Magmatic Records of the Late Paleoproterozoic to Neoproterozoic Extensional and Rifting Events in the North China Craton: A Preliminary Review

14

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Abstract

The North China Craton (NCC) is characterized by multistages of extensional and continental rifting and deposition of thick marine or interactive marine and terrestrial clastic and carbonate platform sediments without angular unconformity during Earth's middle age of 1.70–0.75 Ga. Factors controlling these multistages of extensional and continental rifting events in the NCC can be either from the craton itself or from the neighboring continents being connected during these periods. Two large igneous provinces including the ca. 1.32 Ga mafic sill swarms in Yanliao rift (aulacogen) in the northern NCC and the ca. 0.92–0.89 Ga Xu-Huai–Dalian–Sariwon mafic sill swarms in southeastern and eastern NCC, have recently been identified from the NCC. Rocks from these two large igneous provinces exhibit similar geochemical features of tholeiitic compositions and intraplate characteristics. Formation of these two large igneous provinces was accompanied by pre-magmatic uplift as indicated by the field relations between the sills and their hosted sedimentary rocks. The Yanliao and Xu-Huai–Dalian–Sariwon large igneous provinces represent two continental rifting events that have led to rifting to drifting transition and breakup of the northern margin of the NCC from the Columbia (Nuna) supercontinent and the southeastern margin of the NCC from the Rodinia supercontinent, respectively. As shown by the ca. 200 Ma Central Atlantic Magmatic Province related to breakup of the Pangea supercontinent and initial opening of the Central Atlantic Ocean and the ca. 180 Ma Karoo-Ferrar large igneous province related to initial breakup of Gondwana, magmatism related to continental breakup and rifting to drifting transition can occur as mafic dykes, sills, and/or lavas across the neighboring continents and is mainly tholeiitic in chemical composition. This kind of magmatism should be large in volume and constitute a large igneous province. In many cases, eruption or/and emplacement of breakup-related magmatism were accompanied by pre-magmatic uplift. Large volumes of mafic sill swarms near continental margins and accompanied pre-magmatic uplift in marginal rift basins can most likely be used as important indicators for continental breakup and paleogeographic reconstruction.

Keywords

Late Paleoproterozoic to Meso-Neoproterozoic • Earth's middle age • Continental breakup • Continental rifting • Rodinia supercontinent • Columbia (Nuna) supercontinent • North China Craton

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M. Zhai et al. (eds.), *Main Tectonic Events and Metallogeny of the North China Craton*, Springer Geology, DOI 10.1007/978-981-10-1064-4_14

14.1 Introduction

The period 1.70–0.75 Ga is Earth's middle age that is characterized by environmental, evolutionary, and lithospheric stability that contrasts with the dramatic changes in preceding and succeeding eras (Cawood and Hawkesworth 2014). Two supercontinents, namely Columbia (Nuna) and Rodinia, existed during this period (e.g., Hoffman 1991; Dalziel 1991; Zhao et al. 2002, 2004a, 2011; Rogers and Santosh 2002; Evans 2013). The North China Craton (NCC) during this period is characterized by deposition of thick marine or interactive marine and terrestrial clastic and carbonate platform sediments. Although several disconformities have been identified, no regional angular unconformities have been recognized, indicating no deformation during the deposition of these thick sequences of sedimentary rocks. Except for the high-potassium alkaline mafic-intermediate volcanic rocks in the Dahongyu Formation and the upper part of the Tuanshanzi Formation in Pinggu and Jixian areas within the Yanliao rift (aulacogen) in the northern NCC (e.g., Liu 1991; Yu et al. 1994; Ding et al. 2005; Hu et al. 2007; Zhang et al. 2013b, 2015; Wang et al. 2015a), volcanic rocks are rare within the late Paleoproterozoic to Meso-Neoproterozoic sedimentary sequences. In recent years, many layers of tuffs and K-bentonite beds have been identified from the sedimentary rocks in the Yanliao rift (aulacogen) in the northern NCC and Ruzhou area in southern margin of the NCC, which provide important constraints on ages of the strata of the NCC (Gao et al. 2007, 2008a, b; Su et al. 2008, 2010, 2012; Li et al. 2010a, 2014a; Tian et al. 2015).

Traditionally, the lower boundary age of the Mesoproterozoic period in China has been regarded as 1.80 Ga based on the lower boundary age of the Changzhougou Formation in the Yanliao rift (aulacogen) in the northern NCC (e.g., China National Commission on Stratigraphy 2001; Wang 2014). This boundary age of 1.80 Ga is 200 Ma earlier than that of the Mesoproterozoic period of 1.60 Ga in the International Stratigraphic Chart (e.g., Gradstein et al. 2004; Walker and Geissman 2009; International Commission on Stratigraphy 2012). The lower boundary age of the Changzhougou Formation in the Yanliao rift (aulacogen) was traditionally regarded as 1.80 Ga. However, recently results show that the lower boundary age of the Changzhougou Formation in the Yanliao rift (aulacogen) is likely ca. 1.70 Ga (Wang et al. 1995; Peng et al. 2012) or ca. 1.66–1.65 Ga (Li et al. 2011, 2013; He et al. 2011a, b; Zhang et al. 2013b). Moreover, regional geological mapping results show that the contact between the 1.79–1.76 Ga volcanic rocks of Xiong'er Group and the late Paleoproterozoic to Mesoproterozoic Yunmengshan Formation or Gaoshanhe Formation (BGMRHNP 1989; BGMRSP 1989; GSIHNP 2003, GSISXP 2007; Zhao et al. 2015) is an angular unconformity, indicating that the Xiong'er Group is very different from the late Paleoproterozoic to Meso-Neoproterozoic sedimentary sequences in the NCC and may belong to another structural layer beneath the late Paleoproterozoic to Meso-Neoproterozoic sedimentary rocks in the NCC. A regional deformation event likely occurred between deposition of the Xiong'er Group and the Yunmengshan Formation or Gaoshanhe Formation during ca. 1.75–1.70 Ga. Therefore, the tectonic setting of the Xiong'er Group in the southern NCC is likely very different from that of the other late Paleoproterozoic to Meso-Neoproterozoic sedimentary rocks in the NCC. In this chapter, we will give a preliminary review on the magmatic records of the late Paleoproterozoic to Neoproterozoic (Meso-Neoproterozoic according to the Stratigraphic Chart of China using 1.80 Ga as the lower boundary age of the Mesoproterozoic period) extensional and rifting events in the NCC from ca. 1.75–1.70 Ga.

14.2 Late Paleoproterozoic Magmatism, Extension, and Continental Rifting

14.2.1 The 1.75–1.68 Ga Magmatism and Extension in the NCC

The 1.75–1.68 Ga magmatic rocks are mainly distributed in the northern NCC with minor in the southern margin of the NCC (Table 14.1; Fig. 14.1). Most of them are located within or near the Trans-North China Orogen of the NCC as shown by Zhao et al. (2005). One small alkaline intrusion (Wayao quartz syenite, Wang et al. 2012a) is located in the khondalite belt between the Yinshan and Ordos blocks (Fig. 14.1). Formation of the 1.75–1.68 Ga magmatic rocks is lightly later than eruption of the 1.79–1.76 Ga volcanic rocks of Xiong'er Group in the southern NCC and emplacement of the 1.79–1.77 Ga mafic dyke swarms in the central NCC (e.g., Zhao et al. 2002; Peng et al. 2008; He et al. 2009; Peng 2015). However, their emplacement is earlier than deposition of the Meso-Neoproterozoic sedimentary sequences in the NCC, as indicated by the conformity between the 1.73 Ga Guandaokou quartz syenite porphyry and the Gaoshanhe Formation in the southern margin of the NCC (Ren et al. 2000) and conformity between the 1.68 Ga Shachang rapakivi granite and the Changzhougou Formation in the Yanliao rift (aulacogen) in the northern NCC (He et al. 2011a, b).

The 1.75–1.68 Ga magmatic rocks consist mainly of norite, mangerite, anorthosite, charnockite, gabbro, syenite, monzonite, rapakivi granite, alkaline granite, diorite and mafic (diabase) dykes (Table 14.1). The above rock associations indicate their emplacement in an extensional tectonic

Table 14.1 Summary of zircon U–Pb and $^{40}Ar/^{39}Ar$ ages of the 1.75–1.68 Ga magmatic rocks in the NCC

Location/intrusion name	Longitude (E)	Latitude (N)	Rock type	Age (Ma)	Method	References
Damiao, northern Hebei	117°42′–118°15′	41°08′–41°19′	Norite	1693 ± 7	Zircon TIMS	Zhao et al. (2004b)
			Mangerite	1715 ± 6	Zircon TIMS	Zhao et al. (2004b)
			Mangerite	1718 ± 26	Zircon TIMS	Ren et al. (2006)
			Light anorthosite	1726 ± 9	Zircon SHRIMP	Zhang et al. (2007)
			Mangerite	1739 ± 14	Zircon SHRIMP	Zhao et al. (2009)
			Norite	1742 ± 17	Zircon LA-ICP-MS	Zhao et al. (2009)
			Noritic gabbro	1725 ± 13	Zircon LA-ICP-MS	Teng and Santosh (2015)
			Norite	1687 ± 18	Zircon LA-ICP-MS	Teng and Santosh (2015)
			Leuconorite	1751 ± 15	Zircon LA-ICP-MS	Teng and Santosh (2015)
			Leuconorite	1693 ± 24	Zircon LA-ICP-MS	Teng and Santosh (2015)
			Gabbronorite	1721 ± 17	Zircon LA-ICP-MS	Teng and Santosh (2015)
			Gabbroic anorthosite	1729 ± 14	Zircon LA-ICP-MS	Teng and Santosh (2015)
			Ferroan charnockite	1749 ± 6	Zircon LA-ICP-MS	Yang et al. (2014)
			Ferroan charnockite	1747 ± 10	Zircon LA-ICP-MS	Yang et al. (2014)
			Magnesian charnockite	1756 ± 3	Zircon LA-ICP-MS	Yang et al. (2014)
			Magnesian charnockite	1757 ± 9	Zircon LA-ICP-MS	Yang et al. (2014)
			Magnesian charnockite	1731 ± 17	Zircon LA-ICP-MS	Yang et al. (2014)
			Gabbro	1732 ± 8	Zircon LA-ICP-MS	Yang et al. (2014)
			Gabbroic anorthosite	1747 ± 7	Zircon LA-ICP-MS	Yang et al. (2014)
			Magnetite	1763 ± 22	Zircon LA-ICP-MS	Liu et al. (2016)
			Magnetite	1768 ± 39	Zircon LA-ICP-MS	Liu et al. (2016)
			Magnetite	1752 ± 53	Zircon LA-ICP-MS	Liu et al. (2016)
Changsaoying, northern Beijing	116°46′–117°00′	40°45′–40°49′	K-feldspar granite	1753 ± 23	Zircon SHRIMP	Zhang et al. (2007)
Gubeikou, northern Beijing	117°07′–117°31′	40°40′–40°45′	K-feldspar granite	1692 ± 19	Zircon LA-ICP-MS	Zhang et al. (2007)
Lanying, northern Beijing	116°29′–116°44′	40°45′–40°49′	Anorthosite	1739 ± 43	Zircon LA-ICP-MS	Zhang et al. (2007)
			Quartz syenite	1712 ± 15	Zircon LA-ICP-MS	Zhang et al. (2007)
Pingquan, northern Hebei	118°31′–118°44′	41°02′–41°11′	Clinopyroxene syenite	1726 ± 13	Zircon TIMS	Ren et al. (2006)

(continued)

Table 14.1 (continued)

Location/intrusion name	Longitude (E)	Latitude (N)	Rock type	Age (Ma)	Method	References
Shachang, Miyun, northern Beijing	116°58′–117°07′	40°22′–40°25′	Rapakivi granite	1706 ± 15	Zircon TIMS	Song (1992)
			Rapakivi granite	1715 ± 35	Zircon TIMS	Song (1992)
			Rapakivi granite	1716 ± 21	Hornblende $^{40}Ar/^{39}Ar$	Hu et al. (1990)
			Rapakivi granite	1711 ± 6	Hornblende $^{40}Ar/^{39}Ar$	Song (1992)
			Rapakivi granite	1683 ± 4	Zircon TIMS	Ramo et al. (1995)
			Rapakivi granite	1681 ± 10	Zircon LA-ICP-MS	Yang et al. (2005)
			Rapakivi granite	1679 ± 10	Zircon LA-ICP-MS	Yang et al. (2005)
			Rapakivi granite	1685 ± 15	Zircon SHRIMP	Gao et al. (2008c)
Wenquan, Zhangjiakou, NW Hebei	115°41′–115°50′	40°52′–40°57′	A-type granite	1697 ± 7	Zircon LA-ICP-MS	Jiang et al. (2011)
Miyun, northern Beijing	117°01′–117°09′	40°32′–40°39′	Mafic dyke	1731 ± 4	Baddeleyite TIMS	Peng et al. (2012)
Jianping, western Liaoning	119°33′–119°40′	40°25′–40°35′	Magnetite	1694 ± 12	Zircon LA-ICP-MS	Liu et al. (2011)
			Magnetite diorite	1721 ± 9	Zircon LA-ICP-MS	Wang et al. (2013a)
			Clinopyroxene monzonite	1724 ± 10	Zircon LA-ICP-MS	Wang et al. (2013a)
			Clinopyroxene monzonite	1720 ± 8	Zircon LA-ICP-MS	Wang et al. (2013a)
			Quartz syenite	1717 ± 9	Zircon LA-ICP-MS	Wang et al. (2013a)
			Syenite	1701 ± 9	Zircon LA-ICP-MS	Wang et al. (2013a)
			Quartz syenite	1698 ± 13	Zircon LA-ICP-MS	Wang et al. (2013a)
			Magnetite	1725 ± 26	Zircon LA-ICP-MS	Liu et al. (2016)
Wayao, Guyang, Inner Mongolia	110°33′–110°41′	40°54′–40°57′	Quartz syenite	1702 ± 32	Zircon SHRIMP	Wang et al. (2012a)
Yanyaozhai, Luanchuan, Henan	110°29′	34°05′	Syenite	1750 ± 65	Zircon TIMS	Ren et al. (2000)
Guandaokou, Lushi, Henan	110°04′	34°18′–34°19′	Quartz syenite porphyry	1731 ± 29	Zircon TIMS	Ren et al. (2000)

setting. Although some researchers considered the 1.75–1.68 Ga anorthosite-mangerite-alkali granitoid-rapakivi granite suite in the northern NCC as anorogenic magmatism in continental rifting (e.g., Ramo et al. 1995; Yu et al. 1994, 1996; Ren et al. 2006; Zhai et al. 2014, 2015), others proposed that the 1.75–1.68 Ga magmatic rocks in the NCC were generated in a postcollisional/post-orogenic extensional tectonic environment after continent–continent collision between the Western and Eastern continental blocks of the NCC at ca. 1.85 Ga (Zhang et al. 2007; Wang et al. 2013a; Yang et al. 2014; Teng and Santosh 2015; Liu et al. 2016). Since the 1.75–1.68 Ga magmatic rocks in the NCC are mainly distributed within or near the Trans-North China Orogen of the NCC and their emplacement occurred prior to deposition of the Meso-Neoproterozoic sedimentary sequences, we believe that the 1.75–1.68 Ga magmatism in the NCC occurred in a postcollisional/post-orogenic extensional tectonic environment and represents a long extension period in the NCC after continent–continent collision between the Western and Eastern continental blocks at ca. 1.85 Ga, as

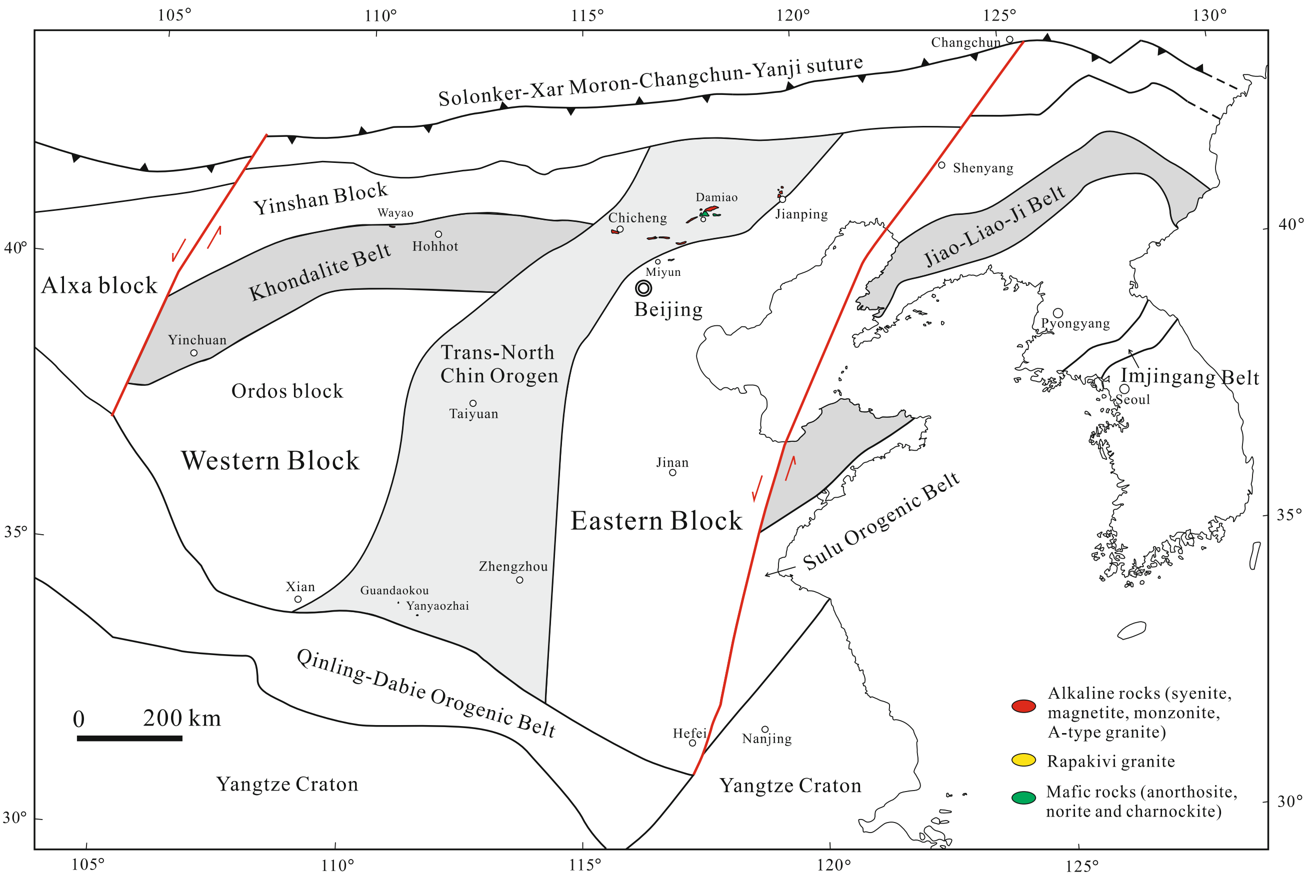

Fig. 14.1 Sketch map showing distribution of the 1.75–1.68 Ga magmatic rocks in the NCC. Boundaries of the late Paleoproterozoic (1.95–1.85 Ga) orogens are from Zhao et al. (2005), Zhao and Zhai (2013)

suggested by our previous study on the 1.75–1.68 Ga anorthosite-mangerite-alkali granitoid-rapakivi granite suite from the northern North China Craton (Zhang et al. 2007).

14.2.2 The 1.64–1.62 Ga Volcanic Rocks in the Yanliao Rift (Aulacogen)

The 1.64–1.62 Ga volcanic rocks are located within the Dahongyu Formation and the upper part of the Tuanshanzi Formation in Pinggu, Jixian, Zunhua, and Luanxian areas in the Yanliao rift (aulacogen) (Figs. 14.2 and 14.3). They are distributed in a SEE-trending zone that is 150 km long and 20 km wide. The volcanic eruption centers are located near Pingpu and Jixian areas with thickness ranging from 60 to 450 m (BGMRHBP 1989). In the Zunhua and Luanxian areas, their thickness is about 2–16 m (BGMRHBP 1989). Zircon LA-ICP-MS (laser ablation-inductively coupled mass spectrometry) U–Pb dating on a potassium-rich volcanic rock in the upper part of the Tuanshanzi Formation in Pinggu area yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 1637 ± 15 Ma and a concordia age of 1641 ± 4 Ma, indicating eruption of the volcanic rocks of the Tuanshanzi Formation at ca. 1.64 Ga (Zhang et al. 2013b). Volcanic rocks from the Dahongyu Formation in Pinggu and Jixian areas yielded zircon $^{207}Pb/^{206}Pb$ ages from 1626 ± 9 to 1622 ± 23 Ma (Lu and Li 1991; Lu et al. 2008b; Gao et al. 2008a; Zhang et al. 2015).

The 1.64–1.62 Ga volcanic rocks are composed mainly of olivine basalt, trachybasalt, trachyandesite, trachyte, phonolite, and some volcanic-clastic rocks. Most of them are classed as alkaline volcanic rocks in the total alkali ($K_2O + Na_2O$) versus silica (SiO_2) classification diagram (Liu 1991; Yu et al. 1994; Ding et al. 2005; Hu et al. 2007; Wang et al. 2015a; Zhang et al. 2015). They are characterized by low contents of SiO_2 and high contents of K_2O and exhibit slightly negative to positive $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ values from −2.1 to 4.3 (Hu et al. 2007; Wang et al. 2015a), indicating that they were likely produced by partial melting of the asthenosphere with assimilation of crustal materials. Most researchers agree that the 1.64–1.62 Ga volcanic rocks in the Yanliao rift (aulacogen) were formed in an intracontinental rift setting (Liu 1991; Yu et al. 1994; Ding et al. 2005; Hu et al. 2007; Wang et al. 2015a; Zhang et al. 2015). Some researchers proposed that the 1.64–1.62 Ga volcanic rocks represent the rifting to drifting (or spreading) transition

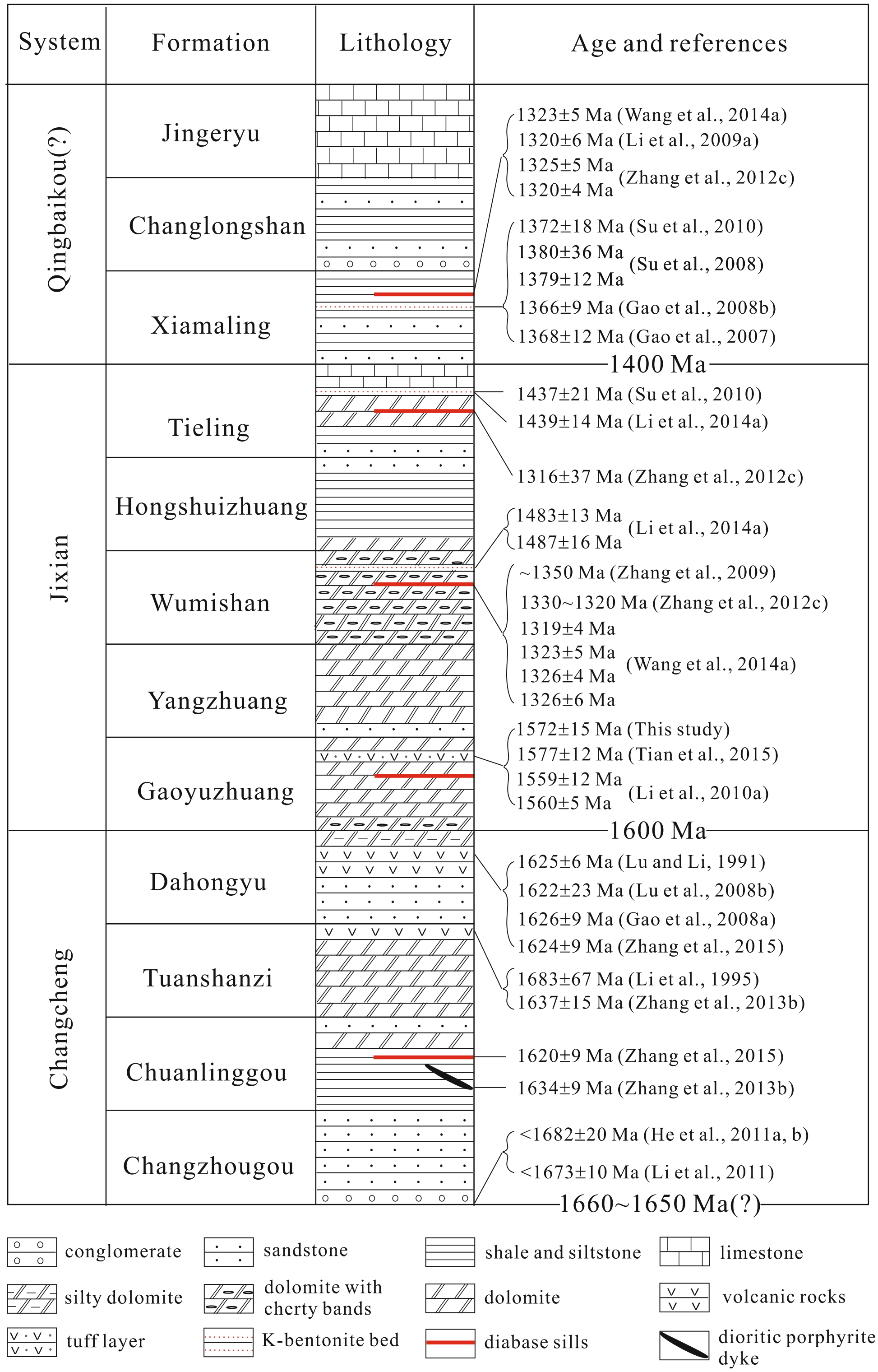

Fig. 14.2 Subdivision and zircon U–Pb age constraints on the late Paleoproterozoic to Mesoproterozoic strata in the Yanliao rift (aulacogen) in the northern NCC (modified after Zhang et al. 2013b)

of the northern NCC from the Columbia supercontinent (Meng et al. 2011; Zhang et al. 2015); others proposed that the continental rifting was aborted shortly after the beginning and has not resulted in rifting to drifting transition (Ding et al. 2005). Since the 1.64–1.62 Ga volcanic rocks are only distributed in a very small area in the Yanliao rift (aulacogen) and are characterized by alkaline geochemical compositions, we propose the 1.64–1.62 Ga volcanic rocks were formed in a failed intracontinental rift that has not developed into a rifting to drifting transition.

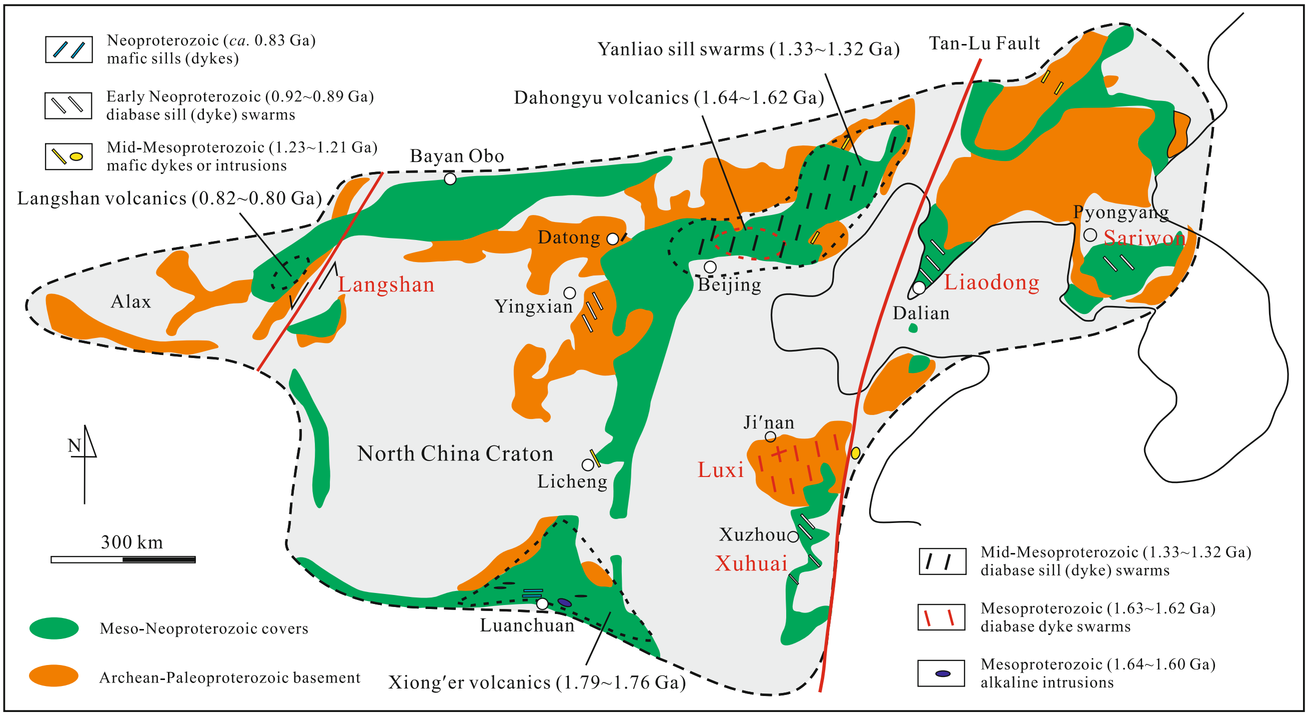

Fig. 14.3 Sketch map showing distribution of the Meso-Neoproterozoic magmatic rocks in the NCC (modified after Peng et al. 2011a)

14.2.3 The 1.68 Ga Laiwu Mafic Dykes in the Eastern NCC

A secondary ion mass spectrometry (SIMS) baddeleyite $^{207}Pb/^{206}Pb$ age of 1680 ± 5 Ma was reported for a NNW-trending mafic dyke from Zoujialanzi village, Laiwu in the Luxi area in the eastern NCC (Li et al. 2015b). The Laiwu mafic dykes are NNW in strike with steeply dipping angles of 65°–85°. They are typical diabase with a mineral assemblage of clinopyroxene and plagioclase, with minor amounts of ilmenite, magnetite, and quartz (Li et al. 2015b). Compared with the 1.63–1.62 Ga mafic dykes in the Luxi area, the 1.68 Ga mafic dykes contain more volumes of plagioclase and Fe–Ti oxides are slightly rich in TiO_2 (Li et al. 2015b). Since these dykes are spatially associated with the 1.63–1.62 Ga mafic dykes, more researches are needed to determine their volumes and relations to the 1.63–1.62 Ga mafic dykes.

14.2.4 The 1.63–1.62 Ga Mafic Dyke Swarms in Luxi Area in the Eastern NCC

The Luxi area in the eastern NCC is characterized by emplacement of large volumes of mafic dyke swarms into the Archean-Paleoproterozoic metamorphic basement rocks (Fig. 14.4). They are generally NW–NNW in strike with a steeply dipping angle. A few of them are NE–NNE in strike. They are unconformably overlain by the Neoproterozoic or Early Cambrian sedimentary rocks. The mafic dykes are less than half a meter to 2–5 m wide and their lengths ranging from several ten meters to >20 km. Most of them are very fresh without deformation and metamorphism. Early zircon SHRIMP (sensitive high-resolution ion micro-probe) U–Pb dating on the NW–NNW-trending mafic dykes from Taishan and Mengyin yielded $^{207}Pb/^{206}Pb$ ages of 1837 ± 18 Ma (Hou et al. 2006) and 1841 ± 17 Ma (Wang et al. 2007), respectively. Recent baddeleyite thermal ionization mass spectrometer (TIMS) and SIMS U–Pb dating on the NW–NNW-trending mafic dykes from Taishan yielded $^{207}Pb/^{206}Pb$ ages of 1621 ± 9 Ma (Lu et al. 2008a) and 1632 ± 4 Ma (Xiang et al. 2012), respectively. These baddeleyite $^{207}Pb/^{206}Pb$ ages are similar to our newly obtained baddeleyite ages of the mafic dykes from Taishan and Zoucheng. Therefore, emplacement of the large volumes of mafic dyke swarms in the Luxi area in the eastern NCC occurred mainly during 1.63–1.62 Ga.

The 1.63–1.62 Ga mafic dykes in the Luxi area consist mainly of gabbro, diabase, or diabase porphyrite with a main mineral assemblage of clinopyroxene and plagioclase (some occur as phenocrysts); other minerals include biotite, hornblende, ilmenite, magnetite, and/or quartz. They are tholeiitic in composition and are characterized by low contents of SiO_2 and MgO, enrichment in large-ion lithophile elements (LILEs) and light rare earth elements (REEs) and depletion in high-field strength elements (HFSEs) and heavy REEs

Fig. 14.4 Field photos of the 1.63–1.62 Ga mafic dykes in the Luxi area in the eastern NCC. **a** Cylindrical columnar joints in the NNW-trending Taishan mafic dyke. **b** NE-trending mafic dyke in eastern Taishan. **c** NNW-trending mafic dyke in eastern Laiwu. **d** NNW-trending mafic dyke in western Laiwu. **e** Diabase porphyrite from a NNW-trending mafic dyke in Fangcheng, Linyi. **f** Intrusive contact between the NNW-trending mafic dyke and Archean gneissic granite in Xiayandian, Linyi

(Hou et al. 2006; Wang et al. 2007; Xiang et al. 2012; Li et al. 2015b). Emplacement of large volumes of mafic dyke swarms in the Luxi area indicates that the eastern NCC experienced widespread extension during 1.63–1.62 Ga. However, it is still uncertain what caused the above widespread extension during 1.63–1.62 Ga in the eastern NCC.

14.2.5 The 1.64–1.60 Ga Alkaline Rocks in the Southern NCC

Several 1.64–1.60 Ga intrusions (Miaoling, Longwangzhuang, and Maping) have been identified from the southern margin of the NCC (Ren et al. 2000; Lu et al. 2003; Bao et al. 2011; Liu 2011; Wang et al. 2013b; Deng et al. 2015; Fig. 14.3). The Miaoling aegirine-augite syenite occurs as dykes or small intrusions within the Xiong'er Group near Songxian in southern Henan Province and zircon TIMS U–Pb dating yielded a upper intercept age of 1644 ± 14 Ma (Ren et al. 2000). The Longwangzhuang granite pluton is located near Luanchuan County in southern Henan Province with an area of 120 km^2. It intruded into the Archean metamorphic basement rocks and its eastern side was intruded by an Early Cretaceous granitoid pluton. It is composed mainly of syenogranite with a main mineral assemblage of K-feldspar (mainly microcline, 40–60 vol.%), quartz (20–35 vol.%), biotite (1–10 vol.%), albite (5–10 vol.%), and hornblende (0–5 vol.%). Zircon U–Pb dating of different samples from the Longwangzhuang pluton by TIMS, SHRIMP, and LA-ICP-MS methods yielded weighted mean $^{207}Pb/^{206}Pb$ ages from 1625 ± 16 to 1602 ± 7 Ma (Lu et al. 2003; Bao et al. 2011; Wang et al. 2013a), indicating its emplacement during 1.63–1.60 Ga. The Maping alkaline complex is located 5 km northwest to Luonan in Shaanxi Province. It occurs as E–W-trending intrusions intruded into the Guandaokou Group in an area that is 5 km long and 500 m wide. It consists mainly of granite porphyry and syenogranite with a main mineral assemblage of K-feldspar, quartz and biotite, and is characterized by high SiO_2 and alkaline ($Na_2O + K_2O$) contents (Liu 2011; Deng et al. 2015). Zircon LA-ICP-MS dating on two granite porphyry samples yielded weighted mean $^{207}Pb/^{206}Pb$ ages of 1600 ± 24 and 1583 ± 28 Ma, respectively (Deng et al. 2015). Zircon SHRIMP U–Pb dating of a syenogranite sample yielded a weighted mean $^{207}Pb/^{206}Pb$ ages of 1598 ± 9 Ma (Liu 2011). Therefore, emplacement of the Maping alkaline complex occurred during ca. 1.60 Ga.

Compared with the 1.64–1.62 Ga volcanic rocks in the Yanliao rift (aulacogen) and 1.63–1.62 Ga mafic dyke swarms in the Luxi area, the 1.64–1.60 Ga alkaline rocks in the southern NCC are small in volume and are only distributed in a narrow belt that is 180 km long along the middle segment of the southern margin of the NCC (Fig. 14.3). Their high alkaline and A-type granitic compositions indicate their formation in an extensional environment. The 1.64–1.60 Ga extension in the southern margin of the NCC might be related to an identified tectonic event represented by the angular unconformity between the 1.79–1.76 Ga volcanic rocks of Xiong'er Group and the Mesoproterozoic sedimentary rock (Yunmengshan Formation or Gaoshanhe Formation). The above inference is consistent with the spatial distribution of the 1.64–1.60 Ga alkaline rocks in the areas with exposure of the Xiong'er volcanic rocks in the southern NCC.

14.3 Mesoproterozoic Magmatism, Large Igneous Province, and Continental Breakup

14.3.1 The ca. 1.32 Ga Yanliao Large Igneous Province and Continental Breakup in the Northern Margin of the NCC

The Yanliao rift (aulacogen) in the northern NCC is characterized by deposition of thick marine clastic and carbonate platform sedimentary rocks from the late Paleoproterozoic to Meso-Neoproterozoic periods (Fig. 14.2). Large volumes of diabases occur as sill swarms within these sedimentary rocks and are especially common within the Xiamaling, Wumishan, Gaoyuzhuang, and Tieling formations (Fig. 14.2). No diabase sills have been identified from the Changlongshan and Jingeryu formations. Usually, three to five layers of diabse sills can be observed within the Xiamaling Formation from western Bejing to Chaoyang in the northern NCC (Fig. 14.5). The sills are several meters to several hundred meters thick and few kilometers to several tens of kilometers long. Due to difficulties in dating mafic-ultramafic rocks such as diabase, these sills were previously regarded as Late Paleozoic (Li and Li 2005), Triassic (BGMRLNP 1965, 1967; BGMRHBP 1969) or Jurassic (BGMRLNP 1969) in age. However, recent baddeleyite and zircon U–Pb/Pb–Pb dating results (Zhang et al. 2009, 2012c, 2016a; Li et al. 2009a; Wang et al. 2014a) on the diabase sills emplaced into the Xiamaling, Tieling, Wumishan, and Gaoyuzhuang formations indicate their simultaneous emplacement during the Mesoproterozoic period at ca. 1.32 Ga (Table 14.2).

The Yanliao diabase sills display typical diabasic texture with similar mineral compositions of pyroxene, plagioclase, magnetite, and hornblende. They are characterized by very similar petrological and geochemical compositions with low contents of SiO_2, high contents of TiO_2, Fe_2O_3T, and MgO and exhibit geochemical features of tholeiitic compositions and intraplate characteristics (Zhang et al. 2012c, 2016a; Wang et al. 2014b). Field investigation results show that the sill swarms are distributed in an area that is >600 km long

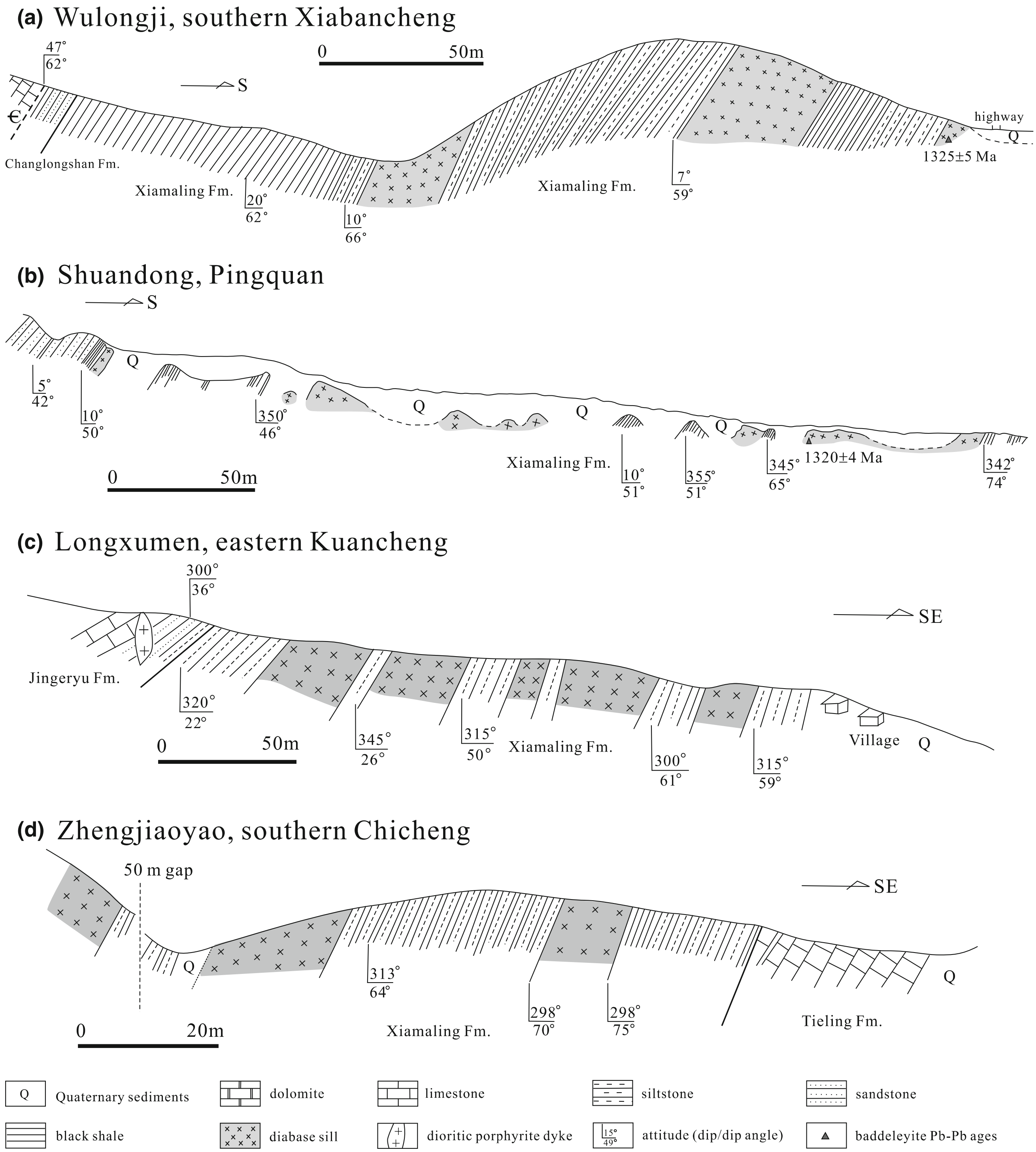

Fig. 14.5 Cross sections showing the diabase sills emplaced into the Xiamaling Formation in the Yanliao rift (aulacogen) in the northern NCC (modified after Zhang et al. 2009, 2012c)

and >200 km wide with areal extent >1.2 × 10^5 km^2 (Fig. 14.3). The cumulative thickness of the sills ranges from 50 m at the margins to >1800 m (Zhang et al. 2016a). Therefore, the diabase sill swarms in the Yanliao rift (aulacogen) constitute a Mid-Mesoproterozoic large igneous province in the northern NCC. If the newly identified ca. 1.32 Ga diabase dykes in Datong in northern Shanxi Province in the north-central NCC are considered together (Peng 2015), the areal extent of the Yanliao large igneous province is much larger 1.2 × 10^5 km^2. The Yanliao diabase sills are

Table 14.2 Summary of zircon and baddeleyite U–Pb ages of the *ca.* 1.32 Ga magmatic rocks in the NCC

Location/intrusion name	Longitude (E)	Latitude (N)	Rock type	Age (Ma)	Method	References
Kuancheng/sill within Xiamaling Fm.	118°21.4′	40°34.8′	Diabase	1320 ± 6	Baddeleyite TIMS	Li et al. (2009a)
Chaoyang/sill within Wumishan Fm.	120°18.4′	41°24.7′	Diabase	1314 ± 6	Zircon SHRIMP	Zhang et al. (2012c)
Chaoyang/sill within Wumishan Fm.	120°18.7′	41°23.7′	Diabase	1323 ± 11	Zircon LA-ICP-MS	Zhang et al. (2012c)
Chaoyang/sill within Wumishan Fm.	120°18.4′	41°24.7′	Diabase	1324 ± 5	Baddeleyite SIMS	Zhang et al. (2012c)
Chaoyang/sill within Tieling Fm.	120°14.2′	41°14.1′	Diabase	1316 ± 37	Baddeleyite SIMS	Zhang et al. (2012c)
Pingquan/sill within Xiamaling Fm.	118°45.5′	40°58.6′	Diabase	1320 ± 4	Baddeleyite SIMS	Zhang et al. (2012c)
Xiabancheng/sill within Xiamaling Fm.	118°08.0′	40°41.2′	Diabase	1325 ± 5	Baddeleyite SIMS	Zhang et al. (2012c)
Kazuoqi/sill within Wumishan Fm.	120°01′ 35.1″	41°06′ 26.9″	Diabase	1319 ± 4	Baddeleyite SIMS	Wang et al. (2014a)
Lingyuan/sill within Xiamaling Fm.	119°34′ 48.1″	41°15′ 31.5″	Diabase	1323 ± 5	Baddeleyite SIMS	Wang et al. (2014a)
Kazuoqi/sill within Wumishan Fm.	119°58′ 00.2″	41°09′ 26.9″	Diabase	1323 ± 5	Baddeleyite SIMS	Wang et al. (2014a)
Kazuoqi/sill within Wumishan Fm.	120°00′ 23.9″	41°05′ 26.5″	Diabase	1326 ± 4	Baddeleyite SIMS	Wang et al. (2014a)
Chaoyang/sill within Wumishan Fm.	120°18′ 19.2″	41°24′ 26.2″	Diabase	1326 ± 6	Baddeleyite SIMS	Wang et al. (2014a)
Kuancheng/sill within Xiamaling Fm.	118°18.6′	40°37.2′	Diabase	1315 ± 11	Baddeleyite SIMS	Zhang et al. (2016a)
Lingyuan/sill within Xiamaling Fm.	119°30.7′	41°13.3′	Diabase	1305 ± 11	Baddeleyite SIMS	Zhang et al. (2016a)
Chaoyang/sill within Gaoyuzhuang Fm.	120°31.2′	41°38.6′	Diabase	1327 ± 6	Baddeleyite SIMS	Zhang et al. (2016a)
Chaoyang/sill within Gaoyuzhuang Fm.	120°31.8′	41°39.8′	Diabase	1321 ± 4	Baddeleyite SIMS	Zhang et al. (2016a)
Lingyuan/sill within Xiamaling Fm.	119°31.9′	41°15.7′	Diabase	1318 ± 4	Baddeleyite SIMS	Zhang et al. (2016a)
Lingyuan/sill within Xiamaling Fm.	119°40.6′	41°02.5′	Diabase	1313 ± 6	Baddeleyite SIMS	Zhang et al. (2016a)
Yixian/sill within Gaoyuzhuang Fm.	121°11.4′	41°39.7′	Diabase	1330 ± 4	Baddeleyite SIMS	Zhang et al. (2016a)
Pingquan/sill within Tieling Fm.	118°42.2′	40°57.3′	Diabase	1324 ± 5	Baddeleyite SIMS	Zhang et al. (2016a)
Shangdu-Huade/granite pluton	113°46.9′	41°47.0′	Granite	1331 ± 11	Zircon LA-ICP-MS	Zhang et al. (2012c)
Shangdu-Huade/granite pluton	113°45.9′	41°44.6′	Granite	1313 ± 17	Zircon LA-ICP-MS	Zhang et al. (2012c)
Shangdu-Huade/granite pluton	113°46.9′	41°47.0′	Granite	1324 ± 14	Zircon LA-ICP-MS	Zhang et al. (2012c)
Shangdu-Huade/granite pluton	113°47.7′	41°48.6′	Granite	1330 ± 12	Zircon LA-ICP-MS	Zhang et al. (2012c)
Wulanhada/granite dyke	113°08′ 07.0″	41°39′ 45.5″	Granite	1318 ± 7	Zircon SHRIMP	Shi et al. (2012)
Wulanhada/granite dyke	113°08′ 07.0″	41°39′ 45.5″	Granite porphyry	1321 ± 15	Zircon SHRIMP	Shi et al. (2012)

characterized by similar Nd and Hf isotopic compositions with positive whole-rock $\varepsilon_{Nd}(t)$ values of 0.40–1.96 and zircon and baddeleyite $\varepsilon_{Hf}(t)$ values of 2.0–8.5 and were likely generated by partial melting of the depleted asthenosphere mantle coupled with slight crustal assimilation (Zhang et al. 2012c). Formation of the Yanliao large igneous province is related to continental rifting events in the northern NCC that have led to the final breakup of the Columbia (Nuna) supercontinent.

The Changlongshan and Jingeryu formations overlaid upon the Xiamaling Formation are only limitedly distributed in the western and southern margins of the Yanliao rift (aulacogen). In most other places, the Xiamaling Formation and sometimes the diabase sills within this formation were disconformably overlain by the Early Cambrian sedimentary rocks. Therefore, formation of the Yanliao large igneous province was accompanied by pre-magmatic uplift as indicated by the absence of sedimentation after Xiamaling Formation in most areas and erosion of some sills near surface. Since uplift of continental margins prior to breakup is typical and an expected process accompanying continental breakup (e.g., Esedo et al. 2012; Frizonde de Lamotte et al. 2015), the above pre-magmatic uplift provides solid evidence for linking the Yanliao large igneous province to breakup the northern margin of the NCC from the Columbia (Nuna) supercontinent.

Laurentia, Siberia, and Baltica are considered as the core of the Columbia supercontinent (Evans and Mitchell 2011). Extension-related magmatism at ca. 1.40–1.25 Ga is widespread around parts of Laurentia, Baltica, and Siberia and is ascribed to Columbia breakup (Evans 2013). Several continental mafic large igneous provinces during this period have been recognized in Laurentia, Baltica, Siberia, Congo, Kalahari, West Africa, North Australia, and East Antarctica cratons (Ernst et al. 2013; Ernst 2014 and references therein). Comparisons of the late Paleoproterozoic to Meso-Neoproterozoic sedimentary rocks and their tuff and K-bentonite beds in the Yanliao rift (aulacogen) in the northern NCC (Fig. 14.2) with the late Paleoproterozoic to Mesoproterozoic strata in other cratons suggest a close relation of the NCC with the Laurentia, Baltica, Siberia and India cratons. Paleomagnetic results on the NCC suggest connections of the NCC with Laurentia, Siberia, Baltica, India, and North Australian cratons in the Columbia (Nuna) supercontinents (Halls et al. 2000; Wu et al. 2005; Pei et al. 2006; Piper et al. 2011; Zhang et al. 2012b; Chen et al. 2013a; Xu et al. 2014). Therefore, the NCC has a close connection with the Siberia, Laurentia, Baltica, India, and North Australian cratons during the Mesoproterozoic period and was likely served as the core of the Columbia (Nuna) supercontinent. The ca. 1.32 Ga Yanliao large igneous province and the accompanying pre-magmatic uplift represent rifting to drifting transition and breakup of the northern NCC from the core of the Columbia (Nuna) supercontinent and initiation of the passive continental margin of the northern NCC.

Except for the large volumes of diabase sill swarms in the Yanliao rift (aulacogen), some Mid-Mesproterozoic granitic plutons and dykes have been identified from the east edge of the Zha'ertai-Bayan Obo-Huade rift zone in the northern NCC (Zhang et al. 2012c; Shi et al. 2012). They emplaced into the Bayan Obo Group (or Huade Group) that composed mainly of sedimentary rocks subjected to low-grade metamorphism. Zircon SHRIMP and LA-ICP-MS U–Pb on six samples yielded emplacement ages of ca. 1.32 Ga, similar to those of the Yanliao diabase sill swarms (Table 14.2). The ca. 1.32 Ga granites are characterized by high contents of SiO_2 (70–76 wt %) and alkaline ($Na_2O + K_2O$ = 6–9 wt%) and exhibit negative whole-rock $\varepsilon_{Nd}(t)$ values of −6.9 to −6.3 and zircon $\varepsilon_{Hf}(t)$ values of −15.9 to −3.6, indicating that they were generated mainly through partial melting of the ancient continental crust, probably induced by the upwelling of hot asthenosphere mantle during continent rifting processes (Zhang et al. 2012c). These granitic plutons and dykes, together with the Yanliao diabase sill swarms, constitute a typical bimodal magmatic association rifting events that are considered to have led to the final breakup of the Columbia supercontinent (Zhang et al. 2012c). However, the present day volume of the ca. 1.32 Ga granites is much smaller than that of the ca. 1.32 Ga diabase sill swarms in the northern NCC.

14.3.2 The 1.23–1.21 Ga Mafic Magmatism in the Eastern and Central NCC

Some 1.23–1.21 Ga mafic intrusions or dykes have been identified from the eastern and central NCC (Pei et al. 2013; Peng et al. 2013; Peng 2015; Wang et al. 2015b; Fig. 14.3). In contrast to the ca. 1.32 Ga mafic rocks occur mainly as sills within the Mesoproterozoic sedimentary rocks, the 1.23–1.21 Ga mafic rocks in the NCC occur mainly as intrusions or dykes in the Archean-Paleoproterozoic metamorphic basement rocks. The 1.23–1.21 Ga magmatic rocks in the NCC include the Tonghua diabase dykes with zircon U–Pb upper intercept age of 1244 ± 28 Ma in the northeastern NCC (Pei et al. 2013), the Yishui gabbro intrusions with zircon $^{207}Pb/^{206}Pb$ age of 1209 ± 6 Ma (Peng et al. 2013), the Jianping mafic dykes with zircon $^{207}Pb/^{206}Pb$ ages of 1231 ± 16 to 1229 ± 10 Ma (Wang et al. 2015b), the Qinglong mafic dykes with zircon $^{207}Pb/^{206}Pb$ age of 1208 ± 24 Ma (Wang et al. 2015b), the Qingyuan mafic dykes with zircon $^{207}Pb/^{206}Pb$ age of 1226 ± 11 Ma (Wang et al. 2015b) and the Licheng mafic dykes with baddeleyite $^{207}Pb/^{206}Pb$ age of 1226 ± 11 Ma (Peng 2015).

The 1.23–1.21 Ga mafic rocks in the eastern and central NCC are composed of gabbro and diabase with a major mineral assemblage of plagioclase, clinopyroxene, and hornblende, and minor orthopyroxene, alkaline feldspar, biotite, quartz, and magnetite (Pei et al. 2013; Peng et al. 2013; Peng 2015; Wang et al. 2015b). They are characterized by low contents of SiO_2 and high contents of Fe_2O_3T and TiO_2 and classified as subalkaline or alkaline basalts in major and trace element classification diagrams and were considered to be derived from partial melting of a depleted asthenospheric mantle or a subduction-modified enriched lithospheric mantle (Pei et al. 2013; Peng et al. 2013; Wang et al. 2015b). Some researchers suggest that 1.23–1.21 Ga mafic magmatism in the NCC is related to a prolonged superplume that led to the final breakup of the Columbia supercontinent (Peng et al. 2013). However, their emplacement ages are younger than those of the Mackenzie and Bear River radiating dyke swarms in the Laurentia (ca. 1.27 Ga, LeCheminant and Heaman 1989; Schwab et al. 2004) that are considered to be related to a mantle plume leading to final of breakup of the Columbia supercontinent (e.g., Zhao et al. 2004a, b; Evans and Mitchell 2011; Ernst 2014). Moreover, evidence for assembly of Rodinia supercontinent as indicated by worldwide orogenic events is very clear after ca. 1.30 Ga (e.g., Li et al. 2008; Ernst et al. 2008; Aitken et al. 2015). Some mafic–ultramafic magmatic events of extensional origin after ca. 1.25 Ga may be related to back arc extension during assembly of the Rodinia supercontinent (Ernst et al. 2008). Recent researches on the 0.92–0.89 Ga mafic sill swarms and Neoproterozoic sedimentary rocks suggested that the southeastern margin of the NCC was probably connected to some other continents that are characterized by strong Grenville magmatism in the Rodinia supercontinent (e.g., Peng et al. 2011b; Zhang et al. 2016b). Therefore, the 1.23–1.21 Ga mafic magmatism represents another intense extension event in the eastern NCC, which may be related to a far-field continental back arc extension during subduction-assembly of the Rodinia supercontinent in its eastern side.

14.3.3 Mesoproterozoic Tuff Layers and K-Bentonite Beds in the Northern NCC

Thin tuff layers and K-bentonite beds are produced by explosive felsic-intermediate volcanism. Since the volcanic components in these rocks can be transported for hundreds of kilometers in the air before deposition in marine basins, they are very useful for stratigraphic correction and paleogeographic reconstruction. In recent years, several tuff layers, including the 1.38–1.37 Ga K-bentonite beds within the Xiamaling Formation (Gao et al. 2007, 2008b; Su et al. 2008, 2010), the 1.44 Ga K-bentonite beds within the Tieling Formation (Su et al. 2010; Li et al. 2014a), the 1.49 Ga K-bentonite beds within the Wumishan Formation (Li et al. 2014a), and the 1.58–1.56 Ga tuff beds within the Gaoyuzhuang Formation (Li et al. 2010a; Tian et al. 2015; Fig. 14.6c and Table 14.3), have been identified from the sedimentary rocks in the Yanliao rift (aulacogen) in the northern NCC (Fig. 14.2). The K-bentonite beds within the Xiamaling, Tieling, and Wumishan formations are usually 1–10 cm thick and can be traced in a large areas in western Beijing, Zhangjiakou, Jixian, Chengde, and Pingquan (Gao et al. 2007, 2008b; Su et al. 2008, 2010; Li et al. 2014a). The tuff layer within the Gaoyuzhuang Formations in the Yanqing area in northern Beijing is about 1.4 m thick (Fig. 14.6a, b) and that in the Jixian area is about 15 cm thick (Tian et al. 2015). The above thickness variations suggest that the volcanic materials came from some areas north to the Yanliao rift (aulacogen) in the northern NCC.

Although tuff layers and K-bentonite beds of 1.58–1.56 to 1.38–1.37 Ga are common in the Yanliao rift (aulacogen) in the northern NCC, no contemporaneous volcanism has been identified in the NCC yet. Therefore, the source areas for these rocks may locate in some other continents near neighbors to the northern margin of the NCC during the Mesoproterozoic period. Explosive felsic-intermediate volcanisms of 1.58–1.56 Ga, 1.49 Ga, 1.44 Ga, and 1.38–1.37 Ga are especially common in Laurentia, Siberia, Baltica, and North and South Australian cratons (Sweet et al. 1999; Ernst et al. 2008, 2013; Ernst 2014 and references therein), which may serve as the sources for the K-bentonite and thin tuff beds in the northern NCC. The above fact supports our paleogeographic reconstruction that the NCC has a close connection with the Siberia, Laurentia, Baltica, India, and North Australian cratons during the Mesoproterozoic period and was likely served as the core of the Columbia (Nuna) supercontinent (Zhang et al. 2016a).

14.4 Neoproterozoic Magmatism, Large Igneous Province, and Continental Breakup

14.4.1 The 0.92–0.89 Ga Large Igneous Province and Continental Breakup in the Southeastern Margin of the NCC

In recent years, some Neoproterozoic mafic magmatism was recognized from the central and eastern NCC (Sino-Korean Craton) (Fig. 14.3; Liu et al. 2006; Gao et al. 2009; Peng et al. 2011a, b; Wang et al. 2012b; Zhang et al. 2016b). These include the Xu-Huai diabase sill swarms in the southeastern NCC (Liu et al. 2006; Gao et al. 2009; Wang et al. 2012b), the Dalian diabase sill swarms in the Liaodong

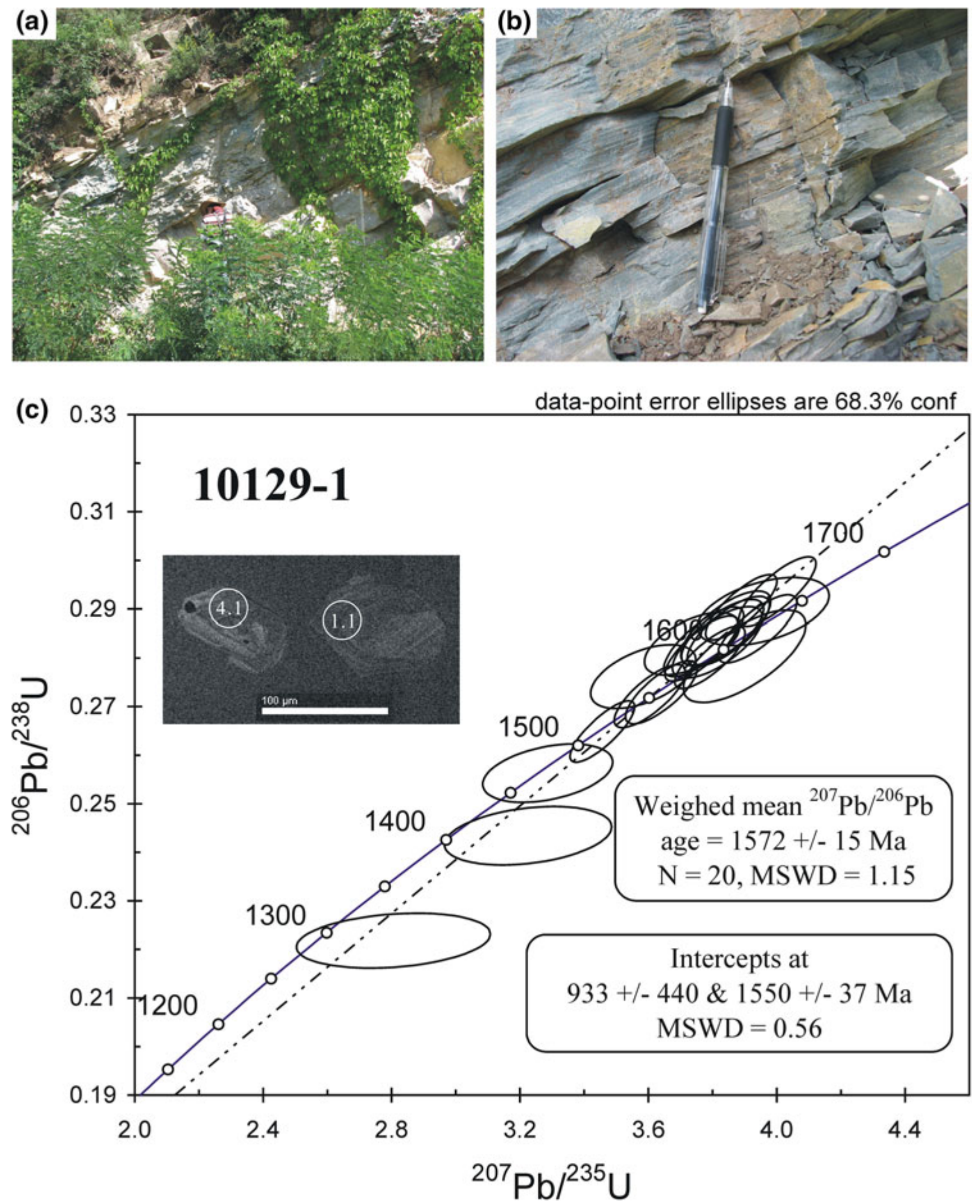

Fig. 14.6 Field photos of tuff layers within the Guangyuzhuang Formation in northern Beijing (**a**, **b**) and its zircon U–Pb concordia diagram and CL images (**c**)

Peninsula (Zhang et al. 2016b), the Sariwon diabase sill swarms in North Korea (2011b) and the Dashigou mafic dykes in the central NCC (Peng et al. 2011a). If corrected the effect of the sinistral strike-slip motion of the Tan-Lu fault zone during the Triassic–Jurassic period, they are distributed in an area that is ca. 700 km long and 100–200 km wide and may constitute an early Neoproterozoic large igneous province along the southeastern margin of the NCC (Fig. 14.7).

The Sariwon diabase sill swarms in North Korea are located in the Pyongnam basin in the southern part of the Nangrim massif (Fig. 14.3). They occur as sills intruded the Songwon System and the Archean-Paleoproterozoic metamorphic basement rocks and are overlain by the upper Neoproterozoic Kuhyon System and the Phanerozoic strata (Peng et al. 2011b). The sills are several meters to 150 m thick and several kilometers to over 10 km long (Peng et al. 2011b). Baddeleyite SIMS dating on a diabase sample yielded a weighed mean $^{207}Pb/^{206}Pb$ age of 899 ± 7 Ma, indicating its emplacement during the early Neoproterozoic at ca. 0.90 Ga (Peng et al. 2011b).

Diabase swarms are very common in the Liaodong Peninsula in eastern NCC and occur mainly as sills within the Neoproterozoic Yongning, Qiaotou, Changlingzi, Nanguanling, Ganjingzi, Yingchengzi, Cuijiatun, and Xingmincun formations. The diabase sills are usually several meters to several hundred meters thick and several hundred meters to over ten kilometers long (Zhang et al. 2016b). They were previously considered as Late Triassic based on zircon U–Pb dating (Yang et al. 2007; Liu et al. 2013). However, our recent zircon U–Pb and baddeleyite Pb–Pb results on five

Table 14.3 SHRIMP U–Pb dating results of zircons from a tuff layer within the Gaoyuzhuang Formation

Grain spot	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	Th/U	$^{204}Pb/^{206}Pb$	$^{207}Pb^*/^{206}Pb^*$	±1σ (%)	$^{207}Pb^*/^{235}U$	±1σ (%)	$^{206}Pb^*/^{238}U$	±1σ (%)	$^{207}Pb^*/^{206}Pb^*$ Age (Ma)	±1σ	$^{207}Pb^*/^{235}U$ Age (Ma)	±1σ	$^{206}Pb^*/^{238}U$ Age (Ma)	±1σ
Sample 10129-1 (collected from Xiamalugou village, Yanqing, northern Beijing, GSP position: E116°12.88′; N40°44.28′)																	
1.1	0.06	140	107	0.79	0.00003	0.0982	1.2	3.791	1.9	0.2801	1.5	1590	22	1591	15	1592	21
2.1	0.00	135	100	0.77	0.00000	0.0968	1.3	3.641	2.0	0.2729	1.6	1562	24	1559	16	1556	22
3.1	0.15	157	165	1.09	0.00008	0.0958	2.2	3.735	2.6	0.2828	1.5	1543	40	1579	21	1606	21
4.1	0.13	117	102	0.90	0.00007	0.0969	1.2	3.764	2.0	0.2819	1.6	1565	23	1585	16	1601	22
5.1	0.11	73	72	1.03	0.00006	0.0974	1.7	3.840	2.4	0.2861	1.7	1574	31	1601	19	1622	25
6.1	0.33	86	71	0.85	0.00018	0.1009	2.3	3.898	3.2	0.2802	2.2	1641	43	1613	26	1592	31
7.1	0.00	105	98	0.96	0.00000	0.0961	1.3	3.605	2.0	0.2722	1.6	1549	24	1551	16	1552	22
8.1	4.37	138	157	1.17	0.00242	0.0960	5.1	3.207	5.3	0.2422	1.7	1548	95	1459	41	1398	21
9.1	0.00	149	107	0.74	0.00000	0.0946	1.1	3.457	1.9	0.2649	1.6	1521	21	1517	15	1515	21
10.1	0.00	133	80	0.62	0.00000	0.0521	3.8	0.323	4.2	0.0450	1.8	289	86	284	10	284	5
11.1	0.28	108	90	0.87	0.00016	0.0974	1.5	3.830	2.2	0.2851	1.6	1576	29	1599	18	1617	22
12.1	2.15	134	111	0.85	0.00119	0.0930	3.8	3.278	4.1	0.2557	1.6	1487	71	1476	32	1468	20
13.1	1.23	125	124	1.03	0.00068	0.0941	2.6	3.579	3.0	0.2758	1.6	1510	49	1545	24	1570	22
14.1	0.00	102	76	0.77	0.00000	0.0999	1.3	3.940	2.1	0.2860	1.6	1623	24	1622	17	1621	23
15.1	0.14	108	78	0.74	0.00008	0.0978	1.4	3.849	2.2	0.2854	1.6	1583	27	1603	18	1619	24
16.1	0.00	81	52	0.67	0.00000	0.0966	1.4	3.773	2.2	0.2833	1.7	1559	27	1587	17	1608	24
17.1	0.14	78	57	0.75	0.00008	0.0977	1.7	3.814	2.4	0.2831	1.7	1581	32	1596	20	1607	24
18.1	5.66	159	217	1.41	0.00314	0.0917	6.9	2.786	7.1	0.2205	1.7	1460	131	1352	53	1284	20
19.1	0.06	137	115	0.87	0.00003	0.0989	1.2	4.002	2.0	0.2936	1.6	1603	22	1635	16	1659	23
20.1	0.96	119	91	0.79	0.00053	0.0991	3.0	3.953	3.4	0.2892	1.6	1608	57	1625	28	1637	23
21.1	0.00	142	101	0.73	0.00000	0.0971	1.1	3.889	1.9	0.2904	1.5	1570	21	1612	15	1644	22

Errors are 1σ; Pb_c and Pb* indicate the common and radiogenic portions, respectively; Common Pb corrected using measured ^{204}Pb

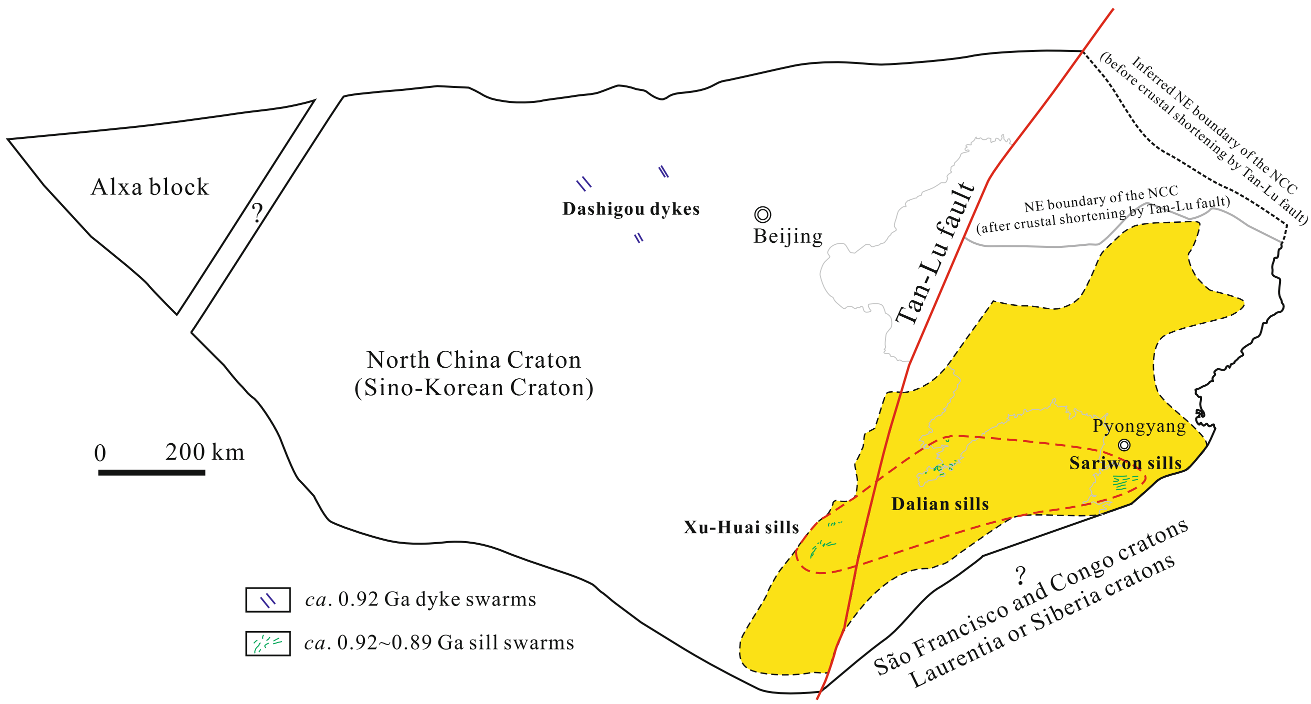

Fig. 14.7 A reconstruction map showing distribution of the early Neoproterozoic mafic sill (dyke) swarms in the NCC (Sino-Korean Craton) during the early Neoproterozoic period (after Zhang et al. 2016b). The southeastern and northeastern boundaries of the NCC are reconstructed by considering the sinistral strike-slip motion of the Tan-Lu fault zone during the Triassic–Jurassic period and possibly crustal shortening in northeastern NCC induced by Tan-Lu fault. *Yellow-shaded area* shows distribution of the early Neoproterozoic sedimentary rocks in the southeastern NCC. *Red dashed line* shows the boundary of the 0.92–0.89 Ga large igneous province inferred by diabase sill swarms

samples emplaced into the Qiaotou, Cuijiatun, and Xingmincun formations indicate their emplacement during the early Neoproterozoic at ca. 0.92–0.89 Ga (Zhang et al. 2016b).

Diabases in Xu-Huai area in the southeastern NCC occur mainly as sills emplaced into the Neoproterozoic Xinxing, Jushan, Jiayuan, Zhaoyu, Niyuan, Jiudingshan, Zhangqü, Shijia, Wangshan, and Jinshanzhai formations (BGMRAHP 1977; BGMRJSP 1978). They are usually several meters to several hundred meters thick and few kilometers to several tens of kilometers long. Zircon SHRIMP and LA-ICP-MS U–Pb dating by several groups yielded weighted mean $^{206}Pb/^{238}U$ ages of 933 ± 14 to 890 ± 14 Ma (Liu et al. 2006; Gao et al. 2009; Wang et al. 2012b), indicating their emplacement during ca. 0.93–0.90 Ga.

Except for the diabase sill swarms in the southeastern and eastern NCC, some early Neoproterozoic mafic dykes (Dashigou dyke swarm) have been identified from the central part of the NCC (Peng et al. 2011a). They are generally NW–NNW in strike and are typically 10–50 m (up to ~100 m) wide and up to 10–20 km long (Peng et al. 2011a). Baddeleyite TIMS U–Pb dating on three mafic dyke samples from Dashigou, Yangjiaogou, and Taohuagou yielded weighed mean $^{207}Pb/^{206}Pb$ ages of 926 ± 2 to 922 ± 3 Ma, indicating their emplacement during ca. 0.92 Ga (Peng et al. 2011a).

Because the Xingmincun Formation in the topmost part of the Neoproterozoic strata in the Liaodong Peninsula and Jinshanzhai and Wangshan Formations in the topmost part of the Neoproterozoic strata in the Xu-Huai area were intruded by the 0.92–0.89 Ga diabase sills, sedimentation of the Neoproterozoic strata had ended prior to ca. 0.92–0.89 Ga and the southeastern and eastern NCC has undergone significant uplift prior to ca. 0.92–0.89 Ga. Therefore, formation of the 0.92–0.89 Ga large igneous province was accompanied by pre-magmatic uplift (Zhang et al. 2016b).

The ca. 0.92–0.89 Ga mafic rocks in the NCC are characterized by similar mineral assemble of clinopyroxene, plagioclase, and Fe–Ti oxides and belong to the tholeiitic series (Peng et al. 2011a, b; Wang et al. 2012b; Zhang et al. 2016b). Most of them fall into the field of within-plate basalt on the Zr/Y versus Zr and Ti–Zr–Y discrimination diagrams and exhibit an evolution trend from within-plate basalt to mid-ocean ridge basalt on the Zr/Y versus Zr discrimination diagram (Wang et al. 2012b; Zhang et al. 2016b). They are characterized by slightly negative to positive $\varepsilon_{Nd}(t)$ values of −1.9 to 4.5 and young Nd isotopic T_{DM} model ages of 1.9–1.1 Ga (Peng et al. 2011a, b; recalculated data from Yang et al. 2007; Liu et al. 2013) and were likely generated by partial melting of the depleted asthenosphere mantle coupled with differential crustal assimilation in a continental rifting setting that have led to breakup of southeastern NCC from some other continents in the Rodinia supercontinent. Breakup of the NCC from the Rodinia supercontinent at around 0.92–0.89 Ga is also supported by pre-magmatic regional uplift of the southeastern NCC prior to ca. 0.92–0.89 Ga and evolution trend of the Dalian and Xu-Huai diabase sills from within-plate basalt to mid-ocean ridge basalt on the Zr/Y versus Zr discrimination diagram (Zhang et al. 2016b).

14.4.2 The ca. 0.83 Ga Mafic Magmatism in the Southern NCC

The ca. 0.83 Ga mafic magmatism (Zenghekou sill swarms; Peng 2015) occurs mainly as sills emplaced into the Meso-Neoproterozoic Guandaokou and Luchuan groups (Fig. 14.3). It is distributed in a NWW-trending zone that is 50 km long and 1 km to 8 km wide from Lushi to Luanchuan counties along the southern margin of the NCC (GSIHNP 2002). It consists mainly of meta-gabbro with a main mineral assemblage of pyroxene (40–60 vol.%, altered to ouralite) and plagioclase (30–50 vol.%); other minerals include biotite, chlorite, epidote, apatite, magnetite, titanite, and zircon. Zircon U–Pb dating on three gabbros yielded weighted mean $^{206}Pb/^{238}U$ ages of 830 ± 6, 830 ± 7, and 826 ± 34 Ma, respectively (Wang et al. 2011), indicating their emplacement during the Mid-Neoproterozoic (Cryogenian) at ca. 0.83 Ga. They are characterized by high contents of TiO_2 and LREE, with negative Zr-Hf and Ti anomalies but without Nb-Ta anomalies and exhibit geochemical features of within-plate alkaline basalt (Wang et al. 2011). They were considered to be generated in a within-plate extensional setting by the low-degree partial melting of the carbonated asthenospheric mantle and interacted with the subduction-metasomatized lithospheric mantle (Wang et al. 2011).

Although the Zenghekou sill swarms were considered as part of the 925–900 Ma Sariwon-Dalian-Xuhuai mafic sill swarms by some researchers (Peng 2015), their ages of ca. 830 Ma (Wang et al. 2011) are younger than those of the Sariwon-Dalian-Xuhuai mafic sill province (925–890 Ma; Liu et al. 2006; Gao et al. 2009; Peng et al. 2011a, b; Wang et al. 2012b; Zhang et al. 2016b). Moreover, their alkaline basaltic compositions (Wang et al. 2011) are very different from the subalkaline tholeiitic compositions of the Sariwon-Dalian-Xuhuai mafic sills (Peng et al. 2011a, b; Wang et al. 2012b; Zhang et al. 2016b). Therefore, the ca. 0.83 Ga mafic sills in the southern NCC might represent a Mid-Neoproterozoic (Cryogenian) extension event in the southern margin of the NCC and are not belong to the Sariwon-Dalian-Xuhuai mafic sill province in the southeastern part of the NCC.

14.4.3 The 0.82–0.80 Ga Magmatism in the Langshan Area

The 0.82–0.80 Ga magmatism in the Langshan area in the eastern margin of the Alax block occurs as meta-felsic volcanic or volcanoclastic layers within the Langshan Group. The volcanic layers are several meters to 20 m thick and several kilometers long (Peng et al. 2010). The Langshan Group in the Alax block is considered as Mesoproterozoic in age and with the Zha'ertai Group in the northwestern margin of the NCC (e.g., BGMRNMAR 1991). However, zircon SHRIMP U–Pb dating on two quartz keratophyre samples from the volcanic layers within the Langshan Group yielded weighted mean $^{206}Pb/^{238}U$ ages of 817 ± 5 and 805 ± 5 Ma, respectively (Peng et al. 2010). Zircon LA-ICP-MS U–Pb dating of a meta-volcanoclastic sample collected from another layer yielded a weighted mean $^{206}Pb/^{238}U$ age of 804 ± 4 Ma (Hu et al. 2014). These new geochronological results clearly indicate that the Langshan Group in the Alax block is Neoproterozoic in age, not Mesoproterozic as previously regarded (e.g., BGMRNMAR 1991).

Although the Alax block is traditionally considered as part of the NCC (e.g., BGMRNMAR 1991), many recent results show that evolution of the Alxa block is very different from the NCC, especially during the Neoproterozoic period (e.g., Geng et al. 2002; Dan et al. 2014) and amalgamation of North China Craton with the Alxa block may occur during latest Early Paleozoic to Late Paleozoic (e.g., Li et al. 2012; Zhang et al. 2012a, 2013a; Yuan and Yang 2015a, b). Intensive Neoproterozoic magmatism in the Alax block (e.g., Geng et al. 2002; Geng and Zhou 2011; Dan et al. 2014), different ages of the Langshan Group in the Alax block, and Zha'ertai Group in the NCC (Peng et al. 2010; Hu et al. 2014) and different detrital zircon age patterns of sedimentary rocks from the Alxa block and the western NCC suggest that the Alxa block may share similar tectonic affinity to the Tarim or South China (Yangtze) cratons, which is very similar to that of the Precambrian microcontinents in the Central Asian Orogenic Belt (e.g., Wang et al. 2001; Zhao et al. 2006; Demoux et al. 2009; Levashova et al. 2010, 2011; Rojas-Agramonte et al. 2011; Han et al. 2011; Kröner et al. 2011, 2014) and the Bainaimiao arc terrain in the northern margin of the North China block (Zhang et al. 2014). Therefore, the 0.82–0.80 Ga magmatism in the Langshan area should be excluded in discussing the evolution of the NCC.

14.5 Late Paleoproterozoic to Neoproterozoic Mineralization and Ore Deposits in the NCC

14.5.1 Damiao Fe–Ti–P Ore Deposit

The Damiao Fe–Ti–P ore deposit is hosted in the 1.74–1.70 Ga Damiao massif-type anorthosite complex in the northern margin of the NCC. It has been mined since the 1960s at an annual production of 2 million tons of ores with an average grade of about 36 wt% Fe_2O_3t, 7.0 wt% TiO_2, 0.3 wt% V_2O_5, and 2.0 wt% P_2O_5 (Chen et al. 2013b). The Damiao massif-type anorthosite complex is the only one unique massif-type anorthosite in China with an exposure area of 120 km^2 (e.g., Xie 2005). The Damiao complex is composed of anorthosite (85 vol.%), norite (10 vol.%), mangerite (4 vol.%), and minor troctolite (<1 vol.%), accompanied by oxide-apatite gabbronorites, ferrodioritic, gabbroic, felsic dikes, and abundant Fe–Ti–(P) ores (Ye et al. 1996; Zhao et al. 2009; Chen et al. 2013b). Field relations indicate an emplacement sequence from anorthosite, norite to mangerite. Norite occurs as irregular veins or lenses, and fills fractures within the anorthosite and displays sharp boundaries with the anorthosite. Anorthosite xenoliths widely enveloped within the norite dykes (Li et al. 2014b). Fe–Ti–(P) ore bodies occur as irregular lenses, veins or pods crosscutting the anorthosite (Sun et al. 2009; Chen et al. 2013b; Li et al. 2014b; Fig. 14.8). Usually, Fe–Ti ores are spatially associated with Fe–Ti–P ores in the deposit (Chen et al. 2013b). Ore minerals consist mainly of vanadium–titanium magnetite, vanadium-bearing magnetite, ilmenite and apatite (Sun et al. 2009). Formation of the Damiao Fe–Ti–(P) ore deposit is considered as a result of accumulation and fractional crystallization of Fe–Ti oxides and apatite from late immiscible nelsonitic melts in the ferrodioritic parental magma formed under low-pressure condition during diapiric emplacement of the Damiao anorthosite complex (Chen et al. 2013b). Hydrothermal remobilization of

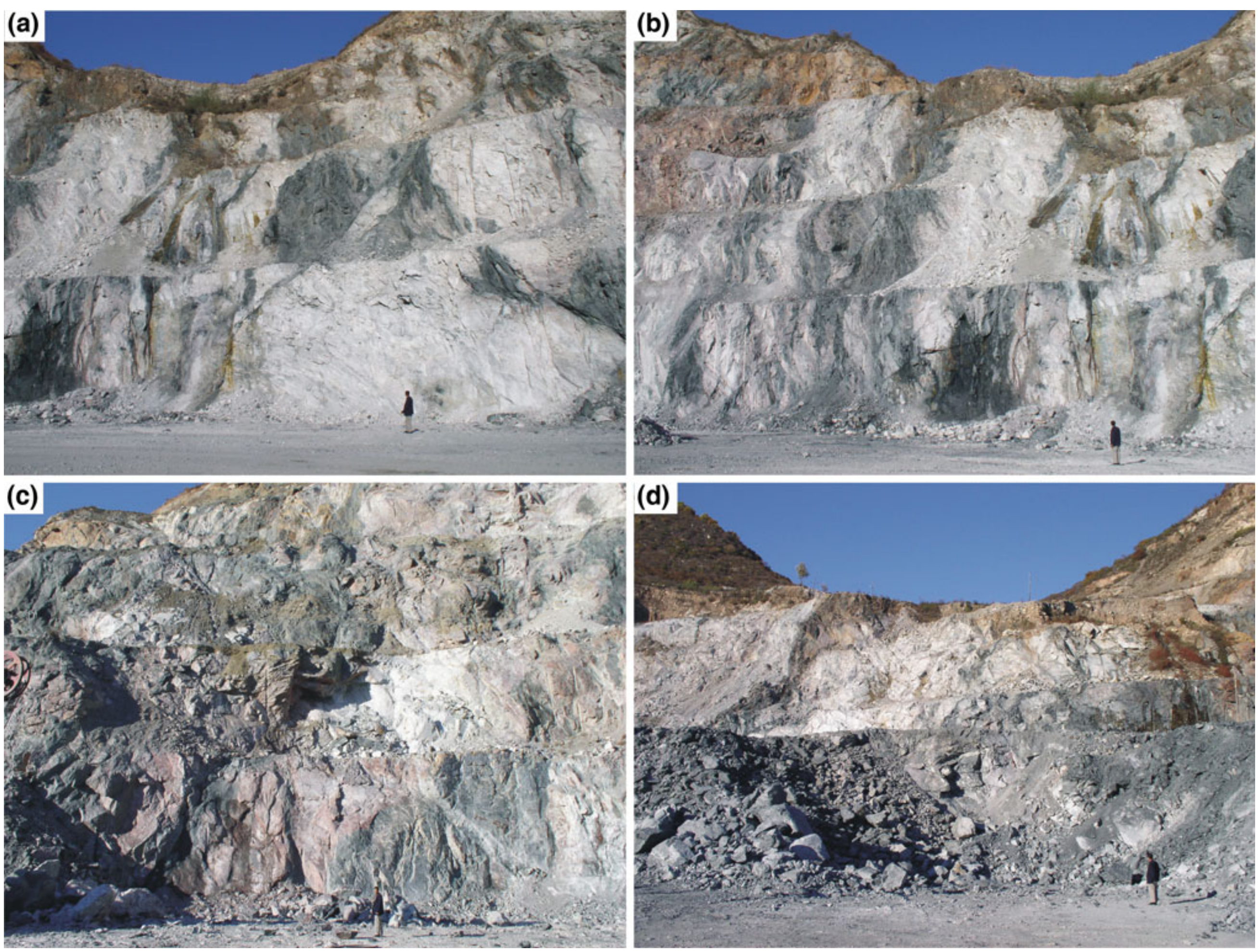

Fig. 14.8 Field photos of the open pit showing occurrences of ore bodies (*dark in color*) within the massive anorthosite (*white in color*) in the Damiao Fe–Ti–P ore deposit in the northern NCC. Post-mineralization faults are very common and cut and moved the ore bodies

Fe and Ti from the host altered anorthosite has also been suggested for the formation of the massive Fe and Fe–P ore-bodies (Li et al. 2014b).

14.5.2 Xuanlong-Type Iron Deposit

The Xuanlong-type iron deposit is one of the most important neritic facies sedimentary iron deposit in China. It is located in Xuanhua, Longguan, and Chicheng areas in northwestern Hebei Province and is near the western edge of the Yanliao rift (aulacogen). The iron deposit is distributed in an area that is 130 km from east to west and 150 km from north to south with a total of iron resources 300 Mt with an average grade of 40–45 % TFe (Liang et al. 2013; Zhang et al. 2014; Li et al. 2015a). Iron ores occur as layers within the Chuanlinggou Formation (Fig. 14.9). They generally include 1–4 layers of 0.5–3 m thick hematite ores and one layer of 0.35–0.4 thick siderite ore (Zhang et al. 2014). The ore-hosting Chuanlinggou Formation is 11–91 m thick and composed of shale, siltstone, and fine-grained sandstone. Primary ore minerals consist mainly of hematite, with minor siderite, magnetite, and limonite (Li and Zhu 2012; Li et al. 2015a). Textures of the ores are oolitic, kidney-shaped, and massive. Among them, the oolitic texture occurs in the upper part, and the kidney texture occurs in the lower part of the mineralized zone (Li et al. 2015a). Microbial activity probably played a key role during Fe accumulation in the near-shore environments (Du et al. 1992; Zhao 1994; Liu et al. 1995, 1997, 1999; Li and Zhu 2012). Geochemical and Fe–Nd isotopic results show that the iron sources of the Xuanlong-type iron deposit are mainly from detrital input and were mainly derived from iron-bearing formations in continents (Li and Zhu 2012). The Xuanlong-type iron deposit was deposited in a shallow marine environment with relatively low oxygen fugacity (Li and Zhu 2012).

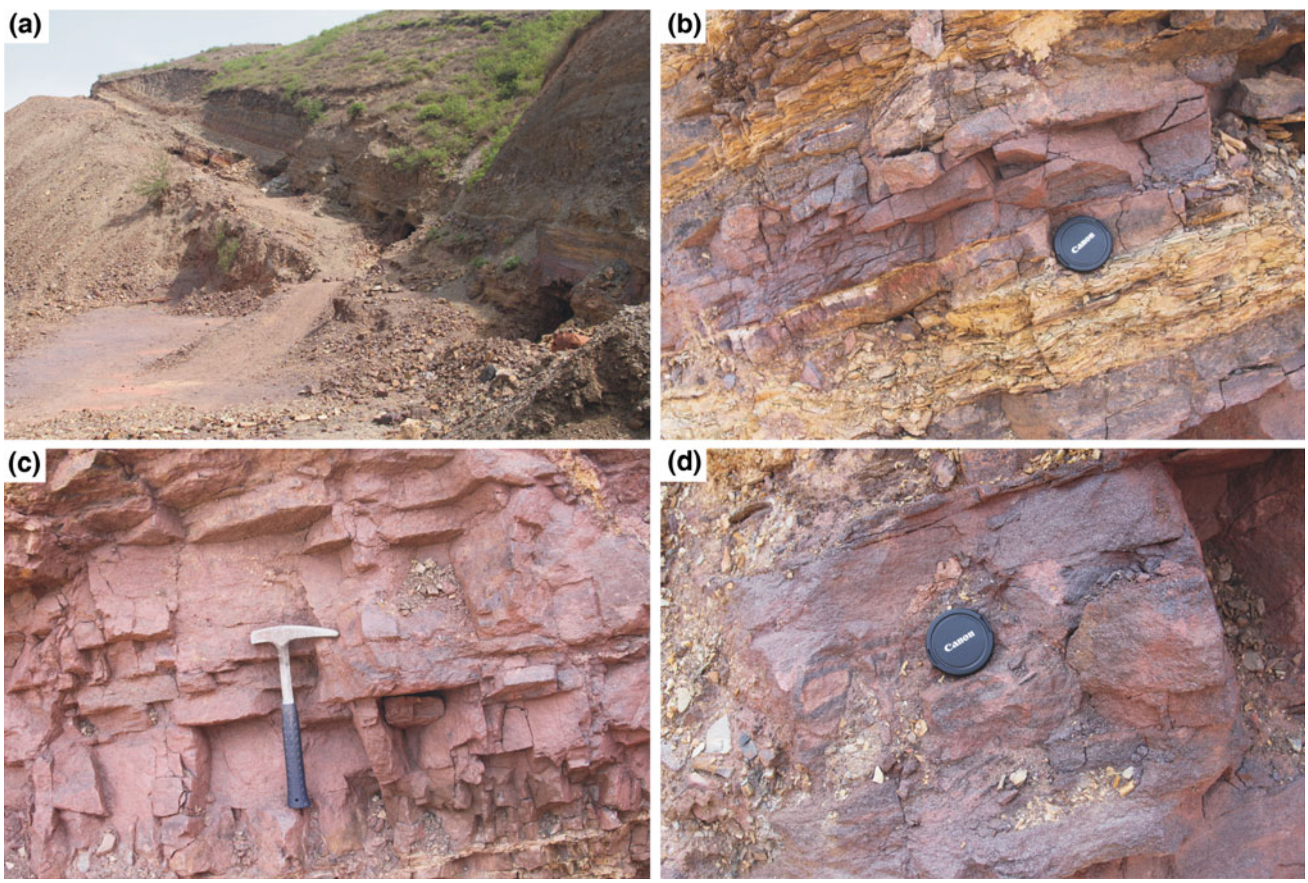

Fig. 14.9 Field photos of the Xuanlong-type iron deposit in the northern NCC. **a** Xuanlong-type iron layer within the Chuanlinggou Formation. **b** Iron layers interbedded with slate and siltstone of the Chuanlinggou Formation. **c** Massive iron ores of the Xuanlong-type iron deposit. **d** Oolitic iron ores of the Xuanlong-type iron deposit

14.5.3 Giant Bayan Obo Fe-REE-Nb Ore Deposit in the Northern Margin of the NCC

The Bayan Obo in the northern margin of the NCC is the world's largest light rare earth element (LREE) deposit and the largest niobium (Nb) and thorium (Th) deposit in China. It is hosted in the late Paleoproterozoic to Mesoproterozoic sediments of the Bayan Obo Group which are distributed in the Zhaertai-Bayan Obo-Huade rifting zone along the northern margin of the NCC (Fig. 14.3). The ore deposit is located in an east–west-trending syncline and is divided into the Main, East, and West ore bodies, which lies along an east–west zone more than 20 km long and 2–3 km wide. The REE and Nb ores occur throughout the Boluotu dolomite (or 'H8' dolomite marble), and Fe ores mainly in the Main, East, and West ore bodies. Although the ore-hosting dolomite marble in the Bayan Obo deposit was considered as sedimentary in origin by some researchers (e.g., Meng 1982; Zhang et al. 2008), most researchers believe that the main component of ore-hosting dolomite marble is magmatic in origin (e.g., Le Bas et al. 2007; Ling et al. 2013; Yang et al. 2011; Sun et al. 2013; Fan et al. 2014; Campbell et al. 2014; Smith et al. 2015; Zhu et al. 2015). Both field relations and geochemical evidence show a close petrogenetic link between the carbonatites and the Bayan Obo REE-Nb mineral deposit (e.g., Bai and Yuan 1985; Le Bas et al. 1992, 2007; Yuan et al. 1992; Wang et al. 2002; Yang et al. 2003, 2009, 2011; Fan et al. 2014; Campbell et al. 2014; Smith et al. 2015; Zhu et al. 2015). Most REE-Nb-rich carbonatites occur as sills emplaced into the slate, sandstone, and minor sedimentary dolomite and limestone of the Jianshan Formation of the Bayan Obo Group (Fig. 14.10); others occur as sills or dykes within the Dulahala Formation of the Bayan Obo Group and the latest Archean to Paleoproterozic metamorphic basement rocks (GSIIMAR 2003). The REE-Nb-rich carbonatites in the Bayan Obo deposit exhibit fine- to coarse-graded massive or banded structure and are composed mainly of dolomite and calcite (>80 vol.%); other minerals include apatite, monazite, barite, bastnäsite, magnetite, hematite, pyrite, fluorite, riebeckite, aegirine, phlogopite, allanite, etc.

Mineralization ages, tectonic setting, and genesis of the deposits have been the subject of much debate for many years (e.g., Ren et al. 1994; Liu et al. 2004; Wu 2008; Zhang et al. 2008). Although the ages of mineralization obtained from the REE-Nb deposit range from the Mesoproterozoic to Early Paleozoic, many results show that the Mid-Mesoproterozoic (1.4–1.2 Ga) is a very important period for REE-Nb mineralization (e.g., Nakai et al. 1989; Conrad and Mckee 1992; Wang et al. 1994; Zhang et al. 1994, 2001; Liu et al. 2004, 2005; Yang et al. 2011; Fan et al. 2014; Campbell et al. 2014; Smith et al. 2015; Zhu et al. 2015). Although the carbonatite rocks in the Bayan Obo REE-Nb-Fe ore deposit have not be precisely dated, their Sm–Nd isochron and zircon U–Pb ages are mainly around 1.4–1.2 Ga (e.g., Zhang et al. 2001; Fan et al. 2006, 2014; Le Bas 2006; Le Bas et al. 2007; Yang et al. 2011; Campbell et al. 2014), indicating their emplacement in the Mid-Mesoproterozoic, probably around 1.3 Ga, which is similar to the emplacement age of the Yanliao large igneous province and the Mid-Mesoproterozoic granite rocks in the Zha'ertai-Bayan Obo-Huade rift zones in the northern NCC. Since there is increasing evidence that many carbonatites are linked both spatially and temporally with large igneous provinces (Ernst and Bell 2009), the Bayan Obo carbonatites and REE-Nb mineralization are closely related to the Yanliao large igneous province leading to rifting to drifting transition and final breakup of the northern margin of the NCC from the Columbia (Nuna) supercontinent.

14.6 Discussion

14.6.1 Magmatism Leading to Continental Breakup or Rifting to Drifting Transition

As shown by the ca. 200 Ma Central Atlantic Magmatic Province related to breakup of the Pangea supercontinent and initial opening of the Central Atlantic Ocean (Fig. 14.11), breakup-related magmatism can occur as tholeiitic mafic dykes, sills or basalt lava flows across the neighboring continents (North America, South America, Africa, and Europe) and can be used as geological records for continental reconstruction (e.g., Deckart et al. 1997; Wilson 1997; Marzoli et al. 1999, 2011; Cirilli et al. 2009; Whalen et al. 2015). This magmatic province could be related to a mantle plume (e.g., Oyarzun et al. 1997; Wilson 1997) or non-plume continental rifting (e.g., McHone 2000; Hole 2015) leading to Pangea breakup. Since continental breakup is mainly developed from intracontinental rifting (e.g., Courtillot 1982; Frizonde de Lamotte et al. 2015), magmatism, and sedimentation in continental margin rift basins can be well correlated (e.g., Cirilli et al. 2009; Marzoli et al. 2011) and used for evidence for paleogeographic reconstruction. Moreover, the ca. 180 Ma Karoo-Ferrar large igneous province related to initial breakup of Gondwana is also characterized by tholeiitic mafic dykes, sills or basalt lava flows across the neighboring continents including southern Africa, the Dronning Maud Land sector of East Antarctica, the Transantarctic Mountains, southern Australia (Tasmania), and New Zealand (e.g., Encarnación et al. 1996; Elliot and Fleming 2000; Jourdan et al. 2008; Neumann et al. 2011; Svensen et al. 2012; Burgess et al. 2015).

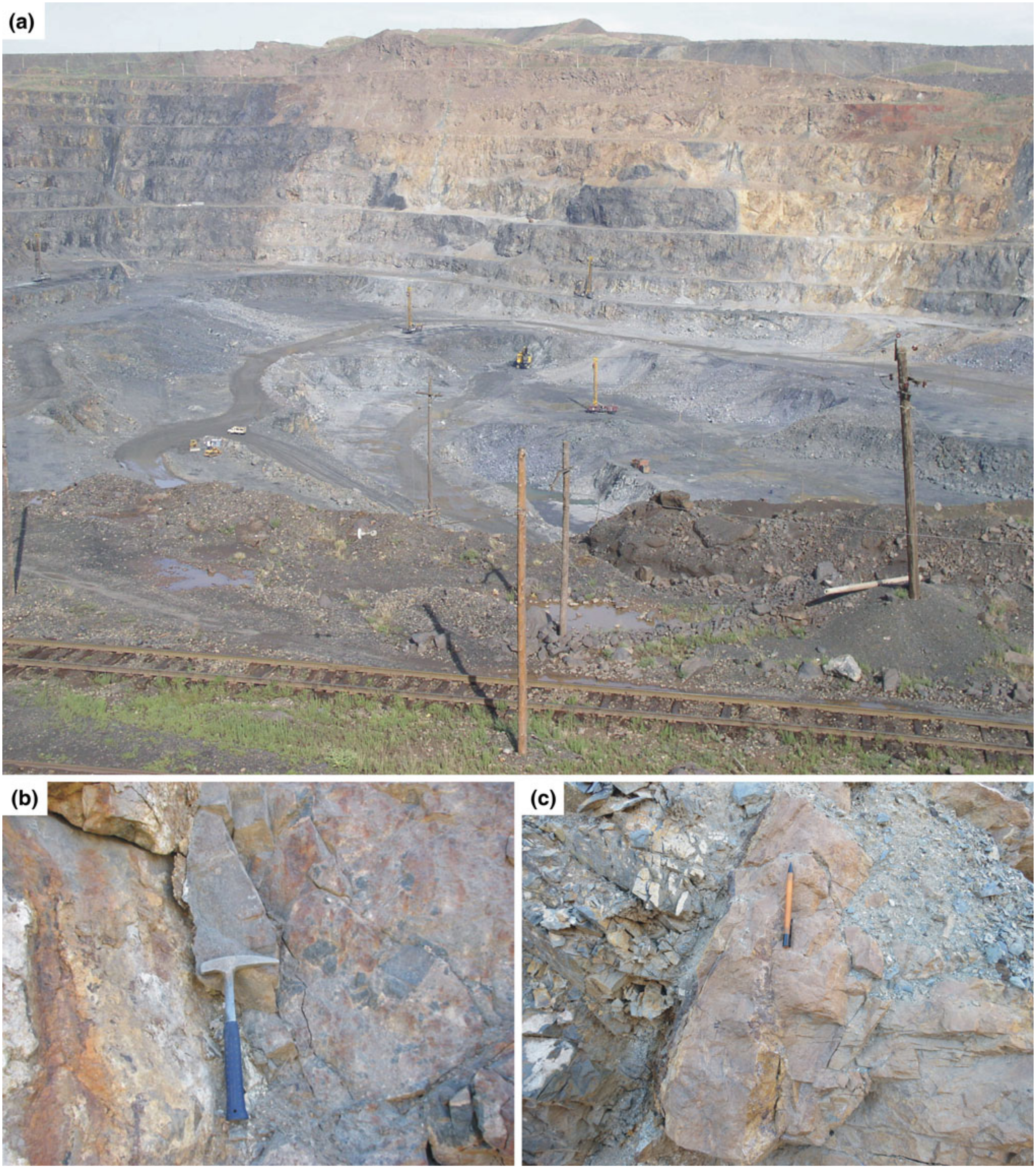

Fig. 14.10 Field photos of the giant Bayan Obo Fe-REE-Nb ore deposit in the northern margin of the NCC. **a** Open pit of the Bayan Obo deposit. **b** Black slate xenoliths of the Jianshan Formation of the Bayan Obo Group within the REE-Nb-rich carbonatites. **c** Intrusive contact between slate of Jianshan Formation and the REE-Nb-rich carbonatites

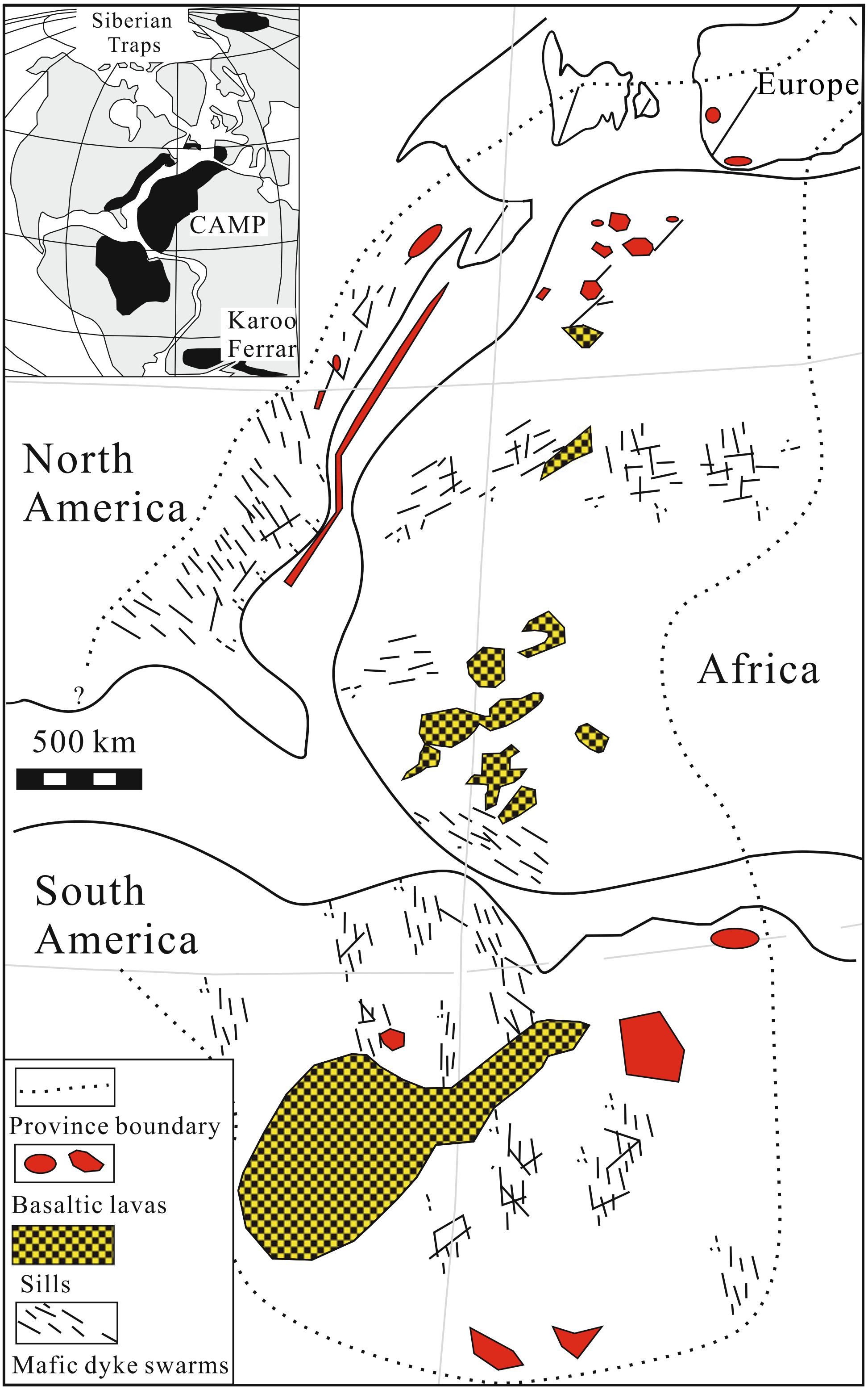

Fig. 14.11 The ca. 200 Ma Central Atlantic Magmatic Province (CAMP) associated with the breakup of Pangea (modified after Marzoli et al. 1999)

However, for the Precambrian continents suffered from long-term erosion and Phanerozoic crustal crustal growth and destruction, the above geological records (mafic dykes, sills or basalt lava flows) can only be partially preserved.

Mafic dyke swarms are especially useful for continental reconstruction, mainly because of their field geometry which can easily identified from geological maps or satellite images (e.g., Ernst and Baragar 1992; Ernst et al. 1995, 2001; Peng et al. 2008, 2011a; Peng 2010). Most of the giant (radiating, linear, and arcuate) mafic dyke swarms are considered as products of mantle plumes and their geochemistry is used to locate the plume centers (e.g., Ernst et al. 1995, 2001; Peng et al. 2008, 2011a; Peng 2010). For mafic sill swarms in continental margin rift basins, a main advantage for continental reconstruction is that both the mafic sills and their host rocks (including the volcanic layers, tuffs, K-bentonite beds, macroscopic fossils and microfossils, etc.) can be used for correlation. Moreover, unconformities or disconformities in the rift basin sequences and their contact relations with mafic sills will provide important information for uplift or subsidence during formation of the mafic sill swarms.

Recent results have revealed that all rifts undergo a phase of uplift before the lithosphere ruptures (Esedo et al. 2012; Frizonde de Lamotte et al. 2015). The signature of this uplift can be a sedimentary hiatus or a rapid change of the paleoenvironment from deep marine to subaerial (Campbell 2007; Frizonde de Lamotte et al. 2015). As talked above, both the ca. 1.32 and 0.92–0.89 Ga mafic large igneous provinces in the NCC were accompanied by pre-magmatic uplift and represent two breakup (rifting to drifting transition) events along its northern and southeastern margins, respectively. Therefore, large volumes of mafic sill swarms continental margins and accompanied pre-magmatic uplift in marginal rift basins can most likely be used as important indicators for continental breakup and reconstruction.

14.6.2 Complexity of the Mafic Dyke Swarms in the NCC

The late Paleoproterozoic to Meso-Neoproterozoic mafic dykes, which emplaced into the Archean-Paleoproterozoic metamorphic basement rocks and have not been affected by regional metamorphism, are very common in the NCC, especially in the central part of the NCC and the Luxi area in the eastern NCC (Fig. 14.3). The non-metamorphosed mafic dyke swarms in the central NCC (North China dyke swarm, Peng et al. 2007, 2008) were previously regarded mainly as ca. 1.78 or 1.80 Ga in age (mainly by zircon U–Pb dating results) and were considered to be related to a mantle plume located at the south-central part (Xiong'er) of the NCC leading to rifting and initial breakup of the NCC from the Columbia (Nuna) supercontinent (Zhai et al. 2000; Peng et al. 2006, 2007, 2008; Hou et al. 2008; Peng 2010; Hou 2012). However, recent baddeleyite U–Pb/Pb–Pb dating results show the North China dyke swarms are really very complex and were emplaced during several stages from late Paleoproterozoic to Neoproterozoic (Peng et al. 2011a; Peng 2015). Emplacement of the non-metamorphosed mafic dykes in the central NCC occurred at least during five stages at ca. 1.78, 1.73, 1.32, 1.23, and 0.92 Ga, respectively (Peng et al. 2011a; Peng 2015). The mafic dykes in the Luxi area in the eastern NCC were emplaced during 1.68 Ga and 1.63–1.62 Ga (Lu et al. 2008a; Xiang et al. 2012; Li et al. 2015b). Some mafic dykes in northern Beijing, eastern Hebei, western Liaoning, and central Jilin Province in the northern NCC were dated at two stages of 1.73 Ga and 1.23–1.21 Ga (Peng et al. 2012; Pei et al. 2013; 2015b). Most of the late Paleoproterozoic to Meso-Neoproterozoic mafic dykes are hosted in the Archean-Paleoproterozoic metamorphic basement rocks of the NCC and are characterized by similar field geometry with strikes mainly in NW–NNW, NEE or E–W (Peng 2015). Complexity of the late Paleoproterozoic to Meso-Neoproterozoic mafic dyke swarms in the NCC indicate that not all of them can be linked with mantle plumes or continental breakup events and some of dyke swarms are likely related to intracontinental extensions resulted either from the NCC itself or the neighboring continents connected with the NCC. Moreover, since the eastern-central NCC is characterized by intense structural deformation and lithospheric destruction (decratonization) from Mesozoic period (e.g., Zhu et al. 2011), intracontinental block rotations in eastern-central NCC during the Mesozoic period as revealed by paleomagnetic results (e.g., Sun et al. 1998; Zhu et al. 2002; Shi et al. 2004; Huang et al. 2007) should be considered when using geometry of the late Paleoproterozoic to Meso-Neoproterozoic mafic dykes for paleocontinental reconstructions.

14.6.3 Zircons and Precisely Dating of Mafic Rocks

Recent advance in dating of mafic rocks (e.g., Heaman and LeCheminant 1993; Söderlund et al. 2005; Heaman 2009; Li et al. 2009b, 2010b; Schmitt et al. 2010) makes it possible to obtain precise crystallization ages of Precambrian mafic dyke (sill) swarms for paleocontinental reconstruction (e.g., Ernst et al. 2013; Ernst 2014 and references therein). Although it is not easy to separate zircons from the silica-unsaturated rocks such as diabase and gabbro for high precise in situ U–Pb dating, it is still possible to obtain synmagmatic zircons from these rocks and yield reliable ages (e.g., Kamo et al. 1989; Wingate et al. 1998; Holm et al. 2006; Liu et al. 2006; Gao et al. 2009; Zhang et al. 2009, 2012c, 2016b; Wang et al. 2012b). However, in some

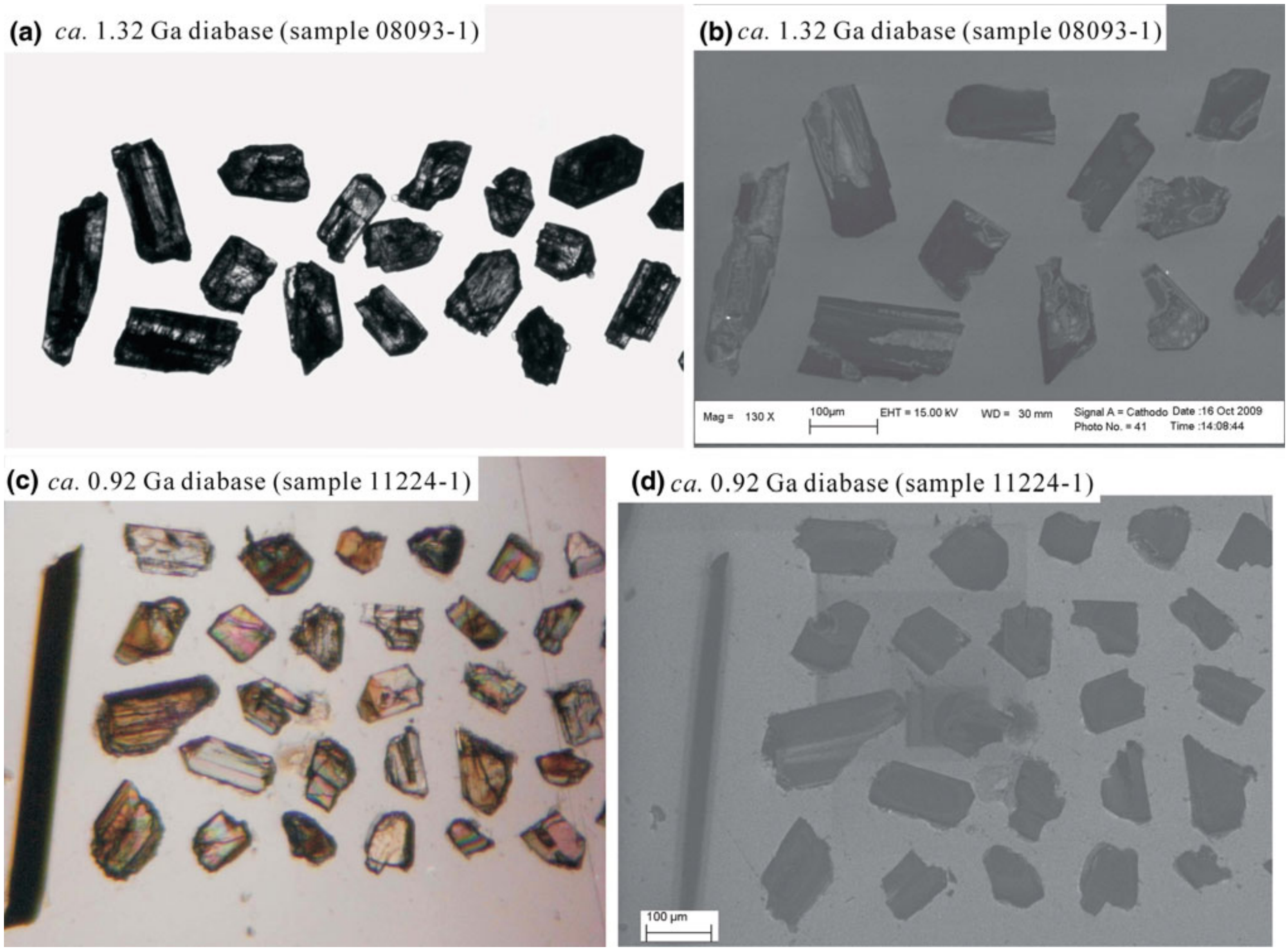

Fig. 14.12 Transmitted-light (**a**, **c**) and CL images (**b**, **d**) of synmagmatic zircons separated from diabase samples in the NCC

cases zircons in mafic rocks can be inherited from their country rocks or contaminated from other rocks during zircon separation processes and therefore yield unreliable ages. For example, the Laiwu mafic dykes in Luxi area were previously dated at 1.16–1.14 Ga by zircon SHRIMP U–Pb method (Hou et al. 2005); however, recent baddeleyite Pb–Pb dating yielded a emplacement of 1.68 Ga (Li et al. 2015b). Emplacement age of the Taishan mafic dykes was previously considered as 1.83 Ga by zircon SHRIMP U–Pb method (Hou et al. 2006); however, recent badeleyite TIMS and SIMS U–Pb dating results indicating their emplacement at 1.63–1.62 Ga (Lu et al. 2008a; Xiang et al. 2012). The Dalian sill swarms were previously considered as 0.21 Ga (Liu et al. 2012) or ca. 2.50 Ga (Liu et al. 2013) by zircon LA-ICP-MS U–Pb method; however, recent zircon LA-ICP-MS U–Pb and baddeleyite Pb–Pb dating results indicate their emplacement at 0.92–0.89 Ga (Zhang et al. 2016b). Different to synmagmatic zircons from intermediate-felsic rocks characterized by strong oscillatory zoning in cathodoluminescence (CL) images (e.g., Corfu et al. 2003; Wu and Zheng 2004), synmagmatic zircons separated from diabase samples are quite homogeneous euhedral to subhedral prisms or irregular broken fragments and exhibit weak oscillatory zoning in CL images and thin schlieren parallel to their long axis in transmitted-light images (e.g., Liu et al. 2006; Gao et al. 2009; Zhang et al. 2009, 2012c, 2016b; Wang et al. 2012; Fig. 14.12). Therefore, much attention should be paid to zircon CL images, morphology, and internal textures as well as field occurrences when using zircons to date the crystallization ages of mafic dyke (sill) swarms.

Compared with zircons, baddeleyites are particularly useful in confirming the emplacement age of mafic-ultramafic rock, as baddeleyites are not inherited (e.g., Heaman and LeCheminant 1993; Wingate 2001; Heaman 2009). Moreover, baddeleyite has the advantage of being apparently less susceptible than zircon to the effects of Pb loss and alteration (Wingate and Compston 2000). Therefore, baddeleyites (TIMS, SIMS, or LA-ICP-MS) have been widely used to date crystallization ages of mafic dyke (sill) swarms (e.g., Wingate 2001; Zhang et al. 2009, 2012c, 2016a, b; Peng et al. 2011a, b; Peng 2015; Ernst 2014 and references therein). In many cases, TIMS method can yield precise baddeleyite U–Pb/Pb–Pb ages to constrain the crystallization ages of mafic rocks, especially when the ages are concordant or nearly concordant (e.g., Söderlund et al. 2005; Li et al. 2009a; Peng et al. 2011a; Gumsley et al. 2015; Teixeira et al. 2015). Since baddeleyite can fully or partially transform into zircon even at low grade metamorphism and some baddeleyite can be surrounded by polycrystalline zircon (e.g., Davidson and van Breemen 1988; Rioux et al. 2010; Söderlund et al. 2008, 2013), CL and back-scattered electron (BSE) images are very important during U–Pb/Pb–Pb dating of baddeleyites. This is really important especially when the baddeleyite U–Pb data obtained by TIMS method are moderately to strongly discordant (e.g., El Bahat et al. 2013). In contrast to mechanisms causing discordance in primary zircon which is commonly attributed to Pb-loss, recrystallization, overgrowth or the presence of a xenocrystic component (e.g. Corfu et al. 2003; Mezger and Krogstad 1997; Söderlund et al. 2013), moderately to strongly discordant baddeleyite data obtained by TIMS U–Pb method are normally caused by mixing between two end members of an older igneous (baddeleyite) and a younger (polycrystalline zircon) component and yield a upper intercept age younger than the crystallization age of the baddeleyite-hosting mafic rocks (e.g. Davidson and van Breemen 1988; Rioux et al. 2010; Söderlund et al. 2013). In this case, SIMS or LA-ICP-MS methods are much better than TIMS method in obtaining precise ages of mafic rocks (e.g., Söderlund et al. 2013).

14.7 Summary and Concluding Remarks

1. The NCC is characterized by multistages of extension and continental rifting and deposition of thick marine or interactive marine and terrestrial clastic and carbonate platform sediments without angular unconformity during Earth's middle age of 1.70–0.75 Ga. Factors leading to these multistages of extension and continental rifting events came either from the NCC itself or from the neighboring continents connected with the NCC during these periods.
2. Two large igneous provinces including the ca. 1.32 Ga mafic sill swarms in Yanliao rift (aulacogen) in the northern NCC and the 0.92–0.89 Ga Xu-Huai–Dalian–Sariwon mafic sill swarms in southeastern and eastern NCC have been identified from the NCC recently. They are characterized by similar geochemical features of tholeiitic compositions and intraplate characteristics. Formation of these two large igneous provinces was accompanied by pre-magmatic uplift. The Yanliao and Xu-Huai–Dalian–Sariwon large igneous provinces represent two continental rifting events that have led to rifting to drifting transition and breakup of the northern margin of the NCC from the Columbia (Nuna) supercontinent and the southeastern margin of the NCC from the Rodinia supercontinent, respectively.
3. Magmatism related to continental breakup and rifting to drifting transition can occur as mafic dykes, sills and/or lavas and is mainly tholeiitic in chemical composition. It should be large in volumes and constitute a large igneous province. In many cases, the breakup-related magmatism was accompanied by pre-magmatic uplift. Large volumes of mafic sill swarms near continental margins and accompanied pre-magmatic uplift in marginal rift basins can most likely be used as important indicators for continental breakup and paleocontinental reconstruction.

Acknowledgments This research was financially supported by the National Basic Research Program of China (2012CB416604). We thank Hangqiang Xie for help during zircon SHRIMP U–Pb analysis. We are grateful to Peng Peng for thoughtful and helpful comments on the manuscript.

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