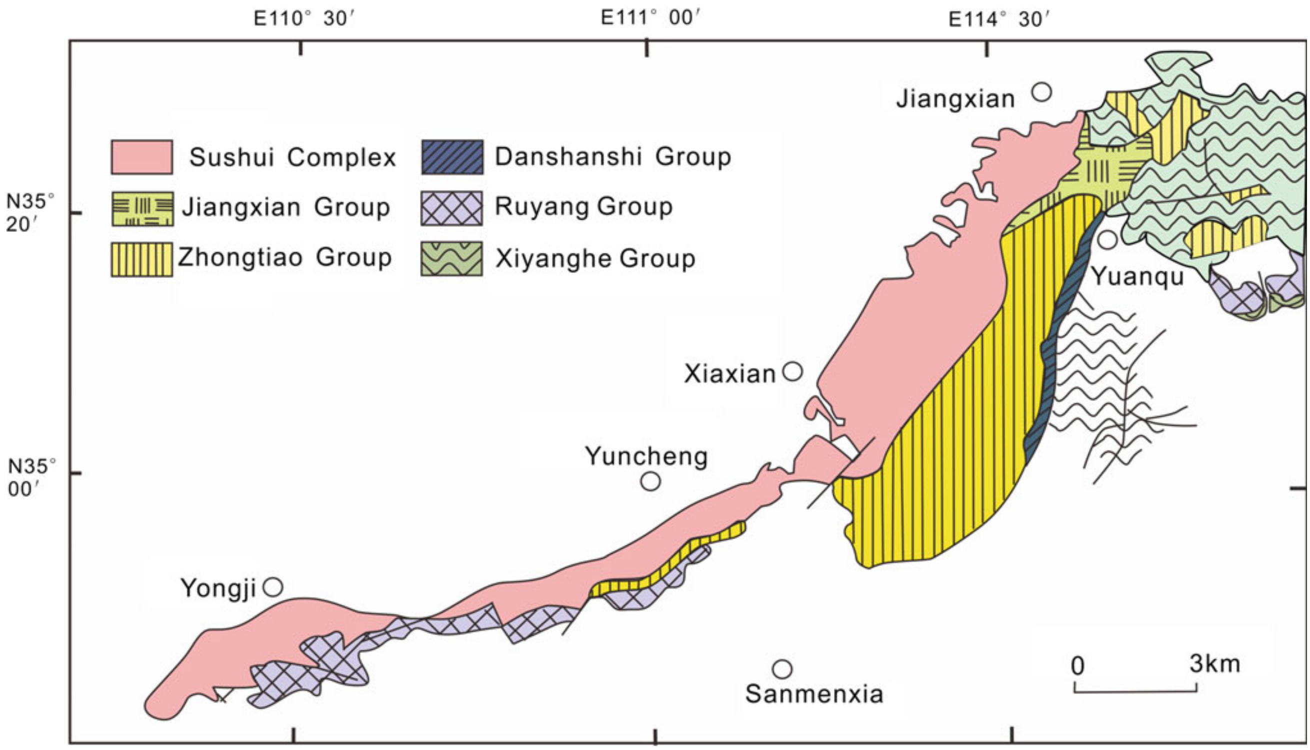


Fig. 2.2 Geological map of the Zhongtiaoshan area (Bai et al. 1997)

exposed at the core of the Hujiayu anticline in the Beiyu area of middle segment of the Zhongtiaoshan covering an area of 2.5 km^2.

The Lengkou supracrustal rocks are unconformably overlain by Quaternary in the northwest and tectonically contacted with Zhaizi gneisses in the southeast. They outcrop predominantly in the Lengkou-Zuantianling area with an area of approximately 6 km^2, and consist of various mica schists and amphibolites with metamorphic grade from greenschist to lower amphibolite faces and composition from mafic to felsic (Sun et al. 1990). Whereas the Chaijiayao supracrustal rocks, which mainly occurred in the Chaijiayao area of the southern Zhongtiaoshan are composed chiefly of metasediments, including large quantities of metapelite and quartzite, and variable amounts of carbonate and conglomerate (Sun et al. 1990). Zircons in an amphibolite sample of the Lengkou area yielded an upper intercept age of 2561 ± 22 Ma using a LA-ICPMS technique, suggesting that the supracrustal rocks of the Zhongtiao Mountains were formed in the Neoarchean (Zhang 2015).

2.2.2 Dengfeng Complex

The Dengfeng Complex, named by Ma Xing-Yuan (1957), is geographically exposed in the Junzhao and Linru areas in the central Henan Province (Fig. 2.3). It is comprised of two distinct lithologic units of the Neoarchean granitoid plutons and supracrustal rocks with essential features of Neoarchean granite–greenstone terrene worldwide (Zhang et al. 1985; Guo 1987, 1988, 1989; Guo and Zhou 1990). The complex also has been identified in drillhole samples from the Xuchang region of Hennan province.

The supracrustal assemblage in the Junzhao and Linru areas was previously named “Dengfeng Group” and “Angou Group”, respectively (Zhang et al. 1985; Guo 1987, 1988, 1989; Guo and Zhou 1990). The Dengfeng Group is a metamorphosed volcano-sedimentary succession, from bottom to top, which has been subdivided into the Guojiayao, Jinjiamen and Laoyanggou formations (Fig. 2.4). The lowermost Guojiayao Formation is chiefly of mafic volcanic rocks with minor felsic volcanics and sedimentary rocks, whereas the overlying Jinjiamen and Laoyanggou formations are composed dominantly of metamorphosed argillo-arenaceous, argillic and siliceous ferruginous rocks with minor mafic volcanic rocks, most of which have been metamorphosed to the medium-pressure almandine-amphibolite facies (Zhang et al. 1982, 1985; Diwu et al. 2011). The Angou group is underlain by the upper part of the Dengfeng supracrustal rocks, and overlain by Paleoproterozoic quartzite of the Songshan Group (Fig. 2.5). Compared with the Dengfeng Group, it has similar rock assemblages, and it also can be subdivided into two parts of Zhaigou and Shitigou formations. The lower Zhaigou Formation comprises bimodal volcanic, volcaniclastic sediments,

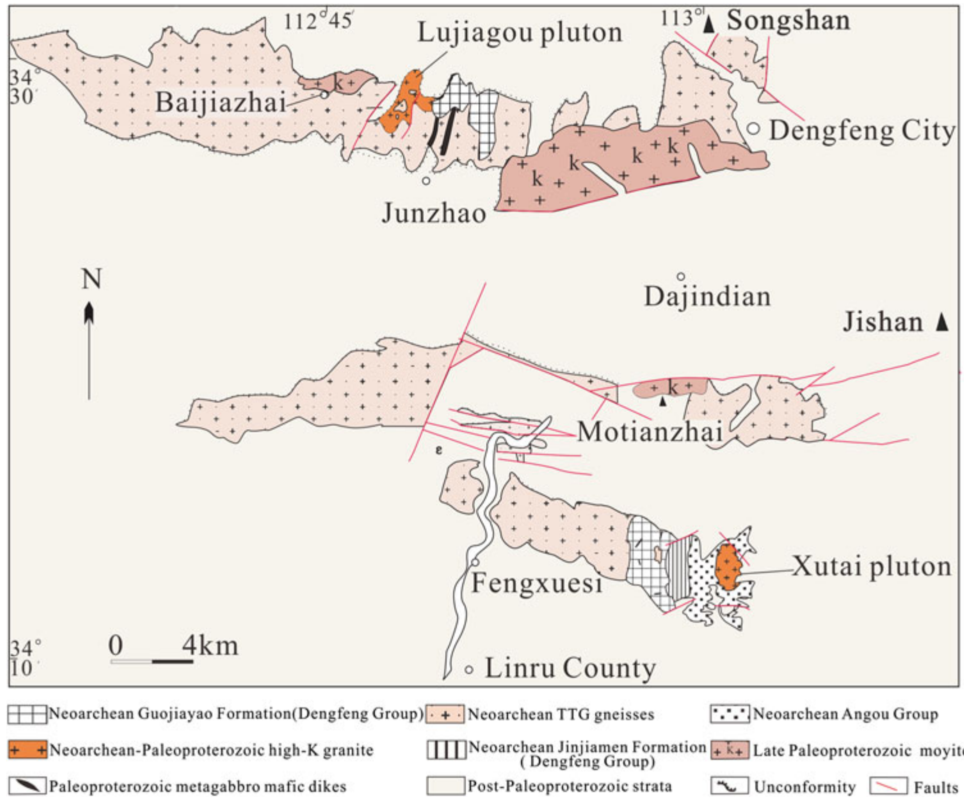


Fig. 2.3 Simplified geological map of the Junzhao-Linru area

and minor sedimentary rocks; while the upper Shitigou Formation consists mainly of littoral-shallow marine terrigenous clastic rocks interbedded associated with minor bimodal volcanic and volcaniclastic rocks. The Angou Group has undergone lower metamorphosed to greenschist facies and less deformed, locally preserving igneous textures, such as amygdaloidal, pillow, and blastoporphyritic primary structures (Zhang et al. 1982; Guo 1987). Previously, based on differences of lithological, structural, metamorphic, and geochronological features, some researchers suggested that the Angou Group is underlain by the Dengfeng Group (Fig. 2.5), thus its formation age is probably younger than that of the Dengfeng Group, and can be limited to the Paleoproterozoic (Zhang et al. 1982; Guo 1987). However, according to the recent SHRIMP zircon U–Pb ages, the Angou Group also formed in the late Neoarchean, which is nearly coeval with the Dengfeng Group (Yang et al. 2009).

The Neoarchean granitoid plutons, which are mainly composed of TTG gneisses, metadiorites, and potassic granites, outcropped in the Junzhao area of the western Dengfeng city (Fig. 2.4), and frequently occurred at the cores of domes or antiforms. They have undergone amphibolite facies metamorphism with strongly polyphase deformation and foliation. The sharp and discordant contacts with surrounding rocks identified in some places suggest that the granitic plutons have been forcefully intruded (Zhang et al. 1982, 1985; Diwu et al. 2011). The metadiorites, named as "Shipaihe metadiorite mass" (Wang et al. 1987, 2004), are located in the central part of the complex in the Junzhao area, and occur as intrusions in the Dengfeng supracrustal assemblage. They are often found to be intruded by ptygmatic felsic veins or dykes in the field. The potassic granites are exposed in the Lujiagou area of the west of the Songshan and Xutai area to the east of the Jishan. The Liujiagou potassic granites crop out with an area of ~3.2 km^2. They intrude into the Neoarchean TTG gneisses and in the lower part of the Dengfeng supracrustal rocks, and are overlain by the Paleoproterozoic Songshan Group in the east and Mesoproterozoic Wufoshan Group in the north. The Xutai potassic granites are about ~4 km^2 in the outcrop, which intrude into the Anguo Group (Fig. 2.5).

2.2.3 Taihua Complex

The Taihua Complex is discontinuously exposed along the southern NCC, extending from Gansu across Shaanxi and Henan to Anhui Province over a distance of 1000 km (Fig. 2.6). In the southeastern margin of the NCC, the equivalents of the Taihua Complex in the Huoqiu and Bangbu areas of Anhui Province have traditionally been named the Huoqiu Group and the Wuhe Group, respectively. Although Huoqiu Group is completely covered by Phaneroic strata and Quaternary sediments, some Archean-Paleoproterozoic rocks

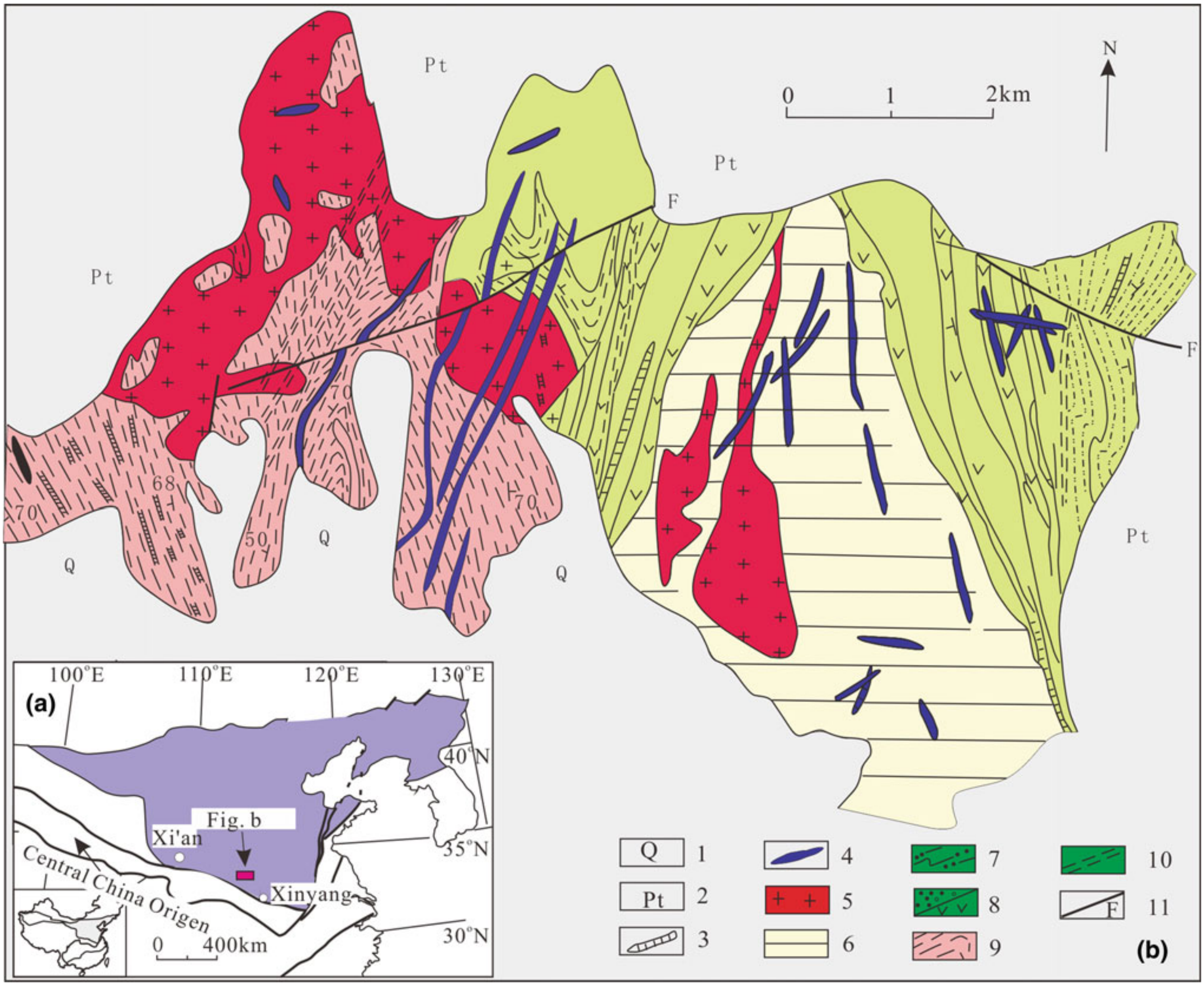


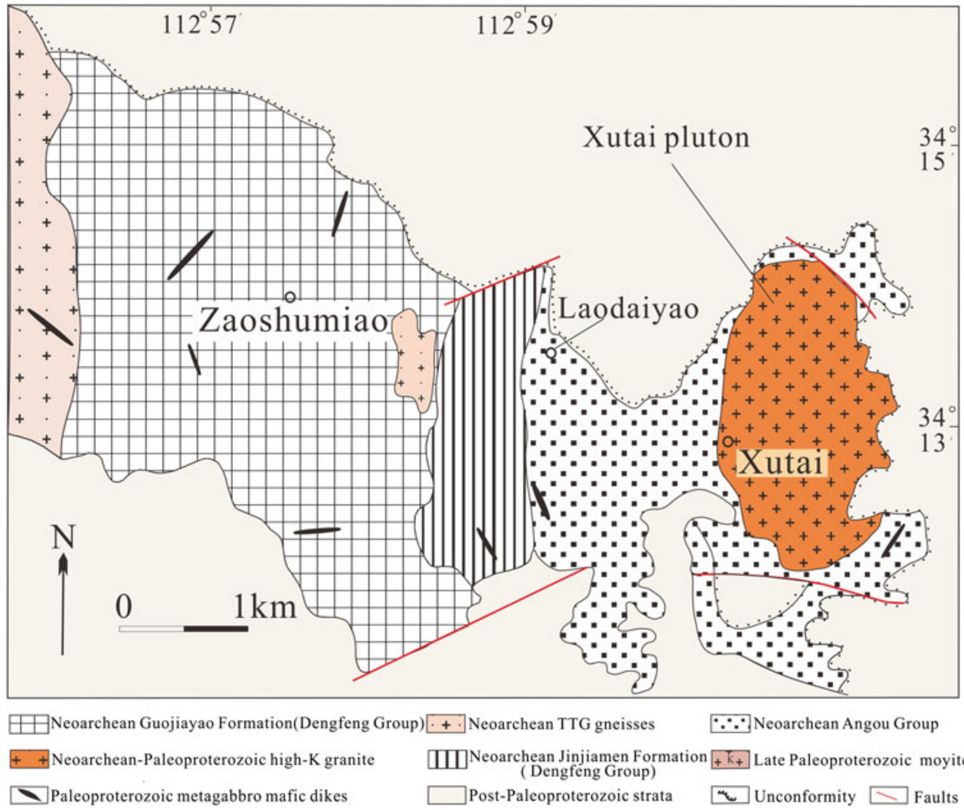
Fig. 2.4 Sketch geological map of the Dengfeng Complex in the Junzhao area (revised after Zhang et al. 1985). *1* Quaternary; *2* early and middle Proterozoic with basal unconformity; *3* felsic dike; *4* mafic dike; *5* granite; *6* metadiorite; *7* metsedimentary; *8* metsedimentary and metavolcanics (amphibolites); *9* TTG gneisses; *10* shear zone; *11* fault

in the Huoqiu area have also been recognized by drilling and zircon U–Pb dating studies (Wan et al. 2010; Wang et al. 2014). Meanwhile, in the most southwestern margin of the NCC, some researchers proposed that the Longshan Complex in the Longshan area of Gansu Province is the equivalents of the Taihua Complex, and some ca. 2.50 Ga tonalitic gneisses have been reported in there (Fig. 2.1) (He et al. 2005).

The Taihua Complex is chiefly located in the Lushan and Xiaoqinling areas. Although it is not a simple lithostratigraphic succession in terms of international stratigraphic nomenclature, it has been traditionally termed as the “Taihua Group”, and was subdivided into lower and upper sequences, named the “Upper Taihua Group” and the “Lower Taihua Group”, respectively. The most complete and best-exposed succession of the complex was found in the Lushan County, Henan Province (Fig. 2.7), and shows features as other typical high-grade metamorphic terranes throughout the world (Sun 1983; Zhang et al. 1985).

In the Lushan area, the Taihua Complex is in fault contact with or unconformably overlain by the Paleoproterozoic Xiong’er Group in the southwest and by the Neoproterozoic Ruyang Group or Cambrian sedimentary rocks in the northeast (Fig. 2.7). Based on the differences of lithological, structural, metamorphic, and geochronological data, we subdivide the Taihua Complex into high-grade gneissic complexes and supracrustal rocks, respectively, which are roughly separated from each other by Dangze River (Sun et al. 1994; Diwu et al. 2010a, 2014). The former located on the north side of the river is composed predominantly of TTG gneisses with minor supracrustal rocks and associated granitic plutons, whereas the latter located on the south side of the river is consisted mainly of high-grade sillimanite-garnet gneisses,

Fig. 2.5 Sketch geological map of the Dengfeng Complex in the Linru area



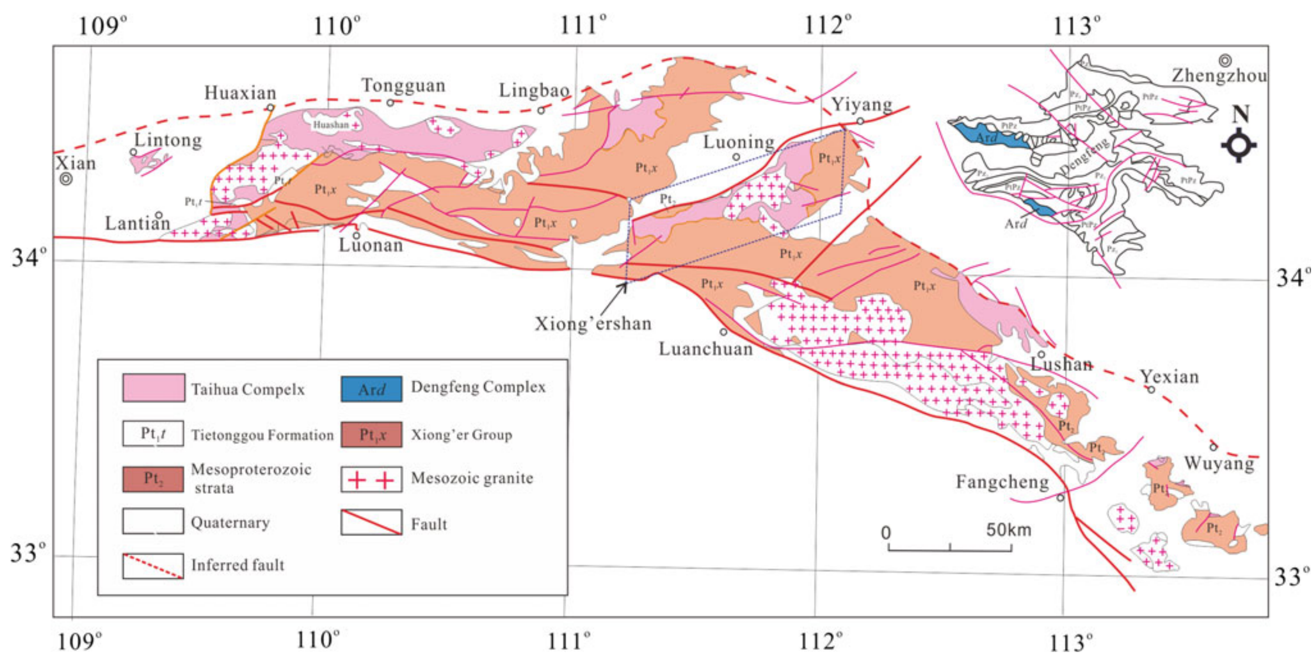


Fig. 2.6 Geological distribution of the Taihua Complex along the southern NCC (revised after Diwu et al. 2014)

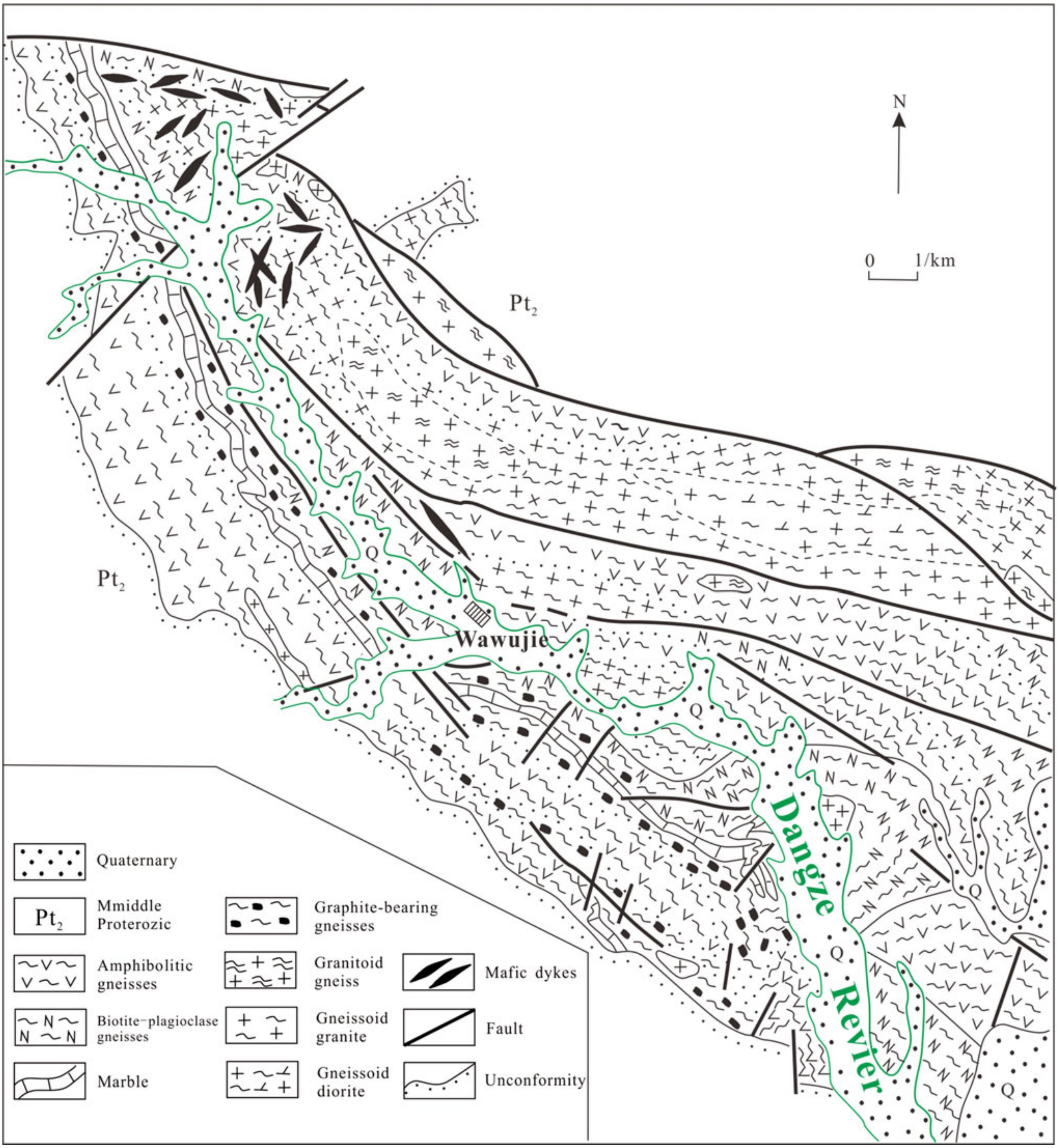


Fig. 2.7 Simplified geological map of the Taihua Complex in the Lushan area, Henan Province (revised after Sun et al. 1994)

graphite-bearing gneisses, quartzite, banded iron formations, and marble, with minor mafic granulites, amphibolites, and syn- or post-tectonic granitoid rocks (Sun 1983, 1994; Zhang et al. 1985). The structural style has revealed a remarkable difference in the two lithological units. The gneissic series are characterized by the development of gneiss domes and tight to isoclinal folds. However, the supracrustal rocks are characterized by layers, and is relatively undeveloped with respect to the above minor structures (Zhang et al. 1982, 1985). Sun (1982, 1983) previously discovered pyroxene granulites, garnet-plagioclase pyroxenites and sillimanite-garnet gneisses from the supracrustal rocks. The P-T calculations indicate that they have experienced a high amphibolite or granulite-facies metamorphism with a relatively high pressure conditions (680–720 °C and 8.0–10.0 kbar). In addition, the geochronological data indicate that the high-grade gneissic complexes were formed at Neoarchean (Sun et al. 1994; Liu et al. 2009a; Diwu et al 2010a; Huang et al. 2010), whereas the formation of the supracrustal rocks can be limited to Palaeoproterozoic (Wan et al. 2006; Diwu et al. 2010a).

Traditionally, the boundary region between the Shaanxi and Henan provinces has been referred to be Xiaoqinling area, where the Taihua Complex is unconformably or tectonically overlain by the widespread Paleoproterozoic Xiong'er Group or locally covered by the Paleoproterozoic Tietonggou Formation (Diwu et al. 2013a). The Taihua Complex in the Xiaoqinling extends from Lintong in the west and across Lantian-Tongguan-Lingbao to the Xiong'ershan in the east, which was previously regarded as a succession of Upper Taihua Group in the Lushan area. However, according to detailed field-based structural, metamorphic, geochemical, and geochronological investigations, they are more complex than previous studies: (1) very rareness of late Mesoarchean basement rocks with the ages of 2827–2802 Ma and abundant of late Neoarchean basement rocks have been recognized most recently (our unpublished data), suggesting that the whole southern NCC has experienced a long geological history can be traced back to Mesoarchean; (2) the database of global zircon ages from both granitoids and detrital sediments show an exceptionally strong minimum between 2450 and 2200 Ma, and this unusual period of time was referred to as a crustal age gap (Condie et al. 2009b), whereas tremendous 2.45–2.20 Ga TTG gneisses and minor dioritic gneisses with peak age of ca. 2.30 Ga were reported in the Xiaoqinling area (Diwu et al. 2014), which makes the southern NCC different from other blocks in the NCC as well as other cratons worldwide, and serve as an excellent key area to investigate the generation and evolution of continental crust during the span of the global crustal age gap. (3) Large Mesozoic and Cenozoic granites intrude into the Taihua Complex in this area, resulting in intensive deformation and dismembered or overprinted original geological relationships of the rocks from the Taihua Complex.

2.3 Distribution and Composition

2.3.1 Hadean-Paleoarchean Crustal Components

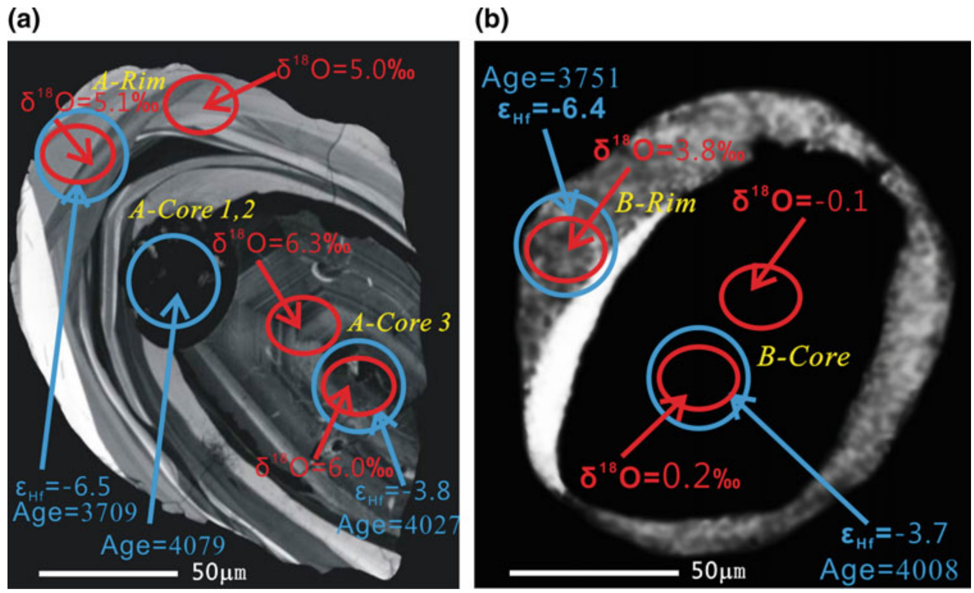
The two ca. 4.10 Ga and one ca. 3.90 Ga xenocrystic zircons from the Ordovician Caotangou Group volcanics have been discovered in the North Qinling Orogenic Belt of the central China (Fig. 2.8) (Wang et al. 2007; Diwu et al. 2010b, 2013b), which is the first report of Hadean crustal material in Phanerozoic igneous rocks, the zircon xenocrysts were incorporated either from the source region or during magma ascent. Moreover, those ancient zircon grains provide important evidence regarding the nature of the basement of the NCC, from which this portion of the orogenic belt is considered to be derived (Zhang et al. 2001; Dong et al. 2011), suggesting that the oldest crustal rocks within the NCC formed as ca. 4.10 Ga (Zhai and Santosh 2011). The $\varepsilon_{Hf}(t)$ values of the North Qinling zircons range from to −4.6 to chondritic, with Hf model ages ranging from 4076 to 4449 Ma, indicate the survival of source rocks as old as ca. 4.45 Ga within the basement of the NCC.

Detrital zircons from both the Paleoproterozoic Songshan quartzites in the Dengfeng area and early Precambrian felsic gneiss in the Jiaozuo area yielded a well-defined upper intercept age of ca. 3.40 Ga (Diwu et al. 2008; Wan et al. 2009b), a few of those ca. 3.40 Ga zircons have low negative $\varepsilon_{Hf}(t)$ values (−4.6 to −3.4) and plot on the average crustal evolution trend of 3.80 Ga, indicating that these zircons may have come from an ancient crust as old as 3.80 Ga (Diwu et al. 2008). Moreover, >3.20 Ga detrital zircons with $^{207}Pb/^{206}Pb$ ages up to ca. 3.60 Ga have also been found from the Paleoproterozoic quartzites of the Tietonggou Formation, they exhibit negative $\varepsilon_{Hf}(t)$ values with the corresponding two-stage Hf continental model ages of 4.40–4.00 Ga (Diwu et al. 2013a). Taken together, it can be inferred that the crustal remnants older than 3.40 Ga might be widely distributed in the southern NCC.

2.3.2 Mesoarchean (2.85–2.80 Ga) Rocks

The Mesoarchean (2.85–2.80 Ga) rocks in the southern NCC have been found only in the Taihua Complex. Since the late 1980s and early 1999s, Kröner et al. (1988) and Sun et al. (1994) reported $^{207}Pb/^{206}Pb$ zircon evaporation ages of 2841 ± 6 Ma, 2806 ± 7, and 2807 ± 4 Ma for TTG gneisses in the Lushan area. These ages were interpreted as the emplacement time of its igneous precursor. Recently, Liu et al. (2009a) used SHRIMP technique to determine U–Pb ages of the high-grade gneissic complexes of the Taihua Complex, they found that the magmatic zircons from tonalite and amphibolite were essentially coeval with a small spread of ages from 2829 ± 18 to 2832 ± 11 Ma in the tonalites and from 2838 ± 35 to 2845 ± 23 Ma in amphibolites, which are identical within error. It is noteworthy that very rareness of the late Mesoarchean basement rocks were also discerned from the Xiaoqinling area, e.g., biotite-plagioclase gneiss (TTG) samples collected from the Xiaofuyu area yielded an upper intercept age of 2827–2802 Ma, which are interpreted as their protolithic ages (our unpublished data).

Fig. 2.8 The ca. 4.1–3.9 Ga xenocrystic zircons from Ordovician volcanics of the Caotangou Group (after Diwu et al. 2013b). The *red circles* and numbers show the $\delta^{18}O$ results, the *blue circles* show the location of the U–Pb analytical sites with age in Ma, and they also show the εHf(t) values, where available



2.3.2.1 Neoarchean (2.80–2.50 Ga) Rocks

Neoarchean crustal formation and evolution of the southern NCC were mainly involved in two major episodic geological events, namely, an early Neoarchean event (2.80–2.70 Ga) and a late Neoarchean event (2.60–2.50 Ga). Although eight of ca. 2.60 Ga zircon grains from a trondhjemitic gneiss of the Dengfeng Complex defined an upper intercept age of 2624 ± 47 Ma (MSWD = 2.3), which is interpreted as the crystallization age of the granitic gneiss protolith (Zhou et al. 2009), we note that there is significant lead loss in some 2.60 Ga zircons; moreover, 2.28–1.90 Ga zircons also contained in the sample, thus whether or not ca. 2.60 Ga crust was preserved in the Dengfeng area is open to question and requires further study. The same to ca. 2.60 Ga granitoid rocks that reported in the Xiezhou and Xiaxian area of the southern–middle region of the Zhongtiaoshan. (Zhang et al. 2012).

The early Neoarchean rocks are widely exposed in the high-grade gneissic complexes of the Taihua Complex in the Lushan area. Zircon dating revealed that abundant of TTG gneisses and amphibolites have been formed during the period of 2794–2752 Ma, and a large number of ca. 2.90 Ga and ca. 3.10 Ga xenocrystic zircons were found in those early Neoarchean rocks (Diwu et al. 2010a; Huang et al. 2010), suggesting that ancient crustal materials as old as 3.10–2.90 Ga probably preexisted in the Lushan area. Moreover, two metamorphic stages in the Neoarchean were recognized in the area: the earlier stage occurred between 2792 and 2772 Ma, and the later occurred at 2671–2638 Ma (Liu et al. 2009a). This can be interpreted as the preexisting inherited zircons were metamorphosed during the close spatial-temporal association magmatic crystallization (Diwu et al. 2010a). Recently, two trondhjemitic and one dioritic gneiss samples were collected from the Changping area of the southern Sushui Complex, and yielded SIMS and LA-ICPMS zircon U–Pb ages of 2722–2702 Ma and ca. 2704 Ma, respectively, indicating that the early Neoarchean rocks were also preserved sparsely in the Zhongtiaoshan (Zhu et al. 2013).

Hundreds of geochronological data, especially in situ zircon U–Pb ages obtained from Precambrian metasedimentary rocks or modern sediment (rive sands) in the NCC indicate that the most important and major tectonothermal events occur at ca. 2.50 Ga (Diwu et al. 2012b; Wan et al. 2011b, 2015). Similar to other high-grade gneissic complexes or low-grade granite–greenstone terranes, the major tectonothermal events in the southern NCC also extensively occurred at ca. 2.50 Ga. A large number of 2.60–2.50 Ga orthogneisses, composed dominantly of TTGs with minor metadioritic gneisses and potassic granites, are extensively distributed in the southern NCC. These 2.60–2.50 Ga rocks which usually contain contemporary layers or lenses amphibolites are widely exposed as high- to medium-grade gneissic complexes in the Jiangxian–Xiaxian–Haizhou areas of the Sushui Complex (Tian et al. 2006; Guo et al. 2008; Zhang et al. 2012), southern Junzhao area of the Dengfeng Complex (Wan et al. 2009a; Zhou et al. 2009, 2011; Diwu et al. 2011) and Xiaoqinling area of the Taihua Complex (our unpublished data). Meanwhile, most of the 2.60–2.50 Ga supracrustal rocks also mainly occurred in the Lengkou and Chaijiayao supracrustal rocks of the Sushui Complex (Sun et al. 1990; Sun and Hu 1993; Zhang 2015), and the Dengfeng as well as the Angou supracrustal rocks of the Dengfeng Complex (Guo 1987; Guo and Zhou 1990; Wan et al. 2009a; Diwu et al. 2011), in which bimodal volcanic assemblages, clastic metasedimentary rocks, BIF and minor limestone were formed during the period.

2.4 Discussion and Synthesis

2.4.1 Coherent Southern Archean Block

With the rapid development of microanalysis in the last decade, including secondary ion mass spectrometry (e.g., SHRIMP, CAMECA) and laser ablation inductively coupled plasma mass spectrometry (including quadrupole and multiple collector), large amounts of high-quality in situ zircon U-Pb isotopic data were obtained from basement rocks in the southern NCC. The spatial and temporal distribution of Archean rocks and xenocrystic or detrital zircons in them suggest that the southern NCC must be a coherent Archean terrane (Fig. 2.1), herein referred to as the Southern Archean Block (SAB) based on the following lines of evidence:

1. The Mesoarchean–Neoarchean (ca. 2.85–2.50 Ga) rocks in southern NCC show an east–west trending belt from the Gansu across Shaanxi and Henan into Anhui Province, stretching over 1000 km long. They are widely developed in the Sushui (Zhang 2015), Dengfeng (Wan et al. 2009a; Diwu 2011) and Taihua complexes (Liu et al. 2009a; Diwu et al. 2014). Moreover, their equivalents probably extend into the Longshan area of Gansu Province in the southwestern margin and the Huoqiu and Bangbu areas of Anhui Province in the most southeastern margin. For example, the ca. 2.50 Ga tonalitic gneisses have been cofirmed in the Longshan Complex (He et al. 2005); a few Archean rocks have also been recognized from the Huoqiu Complex by drilling and zircon U–Pb dating studies in the Huoqiu area (Wan et al. 2010; Wang et al. 2014).
2. Although 2.45–2.20 Ga TTG gneisses associated with coeval dioritic gneisses occurred intensively in the Xiaoqinling area (Diwu et al. 2014), minor ca. 2.10 Ga TTG gneisses, K-feldspar granitic gneisses and granites have also been recognized (Huang et al. 2012). The 2.45–2.20 Ga TTGs and related rocks have two-stage Hf model ages of 2.85–2.70 Ga, which are similar to the crystallization ages of the high-grade gneissic complexes in the Lushan area, indicating that although limited Mesoarchean–Neoarchean rocks are recognized (unpublished data), continental crustal materials as old as 2.85–2.70 Ga probably preexisted in the Xiaoqinling area and constituted sources of those magmatic rocks (Diwu et al. 2014). The recent recognition of 2827–2802 Ma biotite-plagioclase (TTG) gneiss samples further confirm the existence of Mesoarchean–Neoarchean crust in the Xiaoqinling area (unpublished data).
3. It is noteworthy that some 2.85–2.70 Ga rocks in the Lushan Taihua Complex contain a large number of ca. 2.90 Ga and ca. 3.10 Ga xenocrystic zircons (Diwu et al. 2010a; Huang et al. 2010), and some grains show obvious negative $\varepsilon_{Hf}(t)$ values (upto -5.8), and their corresponding Hf model ages (3074–3277 Ma) are significantly older than their crystallization ages (2791–2751 Ma) (Diwu et al. 2010a), suggesting that ancient crustal materials as old as 3.10–2.90 Ga probably preexisted in the Lushan area, and these zircons may be derived from recycled ancient crust with a relatively long crustal residence (Diwu et al. 2010a). Moreover, the ca. 4.10–3.90 Ga xenocrystic zircons from Ordovician volcanics of the Caotangou Group have been discovered in the North Qinling Orogenic Belt (Diwu et al. 2010b, 2013b; Wang et al. 2007), from which this portion of the orogenic belt is considered to be derived of the basement of the southern NCC (Dong et al. 2011; Zhang et al. 2001), indicating that some of Hadean-Eoarchean crustal components were still survival in the basement of the southern NCC during the early Paleozoic, and the SAB may was experienced a long geological history which can be traced back to the Hadean.

2.4.2 Two Marked Episodes of Crustal Growth (2.85–2.70 and Ca. 2.50 Ga)

As we all known, zircon is one of the robust accessory phases in sedimentary, igneous, and metamorphic rocks, which can provide the most valuable information. Individual zircons can be analyzed for U–Pb isotopes to identify a specific sequence of major magmatic events, and their Lu–Hf and O isotopic compositions can provide information on whether the zircon crystallized from juvenile or reworked crustal material. Thus, the combined U–Pb and Lu–Hf isotopic studies have long played a key role in crustal evolution studies (Scherer et al. 2007; Hawkesworth et al. 2010, 2013; Diwu et al. 2012a; Cawood et al. 2013; Kröner et al. 2013; Kemp and Hawkesworth 2014).

The modeling combined zircon U–Pb and Lu–Hf isotopic studies suggest that about 60 % of the present crustal volume of the NCC was generated during the period between the Mesoarchean and late Neoarchean (3.00–2.50 Ga) (Fig. 2.9) (Diwu et al. 2012a, b). Subsequently, the continental crust kept a stable rate of growth and completely formed at the end of the Neoproterozoic (ca. 541 Ma) (Fig. 2.9), which indicates that the present continental crust of the NCC was mainly growth during Precambrian, and the juvenile additions to the continental crust are almost negligible during Phanerozoic (Diwu et al. 2012a).

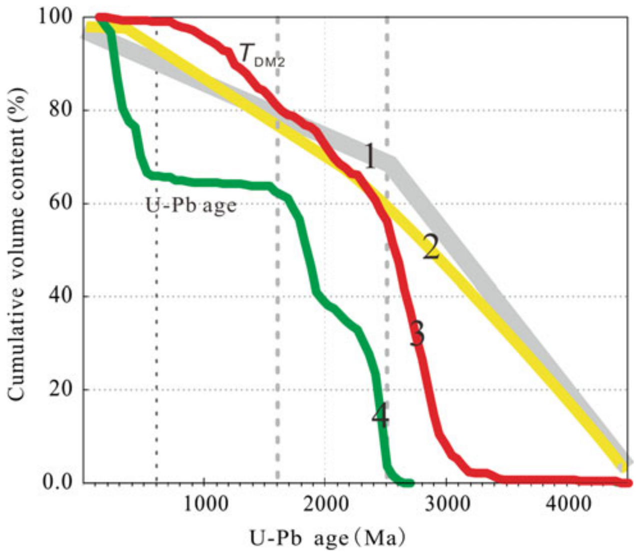


Fig. 2.9 The global lithospheric architecture mapping curve (line 1, after Belousova et al. 2010), global integrated crustal growth curve (line 2, after Belousova et al. 2010), and continental crust growth curves of the NCC that based on two-stage Hf model ages (line 3) and U–Pb ages (line 4) (after Diwu et al. 2012b)

There is no doubt that the most important and intensive tectonothermal events could occured at ca. 2.50 Ga in the NCC during the Archean (Wan et al. 2011b, 2015; Diwu et al. 2012b; Geng et al. 2012). A large volume of TTG gneisses, mantle-derived granites and minor supracrustal rocks were formed during this time, and nearly all the Archean rocks have underwent a strong metamorphism from amphibolite facies to granulite facies, therefore some researchers suggested that the NCC formed through amalgamation of various microblocks by arc-continent collision at the end of the Neoarchean (Zhai et al. 2003; Zhai and Santosh 2011, 2013). However, as discussed above, it still remains controversial about timing of the crust growth in the NCC during the Archean, with one school of researches emphasized that the major crustal growth event in the NCC occur at 2.85–2.70 Ga, similar to many other cratons in the world, whereas the ca. 2.50 Ga tectonothermal event was mainly involved in crustal reworking or partial melting of the early Neoarchean mafic crust formed at 2.85–2.70 Ga (Wu et al. 2005; Geng et al. 2012; Zhao 2014); whereas another group of researchers favored that the age of ca. 2.50 Ga represents a major growth period of continental crust in the NCC (Liu et al. 2009b; Diwu et al. 2011).

The key to solve this debate first is how to define the "juvenile crust" or "crustal growth". The continental crustal growth is the emplacement of new magma directly derived from the mantle and increase in the overall volume of the continental crust through time, whereas the juvenile crust is defined as magmas generated directly from the depleted mantle, or by remelting of material recently extracted from depleted mantle (Belousova et al. 2010; Hawkesworth et al. 2010; Kemp and Hawkesworth 2014). In practice, juvenile crust is likely to have been generated from the mantle in more than one stage, for example, it can be generated from crystallization and remelting of basalt, and radiogenic isotope ratios of the crust have not evolved significantly away from that of its contemporary mantle source (Hawkesworth et al. 2010; Kemp and Hawkesworth 2014).

If a zircon has positive $\varepsilon_{Hf}(t)$ value close to that of the contemporaneous depleted mantle, which can indicate juvenile magmas directly via mantle-derived mafic melts or by remelting of young mantle-derived mafic lower crust, thus zircon U–Pb crystallization age is close roughly to the timing when the Hf isotopic composition of a crustal rock has been isolated from its depleted mantle. Although zircons have considerably variable positive $\varepsilon_{Hf}(t)$ values, which may reflect either insufficient mixing in melting processes or heterogeneity source, the source magma was still dominated by a Hf isotope budget of the depleted mantle (Zheng et al. 2007a, b). The zircon crystallization age can also be utilized to estimates the timing when a new crustal addition in specific regions. Whereas, if a zircon has negative $\varepsilon_{Hf}(t)$ value, which is indicative of rock formation due to the reworking of old continental crust, the timing of Hf crust formation age can be constrained by its model Hf age, and the model age far exceed than its corresponding U–Pb age. However, so far as we known, there are great uncertainties with Hf model ages, for example: (1) the choice of the mantle reservoir from which the new crust was extracted; (2) Lu/Hf ratios and the composition of initial continental crust (Diwu et al. 2012a; Hawkesworth et al. 2010; Kemp and Hawkesworth 2014).

Rocks with ages of 2.85–2.70 Ga are mainly found locally in the gneiss series of the Taihua Complex in Lushan area (Liu et al. 2009a; Diwu et al. 2010a; Huang et al. 2010), majority of the 2.85–2.70 Ga zircons in those rocks have variable but positive $\varepsilon_{Hf}(t)$ values (Fig. 2.10a), and magmatic zircon domains which characterized by oscillatory zoning in CL images present mantle-like O isotopes ($\delta^{18}O$ = 5.1–5.9 ‰) (Liu et al. 2009a), the isotopic characters reflect a somewhat geochemically heterogeneous but depleted mantle Hf isotope reservoir that dominates the source of these rocks. The whole-rock Nd isotopic data show similar characteristics, confirming juvenile sources for their provenance (Fig. 2.10b) (Diwu et al. 2014). Whereas, a few 2.85–2.70 Ga zircon grains show negative $\varepsilon_{Hf}(t)$ values, and their corresponding Hf model ages (3277–3074 Ma) are significantly older than their crystallization ages, which suggests that these were derived from recycled Paleoarchean to Mesoarchean crust with a relatively long residence (0.30–0.40 Ga) time in the local crust (Diwu et al. 2010a). In addition, the majority of ca. 2.70 Ga zircons from the Sushui Complex have high $\varepsilon_{Hf}(t)$ values close to contemporaneous depleted mantle values, and their Hf model ages (2.85–2.70 Ga) are close to the

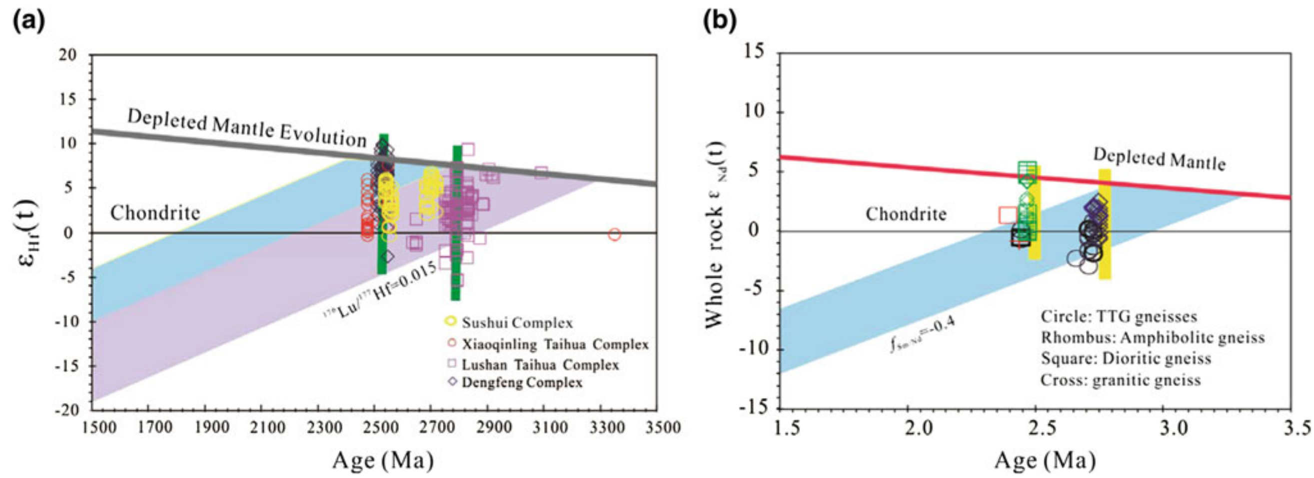


Fig. 2.10 **a** Diagrams of εHf(t) versus $^{207}Pb/^{206}Pb$ age and **b** $\varepsilon_{Nd}(t)$ versus age for samples from the Sushui, Dengfeng and Taihua complexes in the southern NCC. The major age clusters (ca. 2.8 Ga and ca. 2.5 Ga) are shown by the green and yellow lines in Fig. 2.10a and b, respectively. Data from (Liu et al. 2009a; Diwu et al. 2010a, 2011; Huang et al. 2012, 2013; Yu et al. 2013; Zhu et al. 2013; Zhang 2015)

rock-forming ages (Zhu et al. 2013). Hence it can be concluded that the 2.85–2.70 Ga episode with a most prominent peak at ca. 2.80 Ga was a major period of magmatic activity and crustal growth in the southern NCC.

As we discussed above, the Chinese Precambrian geologists commonly agreed that the major continental growth in the NCC occurred at ca. 2.85–2.70 Ga (Wan et al. 2011a, 2014; Zhai and Santosh 2011; Geng et al. 2012; Zhao 2014), and the crustal growth event is suggested to be related to a mantle plume event; whereas the ca. 2.50 Ga tectonothermal event was regarded as mainly involved in crustal reworking or partial melting of the early Neoarchean mafic crust formed at 2.85–2.70 Ga (Wu et al. 2005; Geng et al. 2012; Zhao 2014). Herein, we still suggest that ca. 2.50 Ga is another major period of crustal growth in the NCC as well as in the southern region based on the following lines of evidence:

1. a variable proportion of metabasaltic rocks with ca. 2.50 Ga zircon U–Pb ages exposed in the high-grade gneissic complexes as well as the low-grade granite-greenstone terrenes. Take the Dengfeng Group for example, it is composed of metamorphosed volcano-sedimentary rocks, the ratio of volcanics to sediments being ∼5:1, approximately 58 % of the volcanics are mafic (Zhang et al. 1982; Guo 1987).
2. those metabasaltic rocks in the Dengfeng Group have mixed MORB- and/or arc-like geochemical affinities which are often seen in the back-arc basins, suggesting that they were derived from mantle source with minor continental crust contamination (Diwu et al. 2011).
3. most of the magmatic zircons from TTG gneisses, amphibolites and related rocks in southern the NCC have positive $\varepsilon_{Hf}(t)$ values which similar to those of the contemporaneous depleted mantle at ca. 2.50 Ga (Fig. 2.10 a) (Diwu et al. 2011, 2014), and their Hf model ages of 2.85–2.49 Ga are close to the U–Pb ages of zircons, suggesting that these rocks originated from the juvenile crust at ca. 2.5 Ga.
4. the whole-rock Nd isotopic data of the ca. 2.60–2.50 Ga rocks show similar characteristics (Fig. 2.10b) (Diwu et al. 2014, and references therein), confirming juvenile sources for their provenance.
5. the ca. 2.5 Ga K-rich granite-granodiorite-monzogranite suites (e.g. the Xutai and Lujiagou plutons) were also recognized from the southern NCC (Zhou et al. 2011), which are commonly considered as the proxy of the ending of orogenic processes and final stabilization of the cratons or blocks lithosphere (Laurent et al. 2014).

2.5 Conclusions

1. The Archean rocks are widely recognized in the southern NCC, which show an east-west trending belt from Gansu across Shaanxi and Henan into Anhui Province, stretching over 1000 km long.
2. All the complexes in the southern NCC were aggregated together to form a coherent ancient terrane at end of the Neoarchean, we named it the “Southern Archean Block”.
3. The southern NCC as well as the whole NCC has undergone two marked episodes of continental crust growth at 2.85–2.70 Ga and ca. 2.50 Ga during the Archean. It may have experienced a long geological history that can be traced back to the Hadean.

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