

# Lithotectonic elements of Archean basement on the Liaodong Peninsula and its vicinity, North China Craton, China

Zhuang LI (✉)<sup>1,2</sup>, Bin CHEN<sup>3</sup>

1 State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum (Beijing), Beijing 102249, China

2 College of Geosciences, China University of Petroleum (Beijing), Beijing 102249, China

3 Department of Earth and Space Sciences, Southern University of Science and Technology, Shenzhen 518055, China

© Higher Education Press and Springer-Verlag GmbH Germany, part of Springer Nature 2018

**Abstract** The Liaodong Peninsula, in the northeastern part of the Eastern Block in the North China Craton, China, consists of lithologic units from Archean to Cenozoic in age. The basement rocks consist of widespread amphibolite- to granulite-facies Archean supracrustal assemblages and granitoid gneisses, as well as Paleoproterozoic volcano-sedimentary successions that were intruded by granitic–mafic complexes, and then metamorphosed under greenschist- to amphibolite-facies conditions. The basement rocks are overlain by thick Mesoproterozoic–Cenozoic sedimentary sequences. A synthesis of the available petrological and geochronological data allowed us to establish a geological framework for the Precambrian basement on the Liaodong Peninsula and its vicinity. The basement can be subdivided into three tectonic units: the Neoproterozoic Liaonan Block, the Eo–Neoproterozoic Longgang Block, and the intervening Paleoproterozoic Jiao–Liao–Ji Belt. In this paper we delineate the characteristics of an Archean tectonothermal event, and in a companion paper we examine the Paleoproterozoic lithotectonic assemblages. Rock samples of the Hadean eon are rare worldwide, but Hadean zircons have been identified in rocks of the Liaodong Peninsula, and they provide one of the oldest known mineralogical records on Earth. The Archean gneisses in the Liaonan Block are dominated by quartz dioritic–granodioritic gneisses that were emplaced between 2.55 and 2.44 Ga, and these rocks later underwent a lower-amphibolite-facies metamorphism. On the other hand, the Archean basement in the Longgang Block is dominated by TTG (tonalitic–trondhjemitic–granodioritic) and granitic gneisses, charnockites, and small amounts of supracrustal sequences with much older protolith ages of

up to 3.85 Ga, and these rocks have undergone amphibolite- to granulite-facies metamorphism. Post-tectonic magmatism (ca. 2.5 Ga) marked the end of the Archean tectonothermal event in the Eastern Block of the North China Craton.

**Keywords** Archean, basement, Liaodong Peninsula, North China Craton

## 1 Introduction

In the past two decades, researchers from various countries have carried out extensive investigations on the Precambrian basement of the North China Craton, producing a large amount of new data. Competing interpretations have led to a range of models regarding the formation and evolution of the Precambrian crust of the North China Craton (Zhao and Zhai, 2013 and references therein). However, these investigations and models were limited mainly to two Paleoproterozoic continent–continent collisional belts, namely the Khondalite Belt in the western part of the craton and the Trans-North China Orogen in the central part (e.g., Guo et al., 2005; Zhao et al., 2005, 2010; Wan et al., 2006a, b; Peng et al., 2010, 2011). In contrast, little attention has been paid to the Eastern Block, of which the Liaodong Peninsula represents one of the largest areas of Archean–Paleoproterozoic outcrops. To decipher the evolution of the Liaodong Peninsula and neighboring rocks, previous investigators placed great emphasis on the post-Paleoproterozoic cover (Zhai and Santosh, 2013), and not the Precambrian basement. In particular, the Archean basement rocks were often overlooked due to their high-grade metamorphism and multiple deformations. However, there is now emerging a much more comprehensive knowledge of the Archean–Paleoproterozoic history (e.g., Zhai and Santosh, 2013; Zhao and Zhai, 2013), and

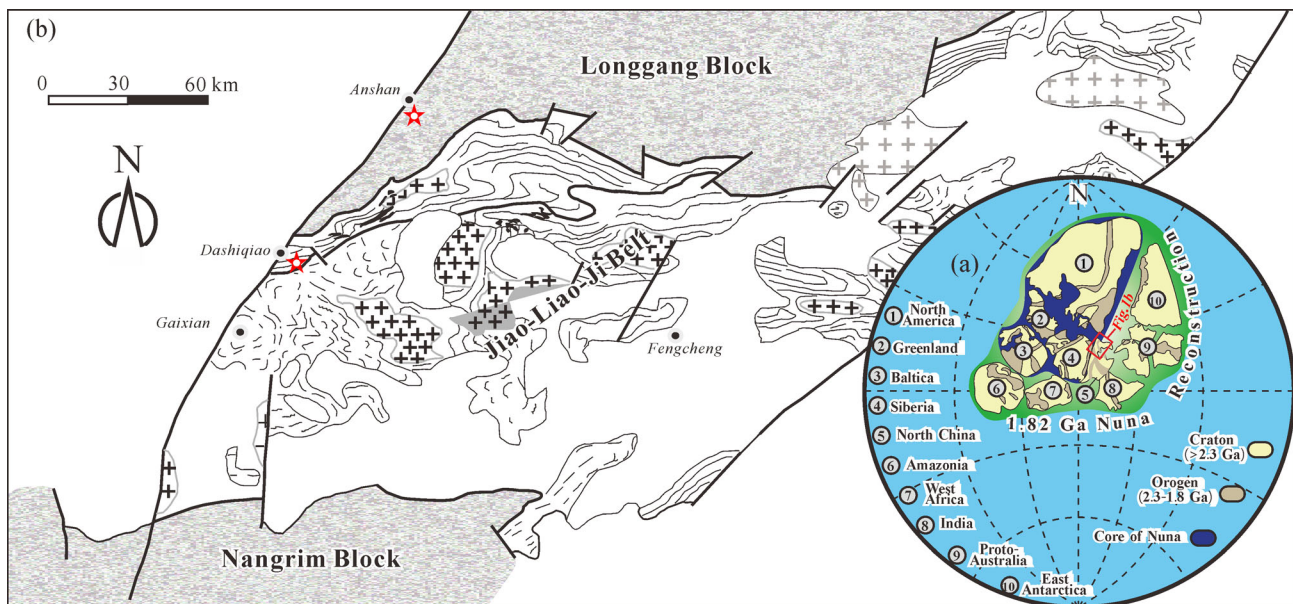
these recent studies have deepened our understanding of the Liaodong Peninsula during early Precambrian time, as well as the formation and evolution of the North China Craton. To make the Archean–Paleoproterozoic tectonic framework clearer, it is important to examine the major lithotectonic units of the Liaodong Peninsula and to determine their tectonic settings. Here, therefore, we present a comprehensive summary and review of the Hadean mineralogical records, the Eo–Mesoproterozoic lithotectonic records, and the Neoproterozoic lithotectonic assemblages in the area. In a companion paper we present a synthesis of the Paleoproterozoic lithotectonic assemblages in the same location. The main results we present here are as follows: (i) a coherent framework for the pre-Paleoproterozoic basement on the Liaodong Peninsula and its vicinity; (ii) details of pre-2.5 Ga magmatism, and not just in the area around Anshan; (iii) a clarification of the geochronological sequence of volcanism, sedimentation, plutonism, and metamorphism at ca. 2.5 Ga in the Longgang Block; and (iv) details of the lithologic differences between the Liaonan and Longgang blocks.

## 2 Regional precambrian geology

The North China Craton is one of the oldest continental nuclei on Earth (Fig. 1(a); Liu, 1991; Liu et al., 1992; Wan et al., 2005c, 2012a; Zhao, 2014), and it is bounded to the north by the Central Asian Orogenic Belt and to the south by the Qinling–Dabie–Sulu ultrahigh-pressure metamorphic belt (Fig. 1(b); Wan et al., 2005a, b; Li et al., 2016b).

Until now, there has been no consensus on subdivisions and tectonic models for the Precambrian basement of the North China Craton (Zhai and Santosh, 2013; Zhao and Zhai, 2013). For example, Zhao et al. (2005, 2006, 2010) suggested that the final assembly of the North China Craton was the result of subduction and collision between two discrete continental blocks at ca. 1.85 Ga, the Western and Eastern blocks, during which time the Trans-North China Orogen was formed above an eastwards-dipping subduction zone (Fig. 1). On the other hand, Trap et al. (2012) postulated that there was an old continental block, named the Fuping Block, that lay between the Eastern and Western blocks, and that these three blocks were separated by the Zhanhuang and Lvliang oceanic plates, which were both being subducted towards the west. The closure of the Zhanhuang Ocean occurred at ca. 2.1 Ga, leading to the amalgamation of the Eastern and Fuping blocks along the Taihangshan suture, while the closure of the Lvliang Ocean took place at 1.9–1.8 Ga, leading to the final assembly of the Eastern and Western blocks along the Trans-North China suture (Faure et al., 2007). However, other geologists proposed that the North China Craton was cratonized at ca. 2.5 Ga, followed either by accretionary processes along the northern margin (Polat et al., 2005; Kusky, 2011) or by reworking during the period 2.3–1.8 Ga that involved rifting, subduction–accretion–collision processes, and subsequent plume-triggered extension and rifting (Zhai and Santosh, 2013).

In any case, in all the models above, it was agreed that an Archean block exists in the east of the North China Craton, namely the Eastern Block (Zhai and Santosh, 2013; Zhao and Zhai, 2013). The basement of the entire Eastern Block



**Fig. 1** (a) Schematic map of reconstructed 1.8 Ga Nuna showing the location of the NCC. (b) Geological sketch map of the Liaodong Peninsula and its vicinity. Stars indicate the known locations of Hadean zircons on the Liaodong Peninsula. See Figs. 3 and 4 for more details. (modified after Zhao et al., 2005; Li et al., 2011, 2016b, c)

can be subdivided into three tectonic units: the Archean Nangrim Block, the Archean Longgang Block, and the intervening Paleoproterozoic Jiao–Liao–Ji Belt (Fig. 1(b); Zhao et al., 2005; Li et al., 2011, 2012, 2016a). Although some researchers have questioned the existence of the Archean Nangrim Block (Chen et al., 2016), Zhao et al. (2006) and Zhang et al. (2017) proposed that the Neoproterozoic tonalitic–trondjemitic gneisses in the Nangrim Massif represent the oldest crustal nucleus on the Korean Peninsula, which is likely to be the Archean Nangrim Block. The Archean assemblage recognized in southern Liaoning Province also constrains the evolution of the eastern North China Craton, and it provides additional evidence that the Archean crustal nucleus was located to the south of the Jiao–Liao–Ji Belt (Lu et al., 2004, 2006; Meng et al., 2013).

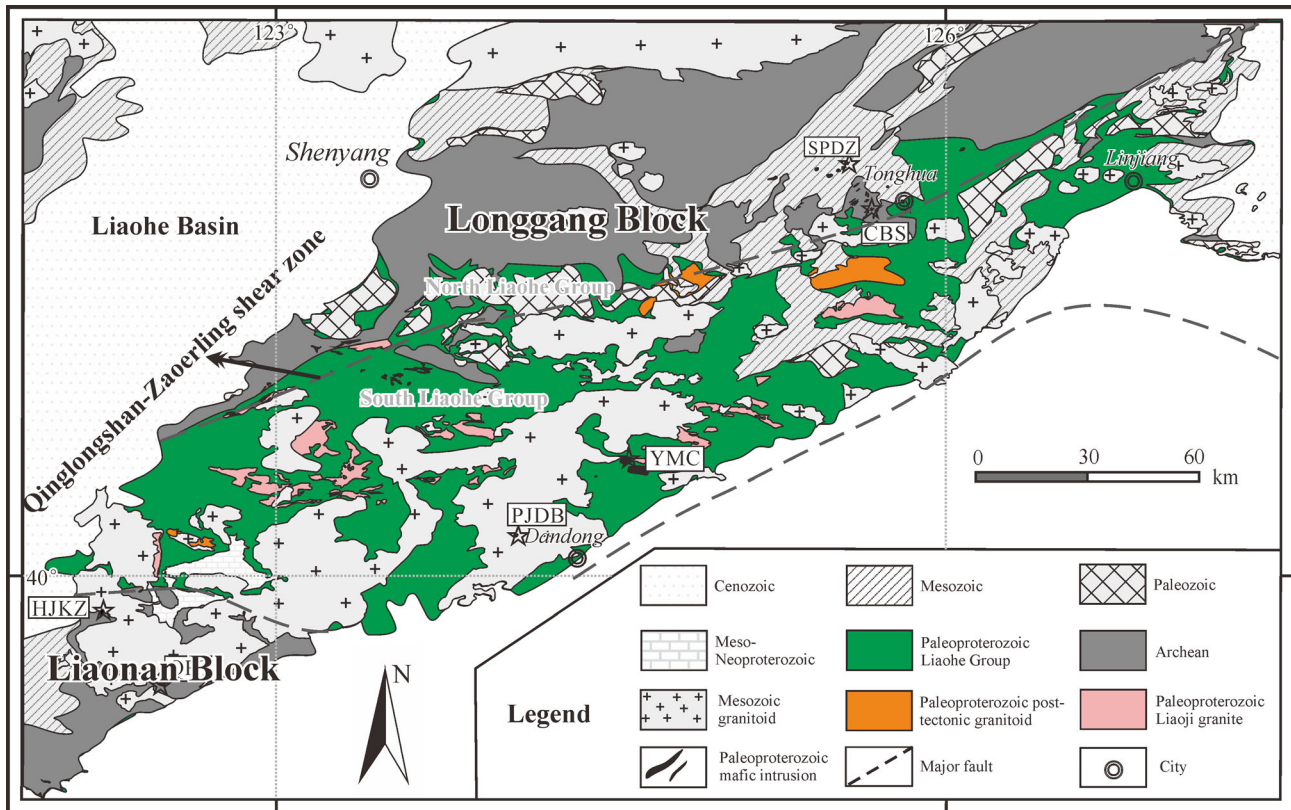
Based on the spatial distribution of Paleoproterozoic metamorphic events in the North China Craton, Peng et al. (2014, 2015) proposed the existence of an old continental arc to the southeast of the Longgang Block, named the Korean Arc, which is similar to the combined Archean Nangrim Block and Paleoproterozoic Jiao–Liao–Ji Belt of Zhao et al. (2005), although their boundaries differ.

The Liaodong Peninsula is on the northeastern margin of the North China Craton (Fig. 1(b); Li et al., 2014a, b), and major disputes continue about its tectonic nature and evolution during the late Neoproterozoic. With regard to the Neoproterozoic Qingyuan granite–greenstone terrane in the Longgang Block, various models for its tectonic setting have been proposed. Based on detailed studies of structures observed in the field, and the geochemistry of the volcanics, Zhai et al. (1985) proposed that the Neoproterozoic rocks were formed in a continental rift setting above a hotspot, whereas Wan et al. (2005a, b) suggested a continental arc setting followed by arc–continent collision. More recently, Wu et al. (2013, 2016) favored a mantle plume model to explain the metamorphic evolution of the garnet amphibolites (protolith of basalt and basaltic andesite) and the zircon U–Pb–Hf isotopic data for the supracrustal sequence, whereas Peng et al. (2015) proposed a mantle-wedge-absent flat hot subduction model with a synchronous vertical mechanism to explain the petrogenesis of the igneous rocks. Wang et al. (2016a, b) carried out geochronological, geochemical, and isotopic studies on the ca. 2.55–2.50 Ga granitoid gneisses, and revealed the presence of a late Neoproterozoic active continental margin in northern Liaoning Province. Li and Wei (2017) suggested that the Neoproterozoic basalts record a rising plume head that mixed with the upper mantle, and they therefore favored a large Archean mantle plume model to account for the generation of the Qingyuan greenstone belt.

Although weighing the merits of the aforementioned models is beyond the scope of this contribution, we prefer the Archean proto-mantle plume model for a geodynamic interpretation of the Eastern Block during the late

Neoproterozoic, as indicated by the transition from Archean planar tectonic systems to Paleoproterozoic linear systems (similar to the Neoproterozoic–Phanerozoic orogeny) documented for the basement of the Liaodong Peninsula. It is of special importance, therefore, to re-evaluate the Precambrian basement within the Liaodong Peninsula and neighboring areas to deepen our understanding of the early stages of Earth's history and further decipher the processes by which continental crust has grown.

As mentioned above, the Archean–Paleoproterozoic basement rocks of the Liaodong Peninsula are overlain by unmetamorphosed rocks of Mesoproterozoic–Cenozoic age. The basement rocks can be subdivided into three tectonic units: the Eoarchean–late Neoproterozoic Longgang Block, the late Neoproterozoic Liaonan Block (western part of the Nangrim Block as suggested by Zhao and Zhai, 2013), and the Paleoproterozoic Jiao–Liao–Ji Belt in between (Fig. 2; Zhao et al., 2005; Zhao and Zhai, 2013; Li et al., 2017). The Archean basement consists mainly of a terrane of high-grade metamorphic rocks and a medium- or low-grade greenstone belt (Wang et al., 2011; Zhao and Guo, 2012). Several greenstone belts have been recognized in the Longgang Block, including Jiapigou in southern Jilin Province, Yanlingguan in western Shandong Province, and Chaoyang–Yixian–Fuxin and Qingyuan in western and northern Liaoning Province (Shen et al., 1992, 1997; Zhai and Santosh, 2013; Zhao and Zhai, 2013), but none occur within the Liaonan Block, in which greenstone belts and large volumes of granitoid intrusions are commonly known as the Neoproterozoic granite–greenstone terranes (Fig. 1(b)). The late Neoproterozoic Liaonan Block consists mainly of quartz dioritic–granodioritic gneisses at Dalian (Lu et al., 2004), with minor granitoid gneisses at Changhai (Meng et al., 2013). The Archean basement rocks in the Longgang and Liaonan blocks were metamorphosed at ca. 2.5 Ga and then subjected to post-tectonic magmatism. Li et al. (2011) proposed that the post-tectonic 2.47–2.33 Ga alkali granite plutons and mafic dike swarms were emplaced after the late Neoproterozoic tectonothermal evolution of the basement rocks, but they did not provide compelling geochronological data, and it is noteworthy that zircon U–Pb dating has provided no direct evidence of this intrusive or volcanic activity, possibly due to the global plate tectonic shutdown (Condie et al., 2009). However, a minor peak at 2.4–2.3 Ga was recognized in the age spectrum of detrital zircons from Paleoproterozoic volcano-sedimentary successions (Li et al., 2015a, b) that unconformably overlie the Archean basement. These sediments were intruded by granitic–mafic complexes and then deformed and metamorphosed under greenschist- to amphibolite-facies conditions at ca. 1.9 Ga (Fig. 2; Zhang and Yang, 1988; Bai, 1993; Hao et al., 2004; Li et al., 2004a, b, 2005, 2006, 2011, 2015a, c; Lu et al. 2004, 2006; Luo et al., 2004, 2008; Li and Zhao, 2007; Li and Chen, 2014, 2015, 2016; Meng et al., 2014; Yuan et al., 2015). Subsequently, the Liaodong Peninsula was covered by thick Meso–Neoproterozoic and Paleozoic



**Fig. 2** Geological map of the Archean–Paleoproterozoic basement and post-Paleoproterozoic cover rocks of the Liaodong Peninsula and its vicinity (modified after Li et al., 2005, 2011, 2016a; Pei et al., 2011).

sedimentary sequences (Fig. 2; Wang et al., 2001; Meng, 2003; Gao et al., 2004; Wu et al., 2005a, 2007; Zhang et al., 2012).

Supplementary materials Table S1 (geochronological data of Eo–Mesoarchean rocks on the Liaodong Peninsula and its vicinity), Table S2 (geochronological data of Neoproterozoic rocks on the Liaodong Peninsula and its vicinity), and Table S3 (zircon U–Pb data of representative rocks from the Liaodong Peninsula and its vicinity) can be found in the online version of this paper.

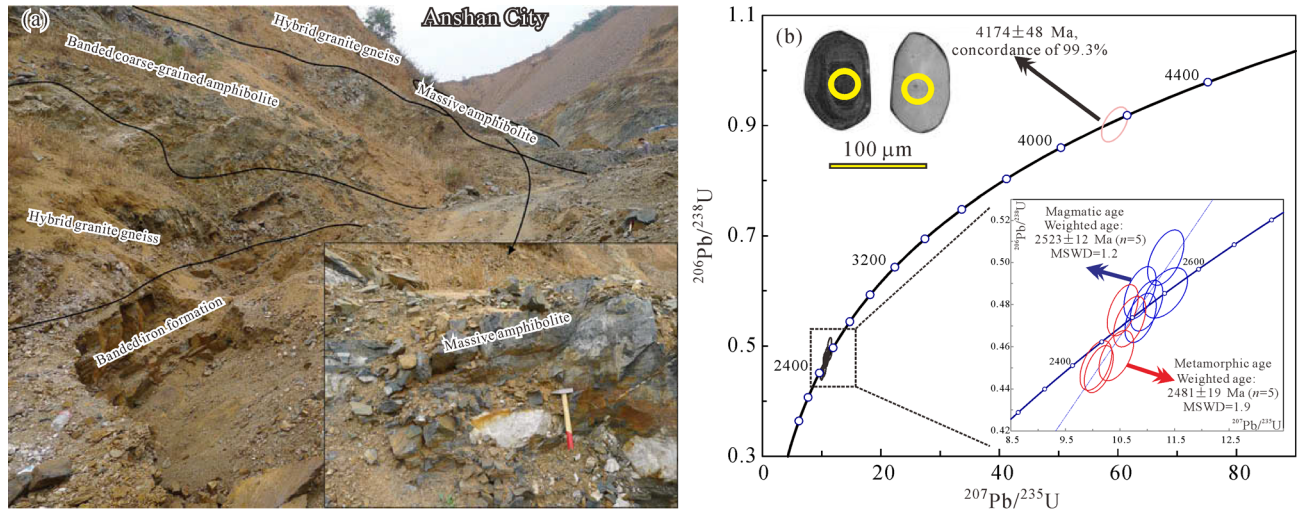
### 3 Hadean mineralogical records

To date, Hadean rocks on Earth have only been identified in the Wopmay Orogenic Belt of Canada as 4.03–3.94 Ga magmatic protoliths of the Acasta gneisses (e.g., Iizuka et al., 2009). Relatively speaking, Hadean zircons have attracted much more attention, since they are widespread and exhibit robust chemical–physical features that enable them to survive even extreme conditions (Nebel et al., 2014), thereby providing a means of understanding the evolution of the early Earth.

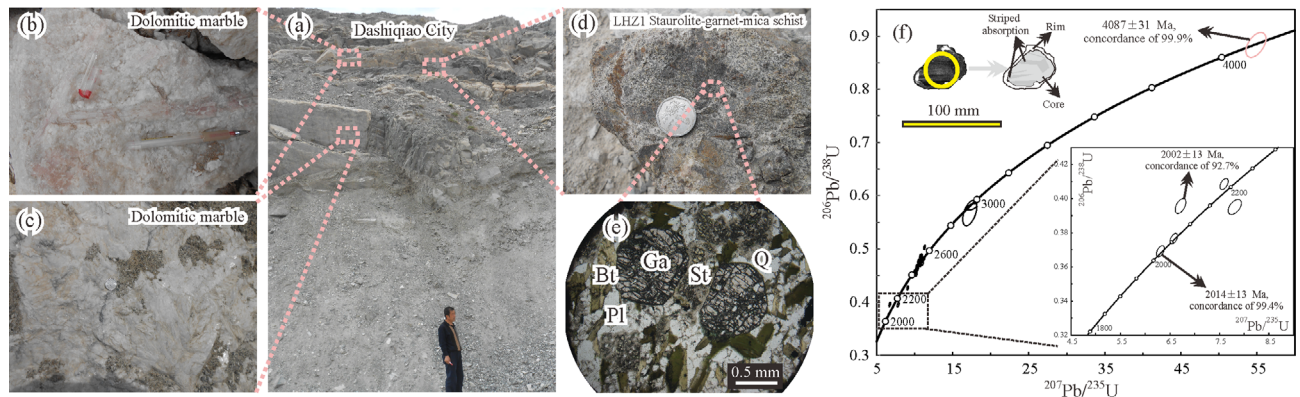
It is noteworthy that most detrital or xenocrystic zircons older than 4.0 Ga have been found at Jack Hills and Mt. Narryer of the Narryer Terrane in Western Australia (e.g.,

Compston and Pidgeon, 1986; Wilde et al., 2001; Cavosie et al., 2007; Harrison, 2009; Nebel et al., 2014; Valley et al., 2014), but Hadean zircons outside Western Australia have also been reported in Canada (Iizuka et al., 2009), West Greenland (Mojzsis and Harrison, 2002), northeast Brazil (Paquette et al., 2015), and China (Fig. 1(a); e.g., Cui et al., 2013; Li et al., 2016b, c).

Two Hadean zircons have been identified in rocks of the Liaodong Peninsula (Fig. 1(b)). Cui et al. (2013) carried out LA–ICP–MS U–Pb dating of zircons from a massive fine-grained Archean amphibolite, and revealed the presence of a Hadean zircon xenocryst with an age of 4174 Ma (concordance of 99.3%) in Anshan City (Fig. 3(a)). The protolith of the amphibolite was basalt erupted at 2523 Ma and metamorphosed at 2481 Ma (Fig. 3(b)). The host rocks of the Hadean zircons in Brazil, Canada, West Greenland, and Western Australia were all formed during the Archean, as is the case for the amphibolite at Anshan. Using the same dating method, Li et al. (2016b) identified another Hadean zircon with an age of  $4087 \pm 31$  Ma (concordance of 99.9%) from Paleoproterozoic staurolite–garnet–mica schist in Dashiqiao. This schist is intercalated with dolomitic marbles, and the field relationships are shown in Figs. 4(a)–4(d). The youngest igneous zircons identified from the schist gave ages of 2014–2002 Ma, which constrained the maximum depositional age of the



**Fig. 3** (a) Photographs showing detailed lithological assemblages in Anshan. The thick lines mark the contacts between different rocks. (b) U–Pb concordia diagram for zircons from the fine-grained amphibolite in Anshan City. Insets in Fig. 3(b) show CL and reflected light images of the structure in a 4174 Ma zircon xenocryst, and U–Pb concordia diagrams of magmatic zircons (blue circles) and metamorphic zircons (red circles) (modified after Cui et al., 2013).



**Fig. 4** (a) Field photograph showing that the staurolite–garnet–mica schist (d) is intercalated with dolomitic marbles (b) and (c) at Dashiqiao. (e) Microphotograph of the staurolite–garnet–mica schist (LHZ1). (f) U–Pb concordia diagram for zircons from the schist. Insets in Fig. 4(f) show a CL image and a schematic of the 4087 Ma detrital zircon, and the U–Pb concordia diagram for the youngest detrital zircons (modified after Li et al., 2016b). Pl = plagioclase; Q = quartz; Ga = garnet; St = staurolite; Bt = biotite.

schist protolith. This sedimentary protolith must have been deposited before the tectonic–metamorphic event at ca. 1.9 Ga because the mica schists from the Liaohe Group were extensively deformed and metamorphosed during the Paleoproterozoic (Li et al., 2017). This event is also recorded by metamorphic zircons with ages of 1930–1835 Ma in the same sample (LHZ1). We are therefore able to say with confidence that the depositional age of the schist protolith was between 2002 and 1930 Ma. Importantly, this was the first report of Hadean crustal material in a Paleoproterozoic sedimentary rock, thereby raising the possibility of obtaining more Hadean material entrained in the Paleoproterozoic sedimentary rocks of the North China Craton and other cratons. The two Hadean zircons obtained from the Liaodong Peninsula share similar

characteristics (Figs. 3(b) and 4(f)). They appear as dark-brown euhedral crystals with length/width ratios of 3:2 and without any cracks or inclusions in reflection images. Distinct cores and rims can be observed in CL (cathodoluminescence) images. The cores are dark-gray, show low luminescence and striped absorption (Fig. 4(f)), and have high Th/U ratios of 0.46 and 0.37, which suggests a magmatic origin, probably of an acidic nature (Nebel et al., 2014; Li et al., 2016b). The rims of the zircons are bright and have irregular shapes, which could be attributed to later overgrowths. Unfortunately, the rims are too narrow to obtain U–Pb age data. These characteristics indicate that the relatively broad cores of the Hadean zircons are igneous in origin, and that the narrow rims probably represent overgrowths formed during late-stage thermal

events or metamorphism (Cui et al., 2013; Li et al., 2016b). We note that China is one of the few places on Earth where ca. 3.8 Ga crustal material has been identified. Rocks of this age are present in Anshan (section 4.1; Liu et al., 1992; Song et al., 1996; Wan et al., 2005c; Wu et al., 2008), and abundant detrital zircons as old as  $3860 \pm 3$  Ma are present in the quartzite in Caozhuang (Wu et al., 2005b). Both of these occurrences lie within the Eastern Block of the North China Craton, and for this reason, the North China Craton, especially the Eastern Block, presents an ideal site for further exploration for Hadean zircons or even Hadean rocks (Cui et al., 2013; Li et al., 2016b, c).

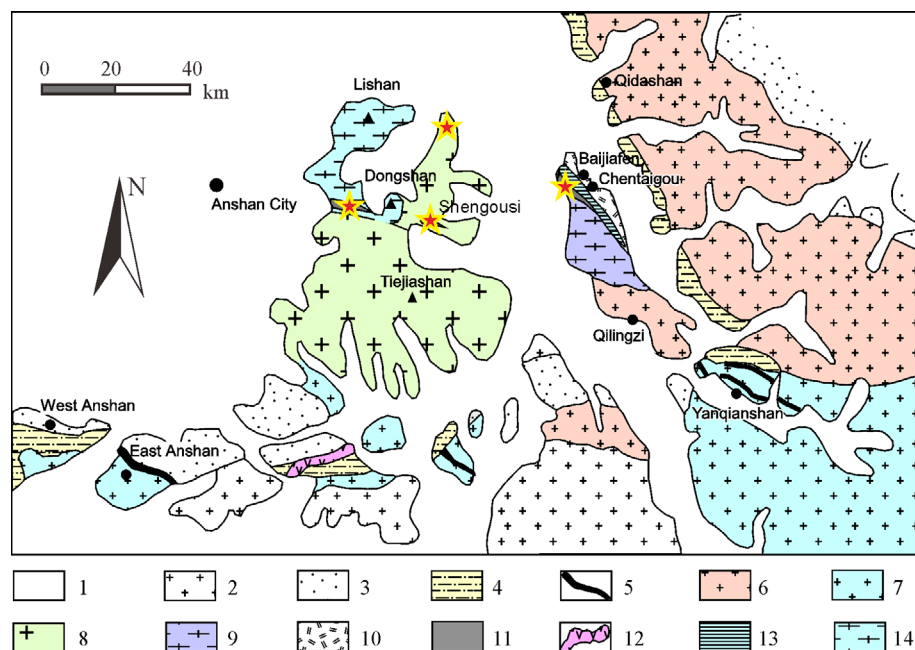
#### 4 Eo–Mesoarchean lithotectonic records

The Eo–Mesoarchean (3.8–2.8 Ga) rocks of the Liaodong Peninsula and neighboring areas have not only been found in Anshan (Supplementary materials Table S1; Figs. 5 and 6; Liu et al., 1992, 2008; Song et al., 1996; Wan et al., 2005c; Wu et al., 2008), but also in Luanjiajie, near the boundary between northern Liaoning Province and southern Jilin Province (Fig. 7; Supplementary materials Table S3). The 3.8–2.8 Ga rocks have undergone greenschist- to amphibolite-facies metamorphism, and there are no relict orthopyroxenes or textural evidence (such as blebby textured pseudomorphs of biotite±hornblende after pyroxene) that would indicate an episode of granulite-facies

metamorphism (Wan et al., 2012a). The majority of the rocks show a gneissic structure, and the others are massive.

##### 4.1 Eoarchean

Eoarchean rocks have only been recognized on a small scale in three different complexes, namely the Baijiafen, Dongshan, and Shengousi complexes (Figs. 6(a)–6(c)). The Baijiafen Complex is in tectonic contact with the 3.3 Ga Chentaigou Granite to the southwest and ultramafic rocks to the northeast, while the other two complexes occur as enclaves in younger Mesoarchean granites (the ca. 3.0 Ga Tiejiaoshan Granite and the ca. 3.1 Ga Lishan Trondhjemite) (Fig. 5). Quartz dioritic–trondhjemitic gneisses and biotite schists provide the only Eoarchean lithotectonic records. SHRIMP U–Pb isotopic dating of zircons from the oldest of these rocks revealed that the Baijiafen mylonitized trondhjemitic gneiss, the Dongshan banded trondhjemitic–quartz dioritic gneiss, and the Shengousi banded trondhjemitic gneiss were emplaced at  $3804 \pm 5$ ,  $3811 \pm 4$  to  $3792 \pm 4$ , and  $3773 \pm 6$  Ma, respectively. Younger Eoarchean trondhjemites have also been recognized with ages of  $3680 \pm 19$ ,  $3620 \pm 23$ ,  $3573 \pm 21$ , and  $3454 \pm 8$  Ma, indicating a complex Eoarchean geological history in Anshan. Field-based mapping revealed that the aforementioned  $3620 \pm 23$  Ma trondhjemite cross-cuts biotite schist, which was therefore formed at some time before 3.6 Ga, although we are unsure



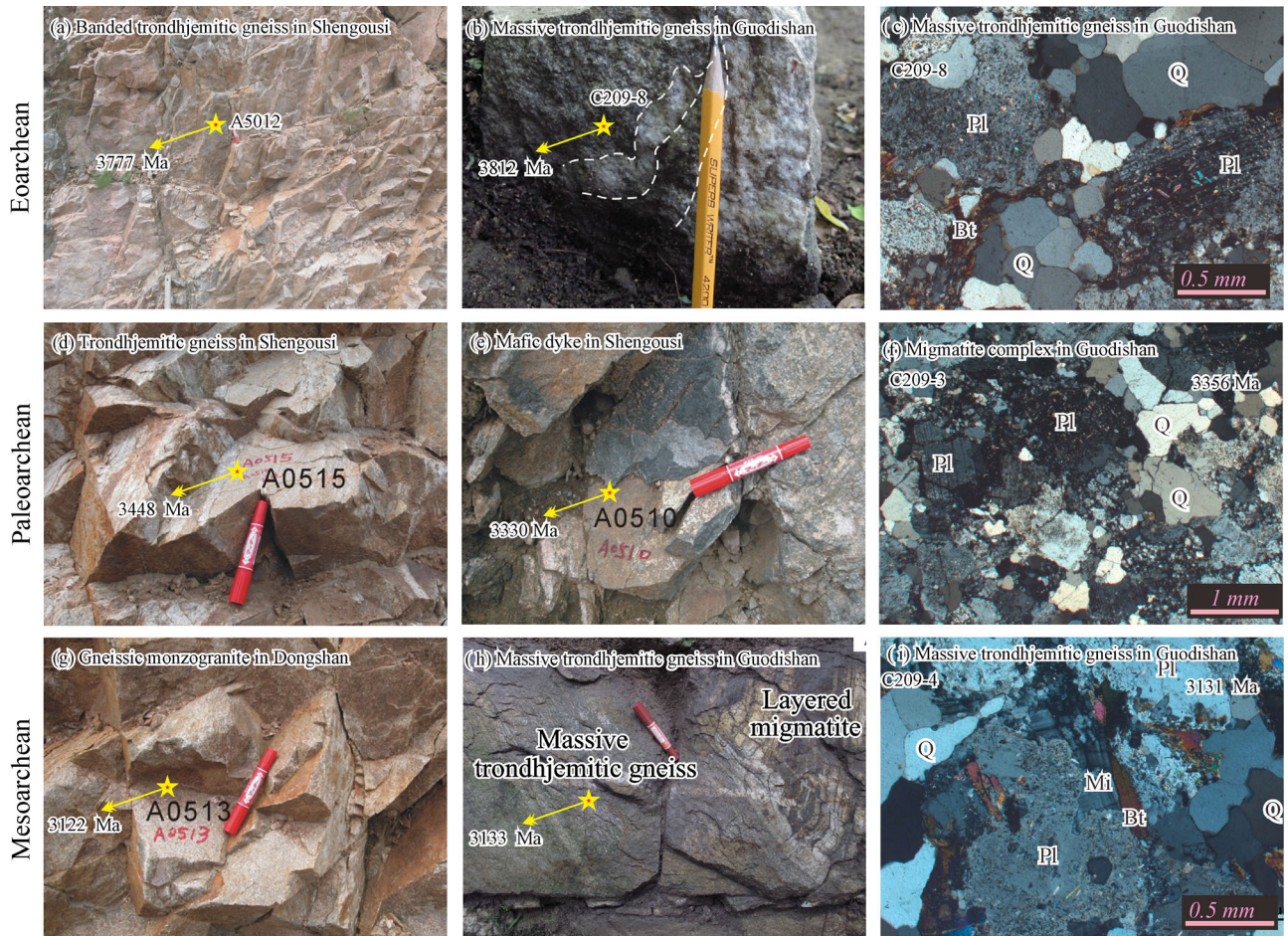
**Fig. 5** Regional distribution of Eoarchean to Neoarchean basement in Anshan (modified after Wu et al., 1998; Wan et al., 2001, 2012a, 2015). Each star represents a locality for the ca. 3.8 Ga trondhjemitic gneiss. Legend: 1 = Cenozoic cover; 2 = Mesozoic granite; 3 = Neoproterozoic quartzite; 4 = Liaohe Group; 5 = BIF in the Anshan Group; 6 = ca. 2.5 Ga Qidashan potassium granite; 7 = ca. 3.0 Ga Dongshan Granite; 8 = ca. 3.0 Ga Tiejiaoshan Granite; 9 = ca. 3.1 Ga Chentaigou Granite; 10 = ca. 3.3 Ga Chentaigou supracrustal rocks; 11 = 3.8–3.3 Ga Baijiafen, Dongshan, Shengousi, and Guodishan complexes; 12 = ultramafic rocks; 13 = ca. 3.3 Ga Chentaigou supracrustal rocks; 14 = ca. 3.1 Ga Lishan Trondhjemite.

whether the protolith was of volcanic or sedimentary origin. The banded trondhjemitic gneiss consists of fine-grained gray melanosomes interlayered with coarse-grained lighter-colored leucosomes up to 1 or 2 cm wide. Plagioclase, quartz, biotite, and minor microcline are found in the gray bands, whereas microcline, plagioclase, and quartz dominate the lighter bands. The quartz dioritic gneiss consists predominantly of plagioclase, biotite, and quartz, along with minor K-feldspar and secondary chlorite and epidote. Based on the  $T_{DM}(Hf)$  model ages for the Archean granites in Anshan, which range from 4264 to 3256 Ma (mostly 3.9 Ga), Liu et al. (2008) suggested that much older crust was not present in the region. However, it is important to note that the relatively old  $T_{DM}(Hf)$  model ages ( $> 4.0$  Ga) and the discoveries of Hadean zircons, as summarized in section 3, confirm the existence of Hadean crust on the Liaodong Peninsula (Li et al., 2015d, 2016d), although the Eoarchean rocks in Anshan crop out on a relatively small scale ( $< 20$  km<sup>2</sup>) and the real extent of Eoarchean crust represented by these rocks remains controversial (Wu et al., 2008, 2009). A recently discovered ca. 3.81 Ga massive to weakly banded

trondhjemitic gneiss (Fig. 6(c)), which is enclosed by a 3.36–3.30 Ga migmatite complex, provides further evidence for the presence of Eoarchean rocks at Guodishan, northern Anshan, also providing new Hf isotopic evidence for the existence of an Eoarchean ultra-depleted mantle domain beneath the North China Craton (Wang et al., 2015).

#### 4.2 Paleoarchean

Paleoarchean rocks are represented by the Shengousi Complex and the Chentaigou supracrustal rocks (Fig. 6(d)–6(f)). The Shengousi Complex consists of ca. 3.45 Ga trondhjemitic and mafic dikes. SHRIMP U–Pb isotopic dating of zircons ( $3454 \pm 8$  and  $3448 \pm 9$  Ma) from the trondhjemitic gneisses shows that they were emplaced at the start of the Paleoarchean (Fig. 6(d)). Compositional banding and stronger deformation are indicators of which are the older of the trondhjemitic gneisses. The zircons from the gray and lighter-colored bands of the banded trondhjemitic gneisses record different times of emplacement, with the gray portions yielding ages up to  $3779 \pm 9$  Ma and the lighter-



**Fig. 6** Photographs of representative Eoarchean rocks (a–c), Paleoarchean rocks (d–f), and Mesoarchean rocks (g–i) in Anshan (see Supplementary materials Table S1 and references therein). Pl = plagioclase; Q = quartz; Mi = microcline; Bt = biotite.

colored portions yielding ages up to  $3458 \pm 8$  Ma (Wan et al., 2012a). These observations provide further confirmation that the trondhjemites were emplaced at ca. 3.8 Ga and that there was a widespread Paleoproterozoic anatexis event in the Anshan area at ca. 3.45 Ga. This was followed by a younger magmatic event represented by the mafic dike and a patch of trondhjemite that gave ages of  $3330 \pm 6$ ,  $3329 \pm 8$ , and  $3311 \pm 4$  Ma using the SHRIMP zircon method. The mafic dike was subjected to a lower-amphibolite-facies metamorphism, when it was thoroughly recrystallized to a mineral assemblage of biotite, plagioclase, epidote, and quartz (Fig. 6(e)). The trondhjemite patch is devoid of compositional layering, which sharply distinguishes it from the ca. 3.45 Ga trondhjemite.

The Chentaigou supracrustal rocks are mainly mafic–ultramafic rocks that have undergone amphibolite-facies metamorphism. However, they were later subjected to a widespread greenschist-facies retrogression, so that the amphibolite-facies assemblages are only locally preserved (Song et al., 1996). The rocks include amphibolites, biotite–plagioclase gneisses, felsic volcanics, fuchsite quartzites, and minor calc-silicate rocks (Wu et al., 1998). The granitic dikes that intrude the Chentaigou supracrustal rocks yielded SHRIMP  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon ages of  $3362 \pm 5$  to  $3342 \pm 10$  Ma, indicating that the Chentaigou supracrustal rocks formed between  $3362 \pm 5$  and  $3342 \pm 10$  Ma (Song et al., 1996), and at least before  $3342 \pm 10$  Ma.

Wu et al. (2008) studied zircons within the Baijiafen and Dongshan gneisses using SHRIMP U–Pb dating, revealing that the zircons record several epochs of granitic magmatism. Some were emplaced at a younger time of 3.3–3.1 Ga, which means these rocks are not entirely Eoarchean in age, as previously proposed, as only a few zircons with ages of ca. 3.8 Ga accompany younger zircons with ages of 3.3–3.1 Ga within a single rock sample (Fig. 6(f)). For example, the trondhjemitic gneisses in Baijiafen were re-dated at ca. 3.32–3.30 Ga, but they contain inherited zircons that record ages up to 3865 Ma. The dioritic and trondhjemitic gneisses in Dongshan were dated at  $3303 \pm 5$  and  $3305 \pm 7$  Ma, respectively, marking the end phase of the Paleoproterozoic (Wu et al., 2008).

### 4.3 Mesoarchean

Mesoarchean rocks are dominated by the Chentaigou Granite, the Lishan Trondhjemite, and the Tiejiaoshan Syenogranite and supracrustal suite (Fig. 6(g)–6(i)). The Chentaigou Granite is rather homogeneous with an augen texture derived by the deformation of K-feldspar megacrysts, and Song et al. (1996) suggested that the Chentaigou Granite was emplaced at  $3306 \pm 13$  Ma based on SHRIMP  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon ages. However, Wu et al. (2008) re-dated the zircons from the Chentaigou medium-grained granodiorite and classified the zircons into two age clusters at ca. 3.1 and 3.3 Ga. The former was interpreted

as the time of emplacement of the Chentaigou Granite, and the latter as the age of inherited zircons. There seems to be some conflict about the timing of the Chentaigou Granite: was it 3.1 Ga (Wu et al., 2008) or 3.3 Ga (Song et al., 1996)? Recalculations of the U–Pb isotopic data of Song et al. (1996) using Isoplot (Ludwig, 2003) yielded a major cluster of ages at 3.3 Ga, but it should be noted that some zircon analyses gave younger ages closer to 3.1 Ga, despite their relatively high discordances. These data obviously point to a date of 3.1 Ga for the emplacement of the Chentaigou Granite. The medium-grained granodiorite at Chentaigou is characterized by intensive mylonitization, with a mineral assemblage of K-feldspar, plagioclase, domains of quartz, and minor biotite (Wu et al., 2008). The Lishan Trondhjemite and Tiejiaoshan Syenogranite occur as a dome. The Lishan Granite is generally fine-grained and relatively massive, without any pronounced pegmatitic banding. It contains abundant enclaves of amphibolite, biotite–plagioclase gneiss, and biotite schist. The U–Pb age data for the zircons suggest that the Lishan Trondhjemite was emplaced at  $3142 \pm 7$  Ma (Song et al., 1996). The Tiejiaoshan Syenogranite, the largest and oldest K-rich granite within the North China Craton, is a weakly porphyritic medium-grained biotite K-rich granite, and zircons from the granite record emplacement ages of  $2992 \pm 10$ ,  $2983 \pm 10$ , and  $2962 \pm 4$  Ma. Scattered enclaves of rocks from the Tiejiaoshan suite, mainly quartz–mica schist, amphibolite, quartzite, and iron-bearing quartzite, occur within the Tiejiaoshan Syenogranite (Wan et al., 2012b). The Tiejiaoshan Syenogranite represents part of the post-tectonic magmatism that marks the end of the Mesoarchean tectonothermal event on the Liaodong Peninsula. Subsequently, the early Neoproterozoic event started.

Mesoarchean granites have also been recognized from the West and East Anshan BIF mining areas, where granites have yielded concordia SHRIMP  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon ages of  $3001 \pm 8$  and  $2994 \pm 8$  Ma, respectively (Song et al., 1996). The supracrustal rocks near the East Anshan mining granites have a mineral assemblage of muscovite, albite, epidote, and quartz, indicating greenschist-facies conditions. A suite of Mesoarchean tonalitic gneisses was recently recognized in Luanjiajie, near southern Jilin Province (Fig. 7(a)). The tonalitic gneisses occur as enclaves in early Mesozoic granitoids, and they have a mineral assemblage of plagioclase, hornblende, quartz, and biotite (Figs. 7(a)–7(c)). The U–Pb isotopic data for zircons from the tonalitic gneisses revealed an emplacement age of ca. 3.0 Ga (Liu et al., 2017; our unpublished data). An amphibolite (Fig. 7(d)) intercalated with the tonalitic gneiss (Fig. 7(b)) suggests that formation of the amphibolite took place no later than 3.0 Ga. However, we were not able to unequivocally distinguish whether the amphibolite was coeval with or older than the tonalitic gneiss, because they both underwent amphibolite-facies metamorphism and extensive deformation, and not



Fig. 7 Field photographs of representative Mesoarchean rocks in Luanjiajie.

enough zircons were obtained from the amphibolite to identify the age of its protolith.

Compared with some of the other oldest cratonic blocks, there is a lack of typical Eo–Mesoarchean granite–greenstone terranes in the North China Craton, not to mention the absence of any relatively complete greenstone belt with a well-developed sequence. If we take the Barberton greenstone belt as an example, which is located in northeastern South Africa and northern Swaziland, and forms part of the Archean Kaapvaal Craton, it contains a strongly deformed 3.5–3.2 Ga volcano-sedimentary succession and has undergone mainly greenschist-facies metamorphism (but up to amphibolite facies in the south). It consists of three rock units in a sequence from a komatiite–tholeiite sequence in the lower part, a calc-alkaline volcanic sequence in the middle, and a volcano-sedimentary sequence in the upper part (Kisters et al., 2010; Nabhan et al., 2016). The rocks preserved in the Eo–Mesoarchean of the North China Craton consist mainly of TTG gneisses, minor supracrustal rocks, and fragments of a granite–greenstone terrane, so “lithotectonic records” might be a more appropriate way of defining the Eo–Mesoarchean basement in the Liaodong Peninsula, and even for the entire North China Craton. The limited exposures of Eo–Mesoarchean rocks may be due primarily to the reworking and overprinting of the intensive Neoproterozoic tectonothermal event, and partly due to the

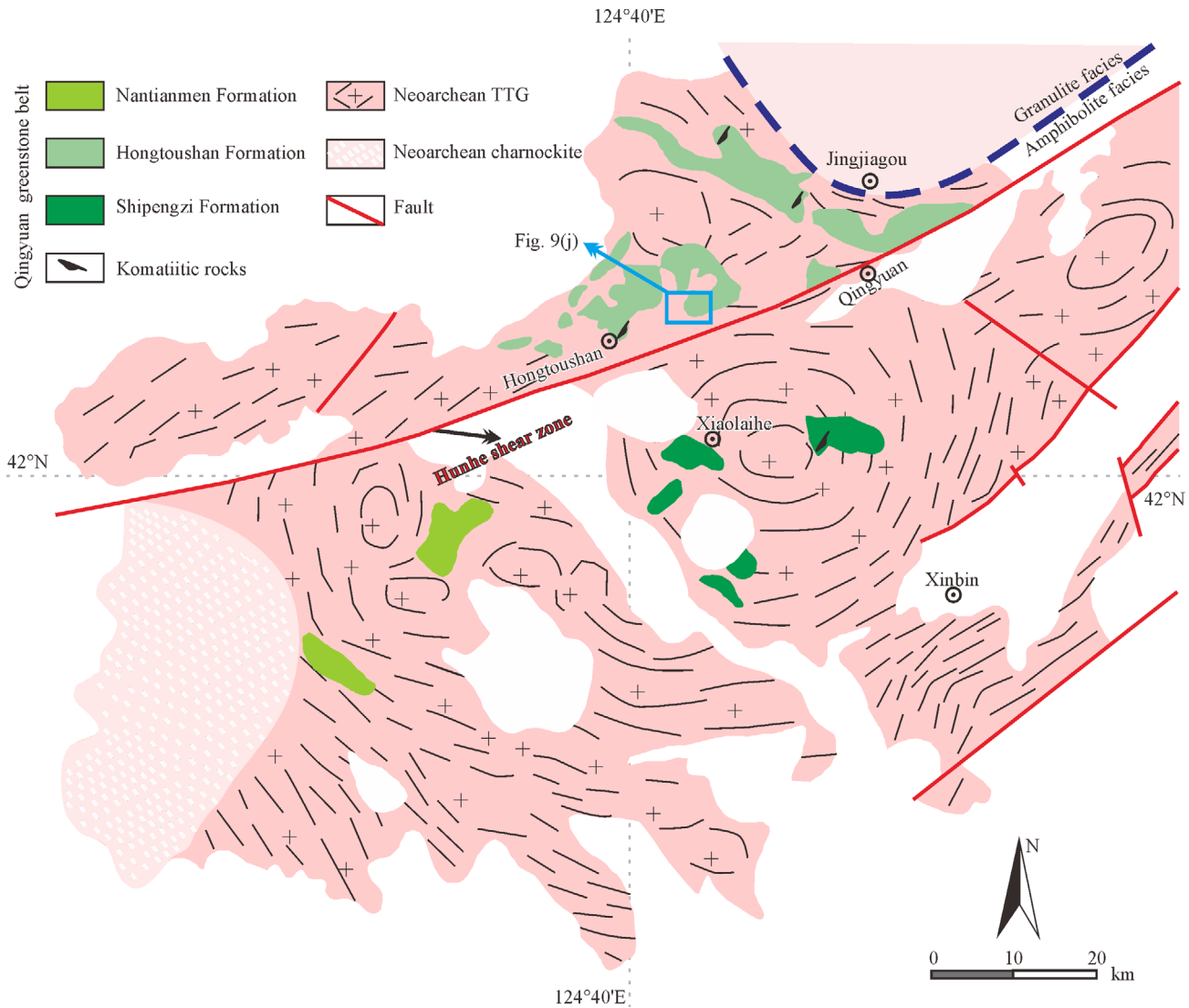
later lithospheric thinning or craton destruction in the Phanerozoic. We can expect, therefore, that fragmentary records might be the harbingers for monitoring critical geodynamic processes in the Eo–Mesoarchean of the North China Craton, and that we might expect eventually to be able to see a relatively complete greenstone belt sequence as a result of further detailed field-based and geochronological studies and analyses of drilling data.

## 5 Neoproterozoic lithotectonic assemblages

The Neoproterozoic events that affected the Liaodong Peninsula and neighboring areas can be divided into events at ca. 2.7 and 2.5 Ga. Conspicuously, the ca. 2.5 Ga event formed the 2.60–2.45 Ga lithologic assemblages over the whole of the Liaodong Peninsula (Supplementary materials S2; Li et al., 2015c), whereas the ca. 2.7 Ga event is only recognized locally in southern Jilin Province.

### 5.1 The ca. 2.5 Ga event in the Longgang Block

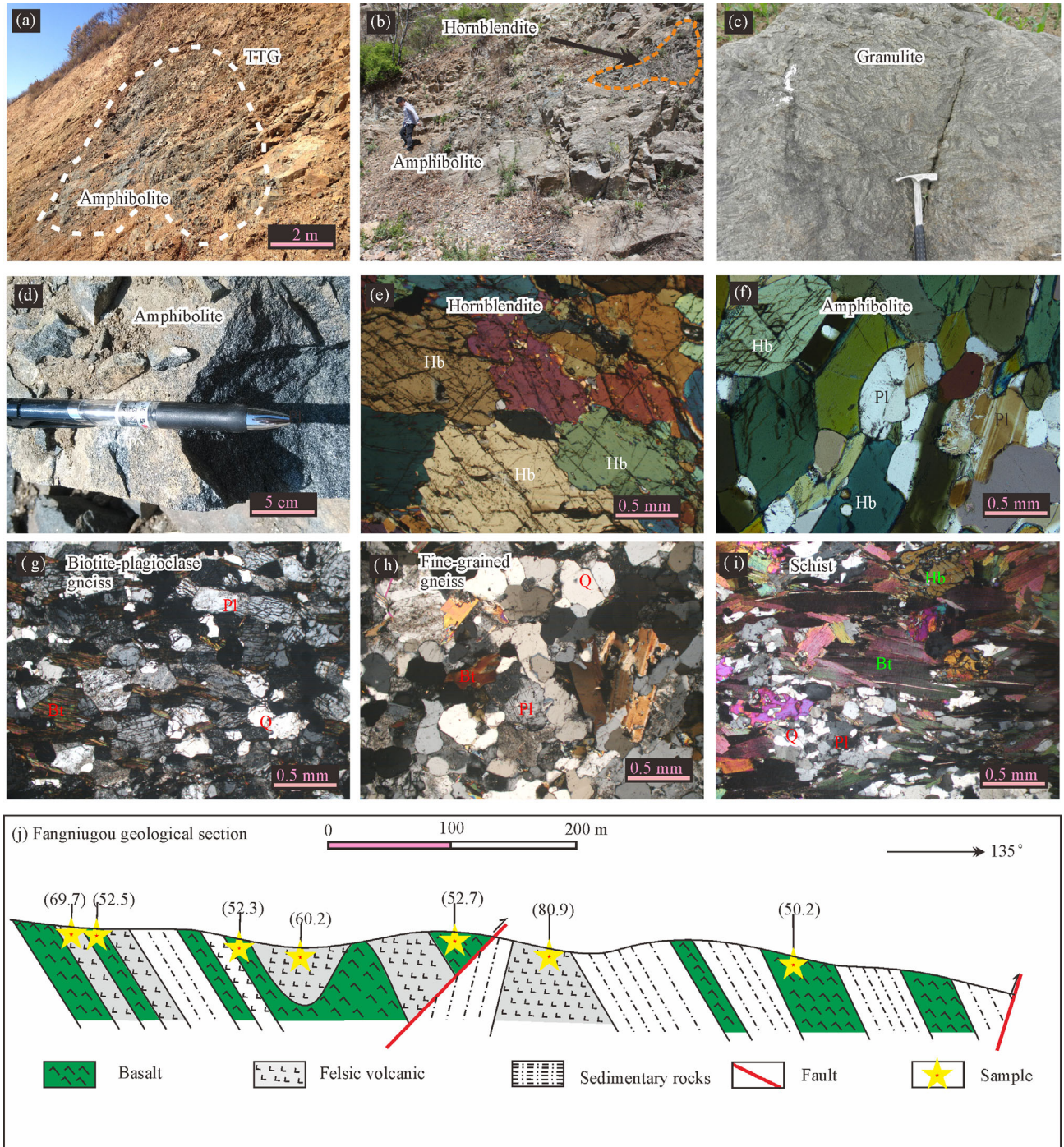
The most representative 2.6–2.5 Ga lithologic assemblages are exposed in Qingyuan in the northeastern part of the Liaodong Peninsula. The supracrustal remnants (i.e., the Qingyuan greenstone belt; Fig. 8), together with large volumes of granitoids (TTG-granitic gneisses and char-



**Fig. 8** Geological sketch map of the Qingyuan granite–greenstone terrane (modified after Li and Shen, 2000; Wan et al., 2005a; Peng et al., 2015).

nockites, volumetrically 70%–80% of the exposed Precambrian crystalline basement in northern Liaoning), are commonly known in the Chinese literature as the Qingyuan Group (Shen et al., 1992, 1997; Wan et al., 2005a, b), the Qingyuan granite–greenstone terrane (Zhai et al., 1985; Peng et al., 2014, 2015), or the Northern Liaoning Complex (Wu et al., 2013, 2016). Previous studies indicated that the Qingyuan granite–greenstone terrane was divided by the NE–SW-trending Hunhe shear zone into two parts, with granulite-facies metamorphism in the NW and amphibolite-facies metamorphism in the SE (Wan et al., 2005a, b). Most recently, our detailed field-based metamorphic investigations have indicated that some of the supracrustal rocks and TTG-gneisses in the NW (e.g., at Hongtoushan and Nantianmen) show similar geological occurrences and mineral assemblages to those in the region of amphibolite-facies metamorphism in the

SE (Figs. 9(a), 9(b), 9(d)–9(f)). For example, the basalts preserved as garnet amphibolites at Hongtoushan consist mainly of plagioclase, hornblende, and garnet, with local clinopyroxene and epidote. Relict grains of clinopyroxene are found in association with amphibole, and are dominantly diopside in composition. The basalts in the south (e.g., the Xiaolaihe BIF mining area) have all undergone an amphibolite-facies metamorphism and are represented by clinopyroxene-bearing amphibolites. However, the basalts at Jingjiagou were subjected to a granulite-facies metamorphism (Fig. 9(c)), and these coarse-grained granulites are hosted by ca. 2.5 Ga TTG gneisses and charnockites. The granulites are dominated by orthopyroxene, hornblende, biotite, plagioclase, and quartz, and garnet is only locally present, possibly due to compositional heterogeneities or pressures. The granulite-facies metamorphism at Jingjiagou is indicated by the occurrence



**Fig. 9** (a–i) Photographs of representative Neoproterozoic supracrustal rocks in Qingyuan. (j) Measured section of the Neoproterozoic supracrustal sequence along the Fangniugou section. The stars represent the locations of selected samples, and the numbers by each star give the  $\text{SiO}_2$  content for each sample. Pl = plagioclase; Hb = hornblende; Bt = biotite; Q = quartz.

of orthopyroxene and garnet, and these rocks are markedly different from those in Hongtoushan and in the southern part of the Hunhe shear zone. The TTG gneisses to the north of Jingjiagou also underwent a granulite-facies metamorphism, as inferred from zircon structures, CL images, U–Th–Pb chemistry, and age data. In the Chaihe

Trondhjemite and Xianjinchang Tonalite, the partial recrystallization of primary magmatic zircon and the growth of new zircon rims indicate a high-grade metamorphic event at 2517–2490 Ma, after the emplacement of the igneous rocks at 2559–2553 Ma (Grant et al., 2009). This means that the Hunhe shear zone is not a

boundary of metamorphic facies, as previously proposed (Wan et al., 2005a, b; Peng et al., 2015; Wu et al., 2016), and that the boundary between the granulite and amphibolite facies should be placed farther northward, towards Jingjiagou, as shown in Fig. 8. Therefore, in Qingyuan, the general lack of granulite-facies mineral associations, or minerals that record retrograde metamorphic reactions, indicates that the basement was generally metamorphosed under the conditions of the amphibolite facies, and that only a small part of these rocks reached granulite-facies metamorphism. Recent research has recognized a felsic granulite in Dasuhe. However, this rock occurs as a massive enclave within the host TTG gneisses, and this provides insufficient evidence to infer a granulite terrane in Dasuhe.

Some researchers have also noted that the supracrustal assemblages and TTG gneisses in the north have yielded Mesoarchean ages of up to 3.0 Ga, while the southern assemblages were formed at ca. 2.5 Ga, according to K–Ar, Ar–Ar, and Sm–Nd ages for minerals and whole-rock samples, and conventional multi-grain zircon U–Pb methods (Zhai et al., 1985; Shen et al., 1994; Li and Shen, 2000). The K–Ar and Ar–Ar systems would have been open during regional metamorphism and deformation, and they cannot be relied upon to yield reliable constraints on ages. Recent geochronological studies have shown that zircons from the supracrustal assemblages and TTG gneisses have complex age patterns, and that they include igneous and metamorphic zircons as well as many inherited or trapped zircons, indicating that the multi-grain zircon U–Pb ages are geologically meaningless. The narrow range of Sm/Nd ratios (Li and Wei, 2017), combined with uncertainties surrounding whether analyzed samples have a cogenetic origin, means that Sm–Nd whole-rock isochron ages are similarly unreliable. In the past decade, zircon U–Pb isotopic dating using the SHRIMP, SIMS, and LA–ICP–MS methods has provided new constraints on the evolution of the Qingyuan granite–greenstone terrane, including its volcanism, sedimentation, plutonism, and metamorphism, as follows.

### 5.1.1 Volcanism

Li and Wei (2017) and Wu et al. (2016) have presented the results of systematic U–Pb geochronological studies of zircons from the basalts of the Qingyuan greenstone belt. Most zircon grains from the basalts are either misty or show weak striped absorption in internal textures on CL images, and have high Th/U ratios ( $> 0.1$ ), indicating a typical mafic magmatic origin. The eruption age of the basalts could be 2.54–2.51 Ga, which is comparable to the age of the andesite–dacite–rhyolites that were erupted at 2.57–2.51 Ga (Wan et al., 2005a; Peng et al., 2015; Wu et al., 2016). The issue is less relevant here, but some researchers have held the opinion that the basalt is fine-

grained in texture, and that the SiO<sub>2</sub> content is relatively low, both of which are unfavorable conditions for the crystallization of zircon. However, it is not difficult to obtain enough magmatic zircons from gabbros and diabases for dating their emplacement ages, and the coarser-grained basalts are similar to diabases in texture and mineralogy, and should provide enough magmatic zircons. In addition, we did find andesites that are intercalated with the basalts, and even some dacites that show conformable contacts with the basalts (Fig. 9(j); Li and Wei, 2017). The LA–ICP–MS U–Pb isotopic dating of zircons from the andesites and dacites reveals that they were erupted at ca. 2.52 Ga, further conforming the late Neoproterozoic eruption age of the basalt (Li and Wei, 2017).

### 5.1.2 Sedimentation

U–Pb analyses of detrital zircons of igneous origin from the sedimentary rocks (metamorphosed to garnet–biotite–plagioclase gneiss) gave a wide range of <sup>207</sup>Pb/<sup>206</sup>Pb zircon ages between 2675 and 2505 Ma, and the youngest igneous zircons with an age of 2505 Ma can be used to constrain the maximum age of deposition. Deposition actually took place before 2484 Ma, because this age corresponds to the regional metamorphic event that is recorded by metamorphic zircons from the same sample (Wu et al., 2016). The supracrustal assemblages, viz. the aforementioned volcanics and sedimentary rocks, constitute the principal part of the Qingyuan greenstone belt. The belt can be subdivided into the Shipengzi, Hongtoushan, and Nantianmen formations from bottom to top (Zhai et al., 1985; Peng et al., 2015), and these formations are found as intercalated successions or as xenoliths in the TTG gneisses and quartz diorite–quartz monzodiorite batholiths (Figs. 8 and 9(a); Bai et al., 2014; Wang et al., 2016a). The Shipengzi Formation consists predominantly of amphibolite and pyroxene hornblendite, with minor amounts of biotite–plagioclase gneiss. The original precursors were tholeiites (Figs. 9(a)–9(d) and 9(f)) and komatiites (Figs. 9(b) and 9(e)), along with some bimodal volcanic rocks. The conformably overlying Hongtoushan Formation consists predominantly of amphibolite and biotite–plagioclase gneiss, with minor amounts of sillimanite- and kyanite-bearing gneiss, and the original precursors were tholeiites, andesites (Fig. 9(g)), rhyolites (Fig. 9(h)), and dacitic tuffs, with minor amounts of pelite. Massive sulfide Cu-ore deposits occur frequently within the amphibolite of the Hongtoushan Formation. The Nantianmen Formation is composed of biotite–plagioclase gneiss, muscovite–biotite–quartz schist (Fig. 9(i)), amphibolite, magnetite quartzite, and marble (Zhai et al., 1985; Wan et al., 2005a; Bai et al., 2014; Peng et al., 2015), and the original precursors were graywacke, dolomitic pelite, siliceous sandstone, acid to intermediate tuff, basalt, chemical sedimentary rocks, and carbonates (Zhai et al., 1985;

Wan et al., 2005a). The locations of the aforementioned samples, which were used for zircon U–Pb dating, covered both margins of the Hunhe shear zone, indicating that the original precursors of the Qingyuan greenstone belt were formed at ca. 2.5 Ga. No supracrustal rocks with ages older than 2.7 Ga have been recognized in the belt, whereas Paleo–Mesoarchean zircons do exist.

### 5.1.3 Plutonism

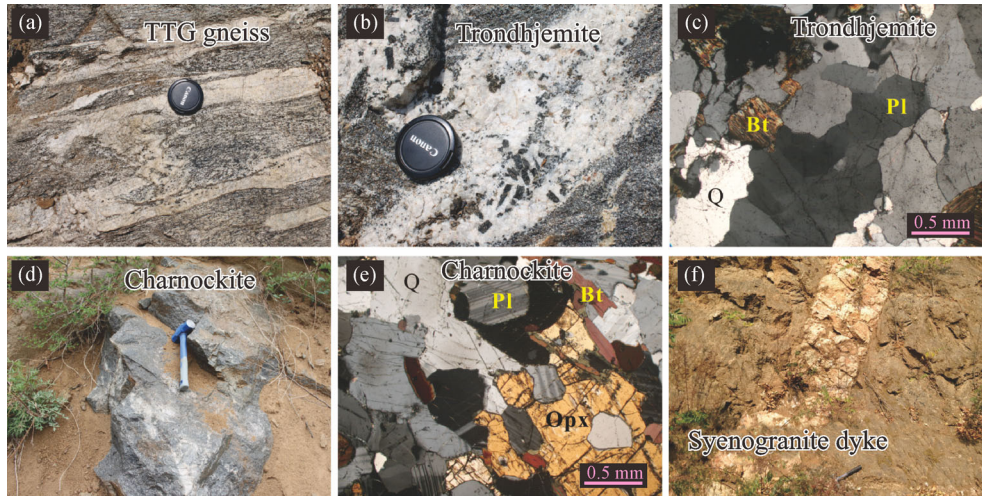
The late Neoproterozoic plutonism is represented by large volumes of granitoid gneisses (Supplementary materials Table S3), along with a smaller amount of charnockite (Supplementary materials Table S3) and mafic dikes. The granitoid gneisses consist of two suites: a Na-rich group (quartz dioritic–TTG gneisses) and a K-rich group (quartz monzodioritic and monzogranitic gneisses). The quartz dioritic–TTG gneisses show medium- to coarse-grained textures and gneissic structures, and consist of plagioclase, hornblende, K-feldspar, quartz, and biotite (Figs. 6(a)–6(c)). The quartz monzodioritic and monzogranitic gneisses display medium- to coarse-grained textures and weakly gneissic to massive structures, and are composed of plagioclase, K-feldspar, orthopyroxene, hornblende, quartz, clinopyroxene, and biotite. Bai et al. (2014) and Wang et al. (2016b) proposed that there were differences in the ages of the two groups. The Na-rich group was emplaced at 2571–2518 Ma, the others at 2522–2496 Ma. Wang et al. (2016a) further divided the tonalitic–trondhjemitic gneisses into two episodes of magmatism at 2600–2570 and 2550–2510 Ma. However, we urge caution in using these age data. Although there seem to be slight differences in the zircon ages for each suite, according to Li et al. (2015d), the LA–ICP–MS zircon U–Pb age dating method has uncertainties of ~4%, which with emplacement ages of 2.6–2.5 Ga means uncertainties in the age data of no less than 100 Ma. In fact, field-based observations show that the two suites of magmatic rocks always cross-cut each other, and we suggest therefore that these two suites represent coeval magmatism rather than separate episodes of magmatism. The charnockite at Jiangjiagou was emplaced at 2.5 Ga (LA–ICP–MS dating of igneous zircons), and was soon modified during a metamorphic event at 2496 Ma (Figs. 10(d) and 10(e); Supplementary materials Table S3). Integration of our data (Li and Wei, 2017; Supplementary materials Table S3) with recent geochronology studies of the Archean basement in Qingyuan shows inconsistencies in the previous model that the northern part of the granite–greenstone terrane was formed at ca. 3.0–2.7 Ga. Instead, our integrated data support the idea that the whole basement was formed at ca. 2.6–2.5 Ga, and that there are no large-scale geological bodies exposed in the granite–greenstone terrane that are older than 2.7 Ga (Supplementary materials Table S2). Recently, Wang et al. (2016a) reported a

tonalitic gneiss with an age of 2.68 Ga in the southwestern Qingyuan granite–greenstone terrane. However, we reprocessed the data using Isoplot (Ludwig, 2003), and a younger emplacement age of  $2581 \pm 6$  Ma was obtained. We suggest that the ca. 2.68 Ga zircons are inherited or trapped zircons that do not represent the timing of emplacement.

### 5.1.4 Metamorphism

The Neoproterozoic basement rocks must have been formed before the regional tectonic–metamorphic event that took place after 2.5 Ga, since they are extensively deformed and metamorphosed (Wan et al., 2005a; Bai et al., 2014; Peng et al., 2015; Wu et al., 2016). Our new U–Pb age data for the metamorphic zircons provide further information about the timing of this regional metamorphism (Li and Wei, 2017; Supplementary materials Table S3). Zircon grains from the andesites show relatively dark structureless rims, suggesting they were formed during a fluid-present metamorphism, and that their U–Pb ages of 2495 Ma represent the metamorphic age (Li and Wei, 2017). This age coincides with the age of zircons from the basalt, which have low Th/U ratios and relatively dark CL images that indicate a metamorphic origin. This metamorphic age is consistent with previously published age data, such as the concordant U–Pb age of 2510–2473 Ma for metamorphic zircons in the volcanics (LA–ICP–MS, SHRIMP, and SIMS zircon U–Pb dating methods; Wan et al., 2005a; Bai et al., 2014; Peng et al., 2015; Wu et al., 2016; Supplementary materials Table S2), and the age of 2516–2469 Ma for the metamorphic rims of zircons in the TTG gneisses (LA–ICP–MS zircon U–Pb dating; Wan et al., 2005a, b; Grant et al., 2009; Bai et al., 2014; Supplementary materials Table S3).

The close spatial and temporal relationships between the Qingyuan granite–greenstone terrane and the other rocks in the Eastern Block at ca. 2.5 Ga (Zhao et al., 2005; Zhao and Zhai, 2013) in terms of volcanism, sedimentation, plutonism, and metamorphism suggest a uniform tectono-thermal evolution. Moreover, it may be that the contemporaneity of the Qingyuan greenstone belt and the TTG-granitoid gneisses is a common phenomenon elsewhere on Earth. For example, the TTG gneisses in the Barberton granite–greenstone terrane developed in two episodes at 3.50–3.45 and 3.23 Ga, each of which is coeval with supracrustal rocks (the Onverwacht Group in the lower part and the Fig Tree and Modies groups in the upper part; Kisters et al., 2010; Nabhan et al., 2016). Other 2.6–2.5 Ga lithologic assemblages in the Longgang Block include the Anshan Group and the granitoids at Anshan in Liaoning Province (Wan et al., 2015), and the TTG gneisses at Helong and the granite–greenstone belt in Jiapigou in southern Jilin Province. The post-tectonic magmatic rocks (e.g., syenogranite) cross-cut the afore-



**Fig. 10** Photographs of representative Neoproterozoic granitoids in Qingyuan. Pl = plagioclase; Opx = orthopyroxene; Bt = biotite; Q = quartz.

mentioned basement rocks, marking the end of the Neoproterozoic tectonothermal event in the Longgang Block (Fig. 10(f); Supplementary materials Table S2). The ca. 2.7 Ga event in southern Jilin Province was not the focus of our work, and for more detailed descriptions, refer to the review papers of Guo et al. (2015, 2016, 2017).

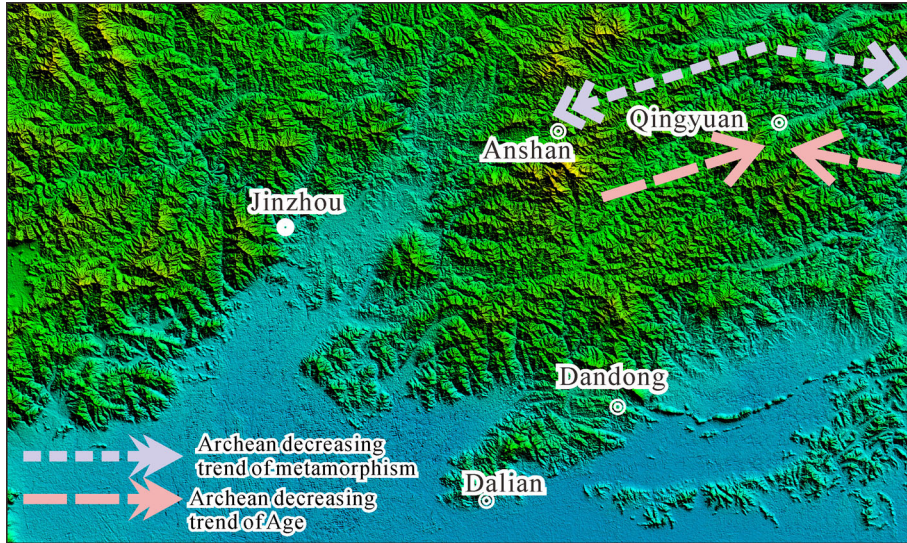
We discuss here the general problems related to the tectonic setting of the Qingyuan granite–greenstone terrane, and we attempt to highlight the issues involved. We draw attention to the following points. 1) The late Neoproterozoic bimodal volcanic assemblages (ultramafic–mafic and dacitic–rhyolitic rocks) shown in the cross-section of the Liaodong Peninsula (Fig. 9(j)) are found elsewhere in the North China Craton, and they contrast with the common unimodal (mainly andesitic) rocks in Phanerozoic magmatic arcs. 2) The large volume of ca. 2.5 Ga granitoid rocks (including the related greenstone belts) across the ~800 km wide Eastern Block shows no systematic spatial progression in terms of ages (Figs. 2 and 8), which is inconsistent with a migrating or successively accreting modern arc environment. 3) The most prominent structural feature is the dome-and-keel structure of the late Neoproterozoic basement, which is inconsistent with the linear magmatic arc environment that typifies Proterozoic and Phanerozoic orogens (Fig. 8). 4) The common occurrence of komatiite and basaltic komatiite within the Qingyuan greenstone belt (preserved as the hornblendite shown in Fig. 9(b)), as well as in other late Neoproterozoic greenstone belts of the Eastern Block, indicates anomalously high temperatures (> 1650°C) that are too high for subduction zones (Li and Wei, 2017). We suggest that the four points listed above do not support a magmatic arc setting, but they are consistent with an Archean proto-mantle plume model.

Fortunately, even though the basement in the Longgang

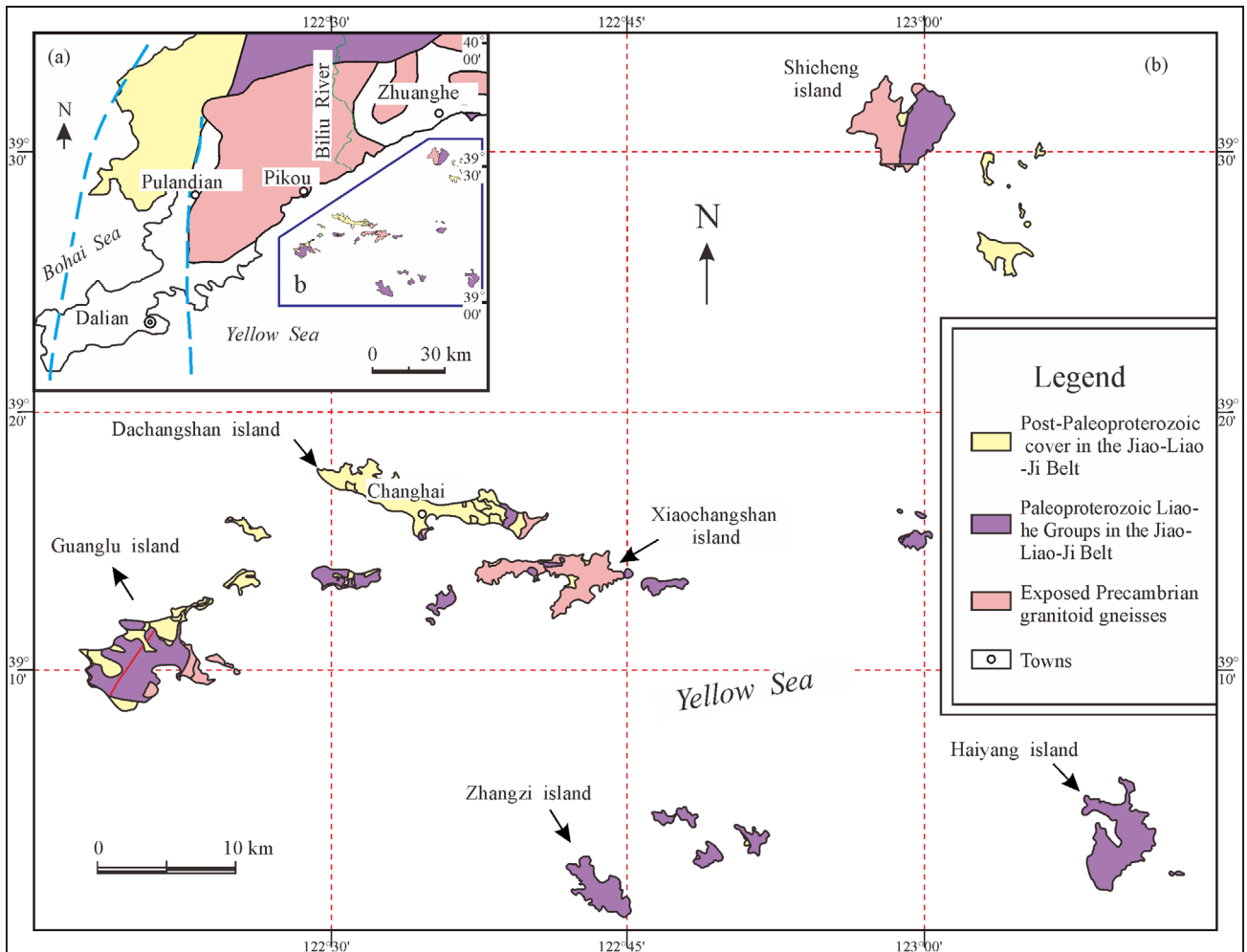
Block has undergone Neoproterozoic high-grade metamorphism, small amounts of older crustal rock are still preserved (Fig. 11). Remarkably, most of the basement in Anshan and the southern Jilin Province was formed at ca. 2.5 Ga, and the pre-2.5 Ga crustal rocks only occupy small areas. In the south, the basement around Anshan records a greenschist- to amphibolite-facies metamorphism and yields ages up to 3.85 Ga (3.8–2.5 Ga). In contrast, in the north, the basement in southern Jilin Province records an amphibolite-facies metamorphism and yields early to late Neoproterozoic ages (2.7–2.5 Ga). However, the basement at Qingyuan, between these two areas, records an amphibolite- to granulite-facies metamorphism and only late Neoproterozoic ages. The Neoproterozoic metamorphism was an intensive tectonothermal event at ca. 2.5 Ga, and while the ca. 2.5 Ga granulite-facies metamorphism fully reworked and overprinted the pre-2.5 Ga crustal rocks, the amphibolite-facies metamorphism only partially did so. The charnockites always occur in a high-grade terrane, as in the exposures in Jingjiagou, northern Qingyuan (Fig. 8), and they are not found in Anshan and southern Jilin Province. That is, the higher the degree of metamorphism the terrane was subjected to, the less likely it is that the more ancient rocks would have been preserved.

## 5.2 The ca. 2.5 Ga event in the Liaonan Block

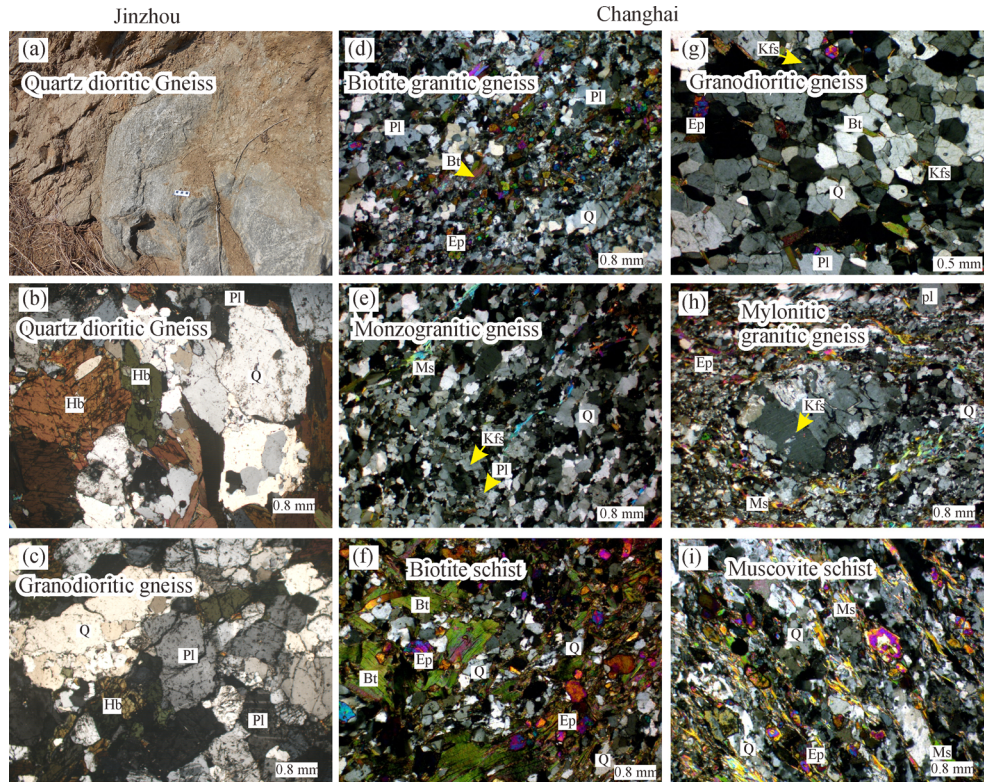
The most representative 2.54–2.44 Ga lithologic assemblages within the Liaonan Block are exposed near Dalian and Changhai (Fig. 12). The basement at Dalian consists mainly of quartz diorite and granodiorite, with ages of 2.50–2.44 Ga (LA–ICP–MS zircon U–Pb dating; Lu et al., 2004, 2006; Figs. 13(a)–13(c)). The Neoproterozoic basement at Changhai is made up mainly of various types of granitoid gneisses and schists (Lu et al., 2004, 2006; Figs.



**Fig. 11** Digital topographic map of Liaoning Province and its vicinity, showing the relationship between metamorphic grade and basement age.



**Fig. 12** Regional distribution of Neoproterozoic basement around Dalian and Changhai in the Liaonan Block (modified after Meng et al., 2013).



**Fig. 13** Photographs of representative Neoproterozoic rocks at Dalian (a–c) and Changhai (d–i). Pl = plagioclase; Hb = hornblende; Bt = biotite; Q = quartz; kfs = K-feldspar; Ep = epidote; Ms = muscovite.

13(d)–13(i)). The granitoid gneisses consist of two suites: a Na-rich suite (biotite monzonitic gneiss, granitic gneiss, garnet-bearing monzogranitic gneiss, and biotite granodioritic gneiss) and a K-rich suite (muscovite-bearing granitic gneiss, monzogranitic gneiss, and biotite granitic gneiss). LA-ICP-MS U–Pb dating of zircons from the granitoid gneisses revealed that they were emplaced at 2.54–2.51 Ga. The garnet–mica schists and quartzites associated with the gneissose rocks represent sediments that were deposited after 2518 Ma (Meng et al., 2013). It is important to note that the zircons from the granitoid gneisses and schists in southern Liaoning Province did not yield ca. 2.5 Ga metamorphic ages, and they only record the peak metamorphism age of 1885 Ma that is coeval with the metamorphism of the Jiao–Liao–Ji belt (Li et al., 2017). This implies that the late Neoproterozoic metamorphism in the Nangrim Block can be constrained to the greenschist- to lower-amphibolite facies.

## 6 Summary

Referring back to sections 5.1 and 5.2, the Liaonan and Longgang blocks show considerable differences in terms of lithological assemblages, geochronology, and metamorphic features, and we offer the following summary of the two blocks. 1) The Archean basement within the

Liaonan Block is dominated by dioritic–granodioritic gneisses (the rocks show a low degree of crustal maturity), along with smaller amounts of granitic gneiss. The rocks were emplaced between 2.54 and 2.44 Ga, and they were then metamorphosed under the greenschist to lower-amphibolite facies (Lu et al., 2004, 2006; Meng et al., 2013). In the Longgang Block, TTG–granitic gneisses make up most of the Archean basement, the protolith ages are much older (up to 3.85 Ga) than in the Liaonan Block (Figs. 8 and 9; Liu et al., 1992; Song et al., 1996; Wan et al., 2005c, 2012a, 2015), and the rocks were metamorphosed under the amphibolite to granulite facies (Liu et al., 1992; Song et al., 1996). The granitoid gneisses in the Nangrim Block and the TTG–granitic gneisses in the Longgang Block can be distinguished by their major element contents (e.g., SiO<sub>2</sub>, K<sub>2</sub>O, and Na<sub>2</sub>O), implying a significant difference in the crustal maturity of the two blocks during the early stages of Earth. 2) In the Longgang Block, small amounts of greenstone belt and BIF are present. However, the only supracrustal rocks in the Liaonan Block are schists at Changhai, and there are no greenstone belts or BIF. 3) Charnockites occur locally in the Longgang Block (e.g., at Jingjiagou, northern Qingyuan), whereas none are found in the Liaonan Block, and this is consistent with the aforementioned difference in the degree of metamorphism in the two blocks. The summary points made above lead us to conclude that the two

Archean blocks are not likely to have been formed by the splitting of a single Archean craton, and this conclusion is consistent with our recent studies on the Jiao–Liao–Ji Belt, which represents a Paleoproterozoic arc–continent collision belt rather than a rift (Li et al., 2017).

**Acknowledgements** We thank the anonymous journal reviewers for their constructive comments and careful corrections that led to significant improvement to the manuscript. We express our gratitude to Dr. Yan Zhan, Dr. Zhiwei Wang and Dr. Boran Guo for their discussions. Our work was supported financially by the Science Foundation of China University of Petroleum, Beijing (2462017YJRC032), the Science Foundation of State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing (PRP/indep-4-1702), the National Key Basic Research Program of China (No. 2012CB416603), and the National Natural Science Foundation of China (Grant Nos. 41430207 and 90914001).

**Supplementary materials** are available in the online version of this article at <https://doi.org/10.1007/s11707-018-0708-x> and are accessible for authorized users.

## References

- Bai J (1993). The Precambrian Geology and Pb–Zn Mineralization in the Northern Margin of North China Platform. Beijing: Geological Publishing House, 132 (in Chinese)
- Bai X, Liu S W, Yan M, Zhang L F, Wang W, Guo R R, Guo B R (2014). Geological event series of Early Precambrian metamorphic complex in South Fushun area, Liaoning Province. *Acta Petrological Sinica*, 30: 2905–2924 (in Chinese)
- Cavosie A J, Valley J W, Wilde S (2007). The oldest terrestrial mineral record: a review of 4400 to 4000 Ma detrital zircons from Jack Hills, Western Australia. *Developments in Precambrian Geology*, 15: 91–111
- Chen B, Li Z, Wang J L, Zhang L, Yan X L (2016). ~2.2 Ga magmatic event in the Liaodong Peninsula and its geological significance. *Journal of Jilin University (Earth Science Edition)*, 46(1): 1–14
- Compston W, Pidgeon R T (1986). Jack Hills, evidence of more very old detrital zircons in Western Australia. *Nature*, 321(6072): 766–769
- Condie K C, O'Neill C, Aster R C (2009). Evidence and implications for a widespread magmatic shutdown for 250 My on Earth. *Earth Planet Sci Lett*, 282(1–4): 294–298
- Cui P L, Sun J G, Sha D M, Wang X J, Zhang P, Gu A L, Wang Z Y (2013). Oldest zircon xenocryst (4.17 Ga) from the North China Craton. *Int Geol Rev*, 55(15): 1902–1908
- Faure M, Trap P, Lin W, Monie P, Bruguier O (2007). Polyrogenic evolution of the Paleoproterozoic Trans–North China Belt, new insights from the Lvliangshan–Hengshan–Wutaishan and Fuping massifs. *Episodes*, 30: 1–12
- Gao S, Rudnick R L, Yuan H L, Liu X M, Liu Y S, Xu W L, Ling W L, Ayers J, Wang X C, Wang Q H (2004). Recycling lower continental crust in the North China Craton. *Nature*, 432(7019): 892–897
- Grant M L, Wilde S A, Wu F, Yang J (2009). The application of zircon cathodoluminescence imaging, Th–U–Pb chemistry and U–Pb ages in interpreting discrete magmatic and high–grade metamorphic events in the North China Craton at the Archean/Proterozoic boundary. *Chem Geol*, 261(1–2): 155–171
- Guo B R, Liu S W, Zhang J, Wang W, Fu J H, Wang M J (2016). Neoproterozoic Andean–type active continental margin in the north-eastern North China Craton: geochemical and geochronological evidence from metavolcanic rocks in the Jiapiougou granite–greenstone belt, Southern Jilin Province. *Precambrian Res*, 285: 147–169
- Guo B R, Liu S W, Zhang J, Yan M (2015). Zircon U–Pb–Hf isotope systematics and geochemistry of Helong granite–greenstone belt in Southern Jilin Province, China: implications for Neoproterozoic crustal evolution of the northeastern margin of North China Craton. *Precambrian Res*, 271: 254–277
- Guo B, Liu S W, Santosh M, Wang W (2017). Neoproterozoic arc magmatism and crustal growth in the north–eastern North China Craton: evidence from granitoid gneisses in the Southern Jilin Province. *Precambrian Res*, 303: 30–53
- Guo J H, Sun M, Chen F K, Zhai M G (2005). Sm–Nd and SHRIMP U–Pb zircon geochronology of high–pressure granulites in the Sanggan area, North China Craton: timing of Paleoproterozoic continental collision. *J Asian Earth Sci*, 24 (5): 629–642
- Hao D F, Li S Z, Zhao G C, Sun M, Han Z Z, Zhao G T (2004). Origin and its constraint to tectonic evolution of Paleoproterozoic granitoids in the eastern Liaoning and Jilin province, North China. *Acta Petrological Sinica*, 20: 1409–1416 (in Chinese)
- Harrison T M (2009). The Hadean crust: evidence from > 4 Ga zircons. *Annu Rev Earth Planet Sci*, 37(1): 479–505
- Iizuka T, Komiya T, Johnson S P, Kon Y, Maruyama S, Hirata T (2009). Reworking of Hadean crust in the Acasta gneisses, northwestern Canada: evidence from in–situ Lu–Hf isotope analysis of zircon. *Chem Geol*, 259(3–4): 230–239
- Kisters A F M, Belcher R W, Poujol M, Dziggel A (2010). Continental growth and convergence–related arc plutonism in the Mesoarchaean: evidence from the Barberton granitoid–greenstone terrain, South Africa. *Precambrian Res*, 178(1–4): 15–26
- Kusky T M (2011). Comparison of results of recent seismic profiles with tectonic models of the North China Craton. *J Earth Sci*, 22(2): 250–259
- Li J J, Shen B F (2000). Geochronology of Precambrian continental crust in Liaoning Province and Jilin Province. *Progress in Precambrian Research*, 23: 249–255 (in Chinese)
- Li S Z, Hao D F, Zhao G C, Sun M, Han Z Z, Guo X Y (2004a). Geochemical features and origin of Dandong granite. *Acta Petrological Sinica*, 20: 1417–1423 (in Chinese)
- Li S Z, Zhao G C (2007). SHRIMP U–Pb zircon geochronology of the Liaoji granitoids: constraints on the evolution of the Paleoproterozoic Jiao–Liao–Ji belt in the Eastern Block of the North China Craton. *Precambrian Res*, 158(1–2): 1–16
- Li S Z, Zhao G C, Santosh M, Liu X, Dai L M (2011). Palaeoproterozoic tectono–thermal evolution and deep crustal processes in the Jiao–Liao–Ji Belt, North China Craton: a review. *Geol J*, 46(6): 525–543
- Li S Z, Zhao G C, Santosh M, Liu X, Dai L M, Sui Y H, Tam P Y, Song M C, Wang P C (2012). Paleoproterozoic structural evolution of the southern segment of the Jiao–Liao–Ji Belt, North China Craton. *Precambrian Res*, 200–203: 59–73
- Li S Z, Zhao G C, Sun M, Han Z Z, Luo Y, Hao D, Xia X P (2005). Deformation history of the Paleoproterozoic Liaohu assemblages in the Eastern Block of the North China Craton. *J Asian Earth Sci*, 24 (5): 659–674

- Li S Z, Zhao G C, Sun M, Han Z Z, Zhao G T, Hao D F (2006). Are the South and North Liaohe Groups of North China Craton different exotic terrains? Nd isotope constraints. *Gondwana Res*, 9(1–2): 198–208
- Li S Z, Zhao G C, Sun M, Wu F Y, Liu J Z, Hao D F, Han Z Z, Luo Y (2004b). Mesozoic, not Paleoproterozoic SHRIMP U–Pb zircon ages of two Liaoji granites, Eastern Block, North China Craton. *Int Geol Rev*, 46(2): 162–176
- Li X H, Liu X M, Liu Y S, Su L, Sun W D, Huang H Q, Yi K (2015d). Accuracy of LA–ICPMS zircon U–Pb age determination: an inter-laboratory comparison. *Sci China Earth Sci*, 58(10): 1722–1730
- Li Z, Chen B (2014). Geochronology and geochemistry of the Paleoproterozoic meta–basalts from the Jiao–Liao–Ji Belt, North China Craton: implications for petrogenesis and tectonic setting. *Precambrian Res*, 255: 653–667
- Li Z, Chen B (2015). Geochronological framework of the early Precambrian rocks in the Liaodong Peninsula and their geodynamic implications. *Journal of Jilin University (Earth Science Edition)*, 45: 1503–1507
- Li Z, Chen B (2016). Geochronological framework and geodynamic implications of mafic dykes in the Liaodong Peninsula, North China Craton. *Acta Geol Sin (English Edition)*, 90(s1): 76–77
- Li Z, Chen B, Liu J W, Zhang L, Yang C (2015a). Zircon U–Pb ages and their implications for the South Liaohe Group in the Liaodong Peninsula, Northeast China. *Acta Petrologica Sinica*, 31: 1589–1605 (in Chinese)
- Li Z, Chen B, Wang J L (2016a). Geochronological framework and geodynamic implications of mafic magmatism in the Liaodong Peninsula and adjacent regions, North China Craton. *Acta Geol Sin (English Edition)*, 90(1): 138–153
- Li Z, Chen B, Wei C J (2016b). Hadean detrital zircon in the North China Craton. *J Mineral Petrol Sci*, 111(4): 283–291
- Li Z, Chen B, Wei C J (2017). Is the Paleoproterozoic Jiao–Liao–Ji Belt (North China Craton) a rift? *International Journal of Earth Sciences*, 106(1): 355–375
- Li Z, Chen B, Wei C J, Wang C X, Han W (2015b). Provenance and tectonic setting of the Paleoproterozoic metasedimentary rocks from the Liaohe Group, Jiao–Liao–Ji Belt, North China Craton: insights from detrital zircon U–Pb geochronology, whole–rock Sm–Nd isotopes, and geochemistry. *J Asian Earth Sci*, 111: 711–732
- Li Z, Meng E, Pei F P, Liu J W, Zhang L (2016d). Geochronology, geochemistry and origin of the Early Cretaceous Jianyi Pluton in Dashaqiqiao, Liaoning Province. *Geology and Resource*, 25: 101–107
- Li Z, Pei F P, Meng E (2014a). Zircon U–Pb age, geochemical and Nd isotopic data of the Middle Jurassic high–Mg dioritic dike in the Liaodong Peninsula, NE China. *Global Geology*, 17: 143–154
- Li Z, Wang J L, Wang M, Zhang L, Liu J W, Qian J H, Yu H L (2014b). Redefinition of the Langzishan Formation in the North Liaohe Group. *Adv Geosci*, 4(06): 397–403 (in Chinese)
- Li Z, Wei C J (2017). Two types of Neoproterozoic basalts from Qingyuan greenstone belt, North China Craton: petrogenesis and tectonic implications. *Precambrian Res*, 292: 175–193
- Li Z, Wei C J, Chen B (2016c). Hadean detrital zircon in China. Abstract Volume of Annual Meeting of Chinese Geoscience Union (CGU), Beijing, 199
- Li Z, Wei C J, Chen Y P (2015c). Petrogenesis of the TTG gneiss: a case study and discussion. Abstract Volume of Annual Meeting of Chinese Geoscience Union (CGU), Beijing, 328–329
- Liu D Y (1991). The discovery of 3.8 Ga paleocontinental crust in China. *China Geology*, 5: 30 (in Chinese)
- Liu D Y, Nutman A P, Compston W, Wu J S, Shen Q H (1992). Remnants of  $\geq 3800$  Ma crust in the Chinese part of the Sino–Korean Craton. *Geology*, 20(4): 339–342
- Liu D Y, Wilde S A, Wan Y S, Wu J S, Zhou H Y, Dong C Y, Yin X Y (2008). New U–Pb and Hf isotopic data confirm Anshan as the oldest preserved segment of the North China Craton. *Am J Sci*, 308(3): 200–231
- Liu J, Liu Z H, Zhao C, Wang C J, Peng Y B, Zhang H (2017). Petrogenesis and zircon LA–ICP–MS U–Pb dating of newly discovered Mesoproterozoic gneiss on the northern margin of the North China Craton. *Int Geol Rev*, 59(12): 1575–1589
- Lu X P, Wu F Y, Guo J H, Wilde S A, Yang J H, Liu X M, Zhang X O (2006). Zircon U–Pb geochronological constraints on the Paleoproterozoic crustal evolution of the Eastern Block in the North China Craton. *Precambrian Res*, 146(3–4): 138–164
- Lu X P, Wu F Y, Lin J Q, Sun D Y, Zhang Y B, Guo C L (2004). Geochronological successions of the Early Precambrian granitic magmatism in southern Liaoning Peninsula and its constraints on tectonic evolution of the North China Craton. *Chinese Journal of Geology*, 39: 123–139 (in Chinese)
- Ludwig K R (2003). ISOPLOT 3: a geochronological toolkit for Microsoft Excel. Berkeley Geochronology Centre Special Publication, 4: 74
- Luo Y, Sun M, Zhao G C, Li S Z, Ayers J C, Xia X P, Zhang J H (2008). A comparison of U–Pb and Hf isotopic compositions of detrital zircons from the North and South Liaohe Groups: constraints on the evolution of the Jiao–Liao–Ji Belt, North China Craton. *Precambrian Res*, 163: 279–306
- Luo Y, Sun M, Zhao G C, Li S Z, Xu P, Ye K, Xia X P (2004). LA–ICP–MS U–Pb zircon ages of the Liaohe Group in the Eastern Block of the North China Craton: constraints on the evolution of the Jiao–Liao–Ji Belt. *Precambrian Res*, 134: 349–371
- Meng E, Liu F L, Liu J H, Liu P H, Cui Y, Liu C H, Yang H, Wang F, Shi J R, Kong Q B, Lian T (2013). Zircon U–Pb and Lu–Hf isotopic constraints on Archean crustal evolution in the Liaonan Complex of northeast China. *Lithos*, 177: 164–183
- Meng E, Liu F L, Liu P H, Liu C H, Yang H, Wang F, Shi J R, Cai J (2014). Petrogenesis and tectonic significance of Paleoproterozoic meta–mafic rocks from central Liaodong Peninsula, northeast China: evidence from zircon U–Pb dating and in situ Lu–Hf isotopes, and whole–rock geochemistry. *Precambrian Res*, 247: 92–109
- Meng Q R (2003). What drove late Mesozoic extension of the northern China–Mongolia tract. *Tectonophysics*, 369(3–4): 155–174
- Mojzsis S J, Harrison T M (2002). Establishment of a 3.83 Ga magmatic age for the Akilia tonalite (southern West Greenland). *Earth Planet Sci Lett*, 202(3–4): 563–576
- Nabhan S, Luber T, Scheffler F, Heubeck C (2016). Climatic and geochemical implications of Archean pedogenic gypsum in the Moodies Group (~3.2 Ga), Barberton Greenstone Belt, South Africa. *Precambrian Res*, 275: 119–134
- Nebel O, Rapp R P, Yaxley G M (2014). The role of detrital zircons in Hadean crustal research. *Lithos*, 190–191: 313–327

- Paquette J L, Barbosa J S F, Rohais S, Cruz S C P, Goncalves P, Peucat J J, Leal A B M, Santos-Pinto M, Martin H (2015). The geological roots of South America: 4.1 Ga and 3.7 Ga zircon crystals discovered in N.E. Brazil and N.W. Argentina. *Precambrian Res*, 271: 49–55
- Pei F P, Xu W L, Yang D B, Yu Y, Wang W, Zhao Q G (2011). Geochronology and geochemistry of Mesozoic mafic-ultramafic complexes in the southern Liaoning and southern Jilin provinces, NE China: constraints on the spatial extent of destruction of the North China Craton. *J Asian Earth Sci*, 40: 636–650
- Peng P, Guo J H, Windley B F, Li X H (2011). Halaqin volcano-sedimentary succession in the central-northern margin of the North China Craton: products of Late Paleoproterozoic ridge subduction. *Precambrian Res*, 187(1–2): 165–180
- Peng P, Guo J H, Zhai M G, Bleeker W (2010). Paleoproterozoic gabbro-noritic and granitic magmatism in the northern margin of the North China craton: evidence of crust-mantle interaction. *Precambrian Res*, 183(3): 635–659
- Peng P, Wang C, Wang X P, Yang S Y (2015). Qingyuan high-grade granite-greenstone terrain in the Eastern North China Craton: root of a Neoproterozoic arc. *Tectonophysics*, 662: 7–21
- Peng P, Wang X P, Windley B F, Guo J H, Zhai M G, Li Y (2014). Spatial distribution of ~1950–1800 Ma metamorphic events in the North China Craton: implications for tectonic subdivision of the craton. *Lithos*, 202–203: 250–266
- Polat A, Kusky T, Li J H, Fryer B, Kerrich R, Patrick K (2005). Geochemistry of Neoproterozoic (ca. 2.55–2.50) volcanic and ophiolitic rocks in the Wutaishan greenstone belt, central orogenic belt, North China craton: implications for deodynamic setting and continental growth. *Geol Soc Am Bull*, 117(11): 1387–1399
- Shen B F, Li J J, Mao D B (1997). Geological features types and evolution of greenstone belts in the North China Platform. *Progress in Precambrian Research*, 20: 2–11 (in Chinese)
- Shen B, Luo H, Han G, Dai X, Jin W, Hu X, Li S, Bi S (1994). Archean Geology and Metallization in North Liaoning Province and South Jilin Province. Beijing: Geological Publishing House, 255 (in Chinese)
- Shen Q H, Xu H F, Zhang Z Q, Gao J F, Wu J S, Ji C L (1992). *Precambrian Granulites in China*. Beijing: Geological Publishing House, 223 (in Chinese)
- Song B, Nutman A P, Liu D Y, Wu J S (1996). 3800 to 2500 Ma crust in the Anshan area of Liaoning Province, northeastern China. *Precambrian Res*, 78(1–3): 79–94
- Trap P, Faure M, Lin W, Breton N L, Monie P (2012). The Paleoproterozoic evolution of the Trans-North China Orogen: toward a synthetic tectonic model. *Precambrian Res*, 222–223: 450–473
- Valley J W, Cavosie A J, Ushikubo T, Reinhard D A, Lawrence D F, Larson D J, Clifton P H, Kelly T F, Wilde S A, Moser D E, Spicuzza M J (2014). Hadean age for a post-magma-ocean zircon confirmed by atom-probe tomography. *Nat Geosci*, 7: 219–223
- Wan Y S, Dong C Y, Liu D Y, Krner A, Yang C H, Wang W, Du L L, Xie H Q, Ma M Z (2012b). Zircon ages and geochemistry of late Neoproterozoic syenogranites in the North China Craton: a review. *Precambrian Res*, 222–223: 265–289
- Wan Y S, Liu D Y, Nutman A, Zhou H Y, Dong C Y, Yin X Y, Ma M Z (2012a). Multiple 3.8–3.1 Ga tectono-magmatic events in a newly discovered area of ancient rocks (the Shengouzi Complex), Anshan, North China Craton. *J Asian Earth Sci*, 54–55: 18–30
- Wan Y S, Liu D Y, Song B, Wu J S, Yang C H, Zhang Z Q, Geng Y S (2005c). Geochemical and Nd isotopic compositions of 3.8 Ga meta-quartz dioritic and trondhjemitic rocks from the Anshan area and their geological significance. *J Asian Earth Sci*, 24(5): 563–575
- Wan Y S, Ma M Z, Dong C Y, Xie H Q, Xie S W, Ren P, Liu D Y (2015). Widespread late Neoproterozoic reworking of Meso- to Paleoproterozoic continental crust in the Anshan-Benxi area, North China Craton, as documented by U-Pb-Nd-Hf-O isotopes. *Am J Sci*, 315(7): 620–670
- Wan Y S, Song B, Geng Y S, Liu D Y (2005a). Geochemical characteristics of Archean basement in the Fushun-Qingyuan area, Northern Liaoning Province and its geological significance. *Geological Review*, 51: 128–137 (in Chinese)
- Wan Y S, Song B, Liu D Y, Li H M, Yang C, Zhang Q D, Yang C H, Geng Y S, Shen Q H (2001). Geochronology and Geochemistry of 3.8–2.5 Ga Ancient Rock Belt in the Dongshan Scenic Park, Anshan Area. *Acta Geol Sin*, 75: 363–370 (in Chinese)
- Wan Y S, Song B, Liu D Y, Wilde S A, Wu J S, Shi Y R, Yin X Y, Zhou H Y (2006a). SHRIMP U-Pb zircon geochronology of Paleoproterozoic metasedimentary rocks in the North China Craton: evidence for a major Late Paleoproterozoic tectonothermal event. *Precambrian Res*, 149(3–4): 249–271
- Wan Y S, Song B, Yang C, Liu D Y (2005b). Zircon SHRIMP U-Pb geochronology of Archean rocks from the Fushun-Qingyuan area, Liaoning province and its geological significance. *Acta Geol Sin*, 79: 78–87 (in Chinese)
- Wan Y S, Wilde S A, Liu D Y, Yang C X, Song B, Yin X Y (2006b). Further evidence for ~1.85 Ga metamorphism in the central zone of the North China Craton: SHRIMP U-Pb dating of zircons from metamorphic rocks in the Lushan area, Henan Province. *Gondwana Res*, 9(1–2): 189–197
- Wang G H, Zhang C H, Wang G S, Wu Z W (2001). Tectonic framework of Western Liaoning Province and its evolution during Mesozoic. *Geoscience*, 15: 1–7 (in Chinese)
- Wang M J, Liu S W, Wang W, Wang K, Yan M, Guo B R, Bai X, Guo R R (2016a). Petrogenesis and tectonic implications of the Neoproterozoic North Liaoning tonalitic-trondhjemitic gneisses of the North China Craton, North China. *J Asian Earth Sci*, 131: 12–39
- Wang W, Liu S W, Bai X, Yang P T, Li Q G, Zhang L F (2011). Geochemistry and zircon U-Pb-Hf isotopic systematics of the Neoproterozoic Yixian-Fuxin greenstone belt, northern margin of the North China Craton: implications for petrogenesis and tectonic setting. *Gondwana Res*, 20(1): 64–81
- Wang W, Liu S W, Cawood P A, Bai X, Guo R R, Guo B R, Wang K (2016b). Late Neoproterozoic subduction-related crustal growth in the Northern Liaoning region of the North China Craton: evidence from ~2.55 to 2.50 Ga granitoid gneisses. *Precambrian Res*, 281: 200–223
- Wang Y F, Li X H, Jin W, Zhang J H (2015). Neoproterozoic ultra-depleted mantle domains inferred from ca. 3.81 Ga Anshan trondhjemitic gneisses, North China Craton. *Precambrian Res*, 263: 88–107
- Wilde S A, Valley J W, Peck W H, Graham C M (2001). Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature*, 409(6817): 175–178
- Wu F Y, Yang J H, Liu X M (2005a). Geochronological framework of

- the Mesozoic granitic magmatism in the Liaodong Peninsula, Northeast China. *Geology Journal of China University*, 11: 305–317 (in Chinese)
- Wu F Y, Yang J H, Liu X M, Li T S, Xie L W, Yang Y H (2005b). Hf isotopes of the 3.8 Ga zircons in eastern Hebei Province, China: implications for early crustal evolution of the North China Craton. *Chin Sci Bull*, 50(21): 2473–2480
- Wu F Y, Zhang Y B, Yang J H, Xie L W, Yang Y H (2008). Zircon U–Pb and Hf isotopic constraints on the Early Archean crustal evolution in Anshan of the North China Craton. *Precambrian Res*, 167(3–4): 339–362
- Wu F Y, Zhang Y B, Yang J H, Xie L W, Yang Y H (2009). Are there any 3.8 Ga rock at Anshan in the North China Craton? Reply to comments on Zircon U–Pb and Hf isotopic constraints on the Early Archean crustal evolution in Anshan of the North China Craton by Nutman et al. *Precambrian Res*, 172: 361–363
- Wu J S, Geng Y S, Shen Q H, Liu D Y, Song B (1998). *Archean Geology Characteristics and Tectonic Evolution of Sino–Korean Paleo–Continent*. Beijing: Geological Publishing House, 220
- Wu K K, Zhao G C, Sun M, Yin C Q, He Y H, Tam P Y (2013). Metamorphism of the northern Liaoning Complex: implications for the tectonic evolution of Neoarchean basement of the Eastern Block, North China Craton. *Geoscience Frontiers*, 4(3): 305–320
- Wu M L, Lin S F, Wan Y S, Gao J F (2016). Crustal evolution of the Eastern Block in the North China Craton: constraints from zircon U–Pb geochronology and Lu–Hf isotopes of the Northern Liaoning Complex. *Precambrian Res*, 275: 35–47
- Wu Z P, Hou X B, Li W (2007). Discussion on Mesozoic basin patterns and evolution in the eastern North China Block. *Geotectonica et Metallogenia*, 31: 385–399 (in Chinese)
- Yuan L L, Zhang X H, Xue F H, Han C M, Chen H H, Zhai M G (2015). Two episodes of Paleoproterozoic mafic intrusions from Liaoning province, North China Craton: petrogenesis and tectonic implications. *Precambrian Res*, 264: 119–139
- Zhai M G, Santosh M (2013). Metallogeny of the North China Craton: link with secular changes in the evolving Earth. *Gondwana Res*, 24(1): 275–297
- Zhai M G, Yang R Y, Lu W J, Zhou J E (1985). Geochemistry and evolution of the Qingyuan Archean granite–greenstone terrain, NE China. *Precambrian Res*, 27(1–3): 37–62
- Zhang Q S, Yang Z S (1988). *Early Crust and Mineral Deposits of Liaodong Peninsula*. Beijing: Geological Publishing House, 450 (in Chinese)
- Zhang S H, Zhao Y, Santosh M (2012). Mid–Mesoproterozoic bimodal magmatic rocks in the northern North China Craton: implications for magmatism related to breakup of the Columbia supercontinent. *Precambrian Res*, 222–223: 339–367
- Zhang X H, Zhang Y B, Zhai M G, Wu F Y, Hou Q L, Yuan L L (2017). Decoding Neoproterozoic to Palaeoproterozoic tectonothermal events in the Rangnim Massif, North Korea: regional correlation and broader implications. *Int Geol Rev*, 59(1): 16–28
- Zhao G C (2014). *Precambrian Evolution of the North China Craton*. Amsterdam: Elsevier, 194
- Zhao G C, Cao L, Wilde S A, Sun M, Choe W J, Li S Z (2006). Implications based on the first SHRIMP U–Pb zircon dating on Precambrian granitoid rocks in North Korea. *Earth Planet Sci Lett*, 251(3–4): 365–379
- Zhao G C, Guo J H (2012). *Precambrian Geology of China: preface*. *Precambrian Res*, 222–223: 1–12
- Zhao G C, Sun M, Wilde S A, Li S Z (2005). Late Archean to Paleoproterozoic evolution of the North China Craton: key issues revisited. *Precambrian Res*, 136(2): 177–202
- Zhao G C, Wilde S A, Guo J H, Cawood P A, Sun M, Li X P (2010). Single zircon grains record two Paleoproterozoic collisional events in the North China Craton. *Precambrian Res*, 177(3–4): 266–276
- Zhao G C, Zhai M G (2013). Lithotectonic elements of Precambrian basement in the North China Craton: review and tectonic implications. *Gondwana Res*, 23(4): 1207–1240