GEOSCIENCE FRONTIERS 3(4) (2012) 375–399

available at www.sciencedirect.com

China University of Geosciences (Beijing)

GEOSCIENCE FRONTIERS

journal homepage: www.elsevier.com/locate/gsf

GSF FOCUS

Mid–Late Neoproterozoic rift-related volcanic rocks in China: Geological records of rifting and break-up of Rodinia

Linqi Xia*, Zuchun Xia, Xueyi Xu, Xiangmin Li, Zhongping Ma

Xi'an Institute of Geology and Mineral Resources, China Geological Survey, Xi'an, Shaanxi 710054, China

Received 8 July 2011; accepted 23 October 2011
Available online 17 December 2011

KEYWORDS
Neoproterozoic;
Bimodal volcanism;
Continental rift;
Mantle plume;
Rodinia supercontinent;
China

Abstract Early Cambrian and Mid–Late Neoproterozoic volcanic rocks in China are widespread on several Precambrian continental blocks, which had aggregated to form part of the Rodinia supercontinent by ca. 900 Ma. On the basis of petrogeochemical data, the basic lavas can be classified into two major magma types: HT (Ti/Y $>$ 500) and LT (Ti/Y $<$ 500) that can be further divided into HT1 (Nb/La $>$ 0.85) and HT2 (Nb/La $\leq$ 0.85), and LT1 (Nb/La $>$ 0.85) and LT2 (Nb/La $\leq$ 0.85) subtypes, respectively. The geochemical variation of the HT2 and LT2 lavas can be accounted for by lithospheric contamination of asthenosphere- (or plume-) derived magmas, whereas the parental magmas of the HT1 and LT1 lavas did not undergo, during their ascent, pronounced lithospheric contamination. These volcanics exhibit at least three characteristics: (1) most have a compositional bimodality; (2) they were formed in an intracontinental rift setting; and (3) they are genetically linked with mantle plumes or a mantle surperplume. This rift-related volcanism at end of the Mid–Neoproterozoic and Early Cambrian coincided temporally with the separation between Australia–East Antarctica, South China and Laurentia and between Australia and Tarim, respectively.

* Corresponding author. Xi'an Institute of Geology and Mineral Resources, China Geological Survey, East Youyi Road 438, Xi'an, Shaanxi 710054, China. Tel.: +86 29 87821934; fax: +86 29 87821900.
E-mail address: geologyx@pub.xaonline.com (L. Xia).

Peer-review under responsibility of China University of Geosciences (Beijing).
doi:10.1016/j.gsf.2011.10.004

Production and hosting by Elsevier

The Mid–Late Neoproterozoic volcanism in China is the geologic record of the rifting and break-up of the supercontinent Rodinia.

1. Introduction

Mid–Late Neoproterozoic rift-related volcanic rocks are widespread on several Precambrian blocks including the Tarim Craton and neighboring blocks in northwestern China, the Bikou, Hannan, Niushan, Pingli and Wudangshan blocks in central China, the Yangtze Craton and the Cathaysia Block in southern China (Figs. 1–6). These volcanic rocks, which consist mainly of huge volumes of basic rocks and variable amounts of silicic volcanics, with small amounts (Fig. 7b, c) or a lack of intermediate rocks that display a compositional bimodality (Fig. 7a, d, e), have attracted a number of recent studies (Xia et al., 1991, 1996a,b, 1999, 2001, 2002, 2007a,c, 2008a, 2009a,b; Tang and Zhou, 1997; Tang et al., 1997, 1998; Zhao et al., 1997, 1999, 2006; Zhang et al., 1999a,b; Ge et al., 2000; Jiang et al., 2001; Lai et al., 2001, 2003; Li et al., 2001, 2002a,b, 2005a,b,c, 2008a,b; Ling et al., 2002a,b,c, 2003; Zhou et al., 2002a, 2003, 2004, 2007; Wang and Li, 2003; Wang et al., 2003a,b, 2004, 2006, 2007, 2008, 2009; Yan et al., 2003, 2004a,b; Xu et al., 2005; Su et al., 2006; Lu and Gu, 2007; Song et al., 2010).

The petrogenesis and tectonic affiliations of these Chinese volcanic rocks are still controversial. Some workers have considered that they are products of intraplate volcanism attributed to mantle plumes or a mantle superplume that caused rifting and fragmentation of the Rodinia supercontinent (Li et al., 1999b, 2003b, 2008c, 2009b; Ling et al., 2003; Li et al., 2002a,b, 2005a,b,c, 2006, 2008a,b; Song et al., 2010; Wang et al., 2007, 2008, 2009; Wang et al., 2010; Xia et al., 1996a,b, 2002, 2007a,c, 2008a, 2009a,b; Xu et al., 2005; Zhou et al., 2002a, 2007). Others have proposed that most of these volcanic rocks in central and southern China were formed in either collisional (Li, 1999; Zhao and Cawood, 1999; Wang et al., 2003b, 2004, 2006) or arc settings (Ling et al., 2002b,c; Lai et al., 2001, 2003; Munteanu and Wilson, 2009; Yan et al., 2003, 2004a,b; Zhou et al., 2002b,c, 2003, 2004, 2006a,b).

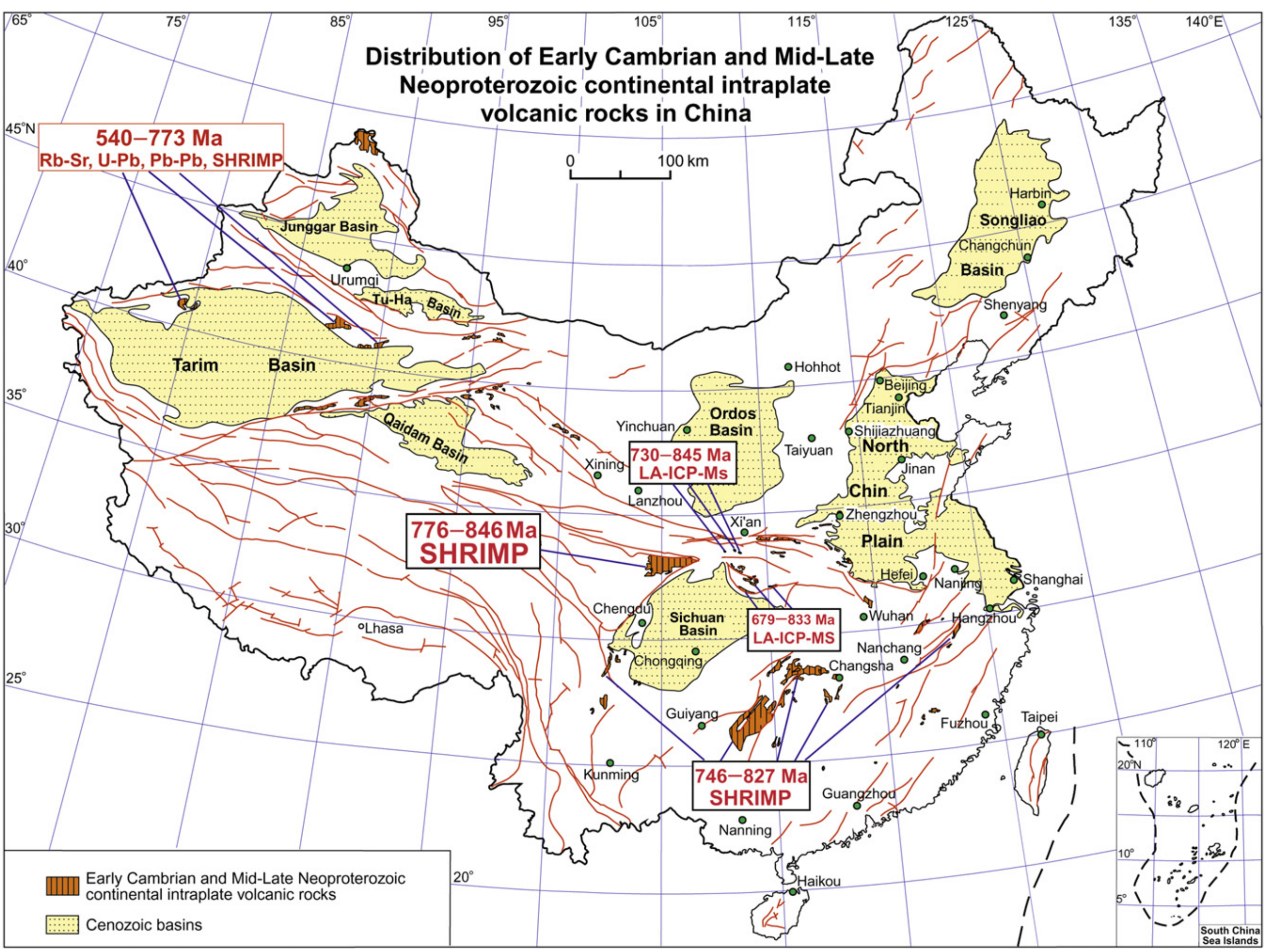

Figure 1 Sketch map showing the distribution of Early Cambrian and Mid–Late Neoproterozoic (846–540 Ma) continental intraplate volcanic rocks in China.

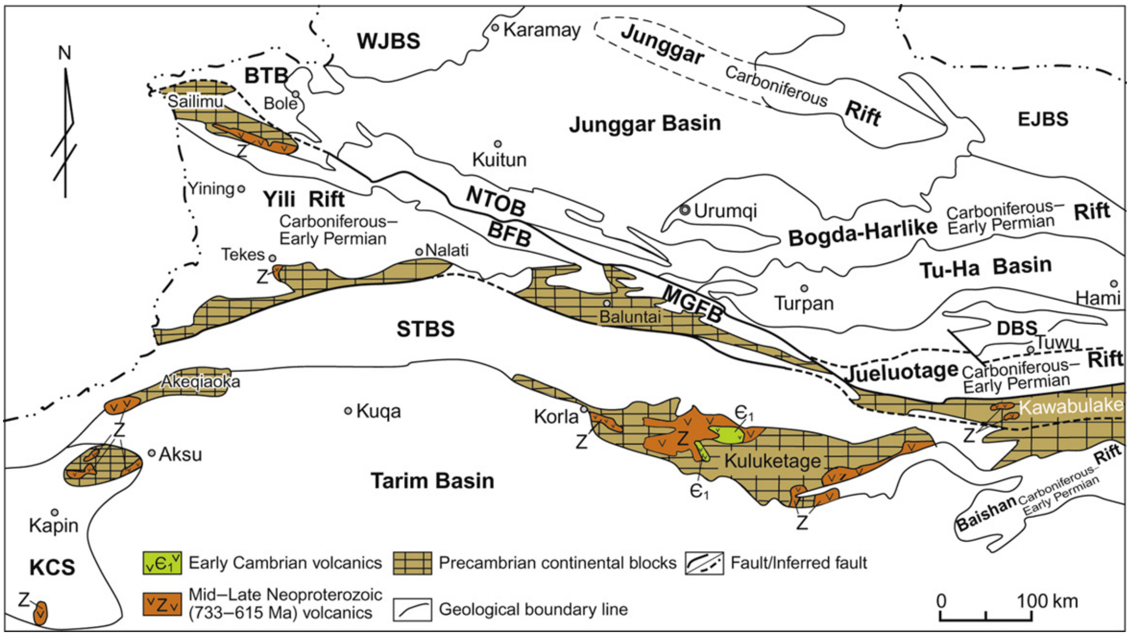

Figure 2 Sketch map showing the distribution of Early Cambrian and Mid–Late Neoproterozoic (773–540 Ma) volcanic rocks in the Tarim Craton and its neighboring areas (modified after Xia et al., 2002, 2007c, 2008b). WJBS – West Junggar trench-arc-basin system (Early Paleozoic–Devonian); EJBS – East Junggar arc-basin system (Early Paleozoic–Devonian); BTB – Bole tectonomagmatic belt (Late Paleozoic); NTOB – North Tianshan ophiolite belt (Carboniferous); BFB – Boluokenu foldbelt (Early Paleozoic); MGFB – Mishigou-Gangou foldbelt (Early Paleozoic); DBS – Devonian arc-basin system; STBS – South Tianshan trench-arc-basin system (Early Paleozoic–Devonian); KCS – Kapin continental shelf (Neoproterozoic–Paleozoic).

This paper, in aiming to test the proposed Neoproterozoic mantle plume or superplume hypothesis, presents a brief synthesis of the distribution, age, and petrogeochemical data of the Mid–Late Neoproterozoic volcanic rocks from China and reassesses the nature, tectonic setting and petrogenesis of the basic lavas ($SiO_2 \leq 56\%$) in these volcanic successions.

2. Geological background

2.1. Tarim Craton and neighboring blocks in northwestern China

Several Precambrian continental blocks, including the Tarim Craton and the Yili, Saillimu and Kawabulake blocks are distributed in the Tianshan orogenic belt and its neighboring areas (Figs. 1 and 2). Lower Neoproterozoic basement rocks are covered by Paleozoic strata in the southern and central Tarim Craton, and outcrop widely in the northern Tarim Craton and the blocks in the Tianshan. The Mid–Upper Neoproterozoic strata unconformably overlie the Lower Neoproterozoic Pargangtage Group in the Kuluketage area of the Tarim Craton and the Kawabulake Block of the Tianshan Mountains, the Aksu Group in the Aksu-Kapin area of the Tarim Craton and the Kusongmuqieke Group in the Sailimu Block of the Tianshan, and are unconformably overlain by Lower Cambrian strata (Gao et al., 1985, 1993; Gao and Chen, 2003; Xu et al., 2005; Fig. 8).

The thickest and most complete Mid–Upper Neoproterozoic sections consist of, from bottom to top, eight formations: Beiyixi, Zhaobishan, Aletonggou, Tereeken, Zhamoketi, Yukengou, Shuiquan and Hangelchaok that occur in the Kuluketage area, Tarim Craton (Xu et al., 2005; Fig. 8). The Beiyixi, Aletonggou, Tereeken and Hangelchaok formations are characterized by containing tillites that are the product of the Neoproterozoic global glacial events. Previous studies (e.g., Gao et al., 1985, 1993; Gao and Chen, 2003; Jiang et al., 2001; Xu et al., 2005; Xia et al., 2002, 2007c) revealed that the rift-related volcanic rocks are distributed in Mid–Upper Neoproterozoic and Lower Cambrian strata and that they most completely occur in the Kuluketage area. These volcanic successions comprise four volcanic units: the Beiyixi Unit (early Middle Neoproterozoic); the Zhamoketi Unit (late Middle Neoproterozoic); the Shuiquan Unit (Late Neoproterozoic); and the Xishanbulake Unit (earliest Cambrian) (Jiang et al., 2001; Xia et al., 2002, 2007c; Fig. 8). The volcanic rocks of the Beiyixi Unit develop mainly in the Kuluketage area and the Saillimu and Kawabulake blocks from the Tianshan Mountains; those of the Zhamoketi Unit occur in the Kuluketage and Aksu-Kapin areas; those of the Shuiquan Unit are only in the Kuluketage area; those of the Xishanbulake Unit have been found in the Kuluketage area and the Kawabulake Block (Fig. 8). The abovementioned volcanic successions are made up mainly of basic volcanic rocks and subordinate amounts of silicic volcanic rocks, with small amounts of intermediate rocks, only in the Beiyixi Unit, which generally show a compositional bimodality (Fig. 7a). All previous studies (Jiang et al., 2001; Xu et al., 2005; Xia et al., 2002, 2007c; Wang et al., 2010) proposed that these volcanic rocks were produced within a common intraplate setting and were related to mantle plume activities and continental rifting during the break-up of Rodinia.

Four available geochronology data from the Beiyixi volcanic unit have been published, which include a Pb-Pb age of 773 Ma (Zhu and Sun, 1987) and three U-Pb SHRIMP zircon ages of 755 Ma (Xu et al., 2005), 740 Ma and 725 Ma (Xu et al., 2009). In addition, Zhu and Sun (1986) obtained a U-Pb age of 740 Ma for

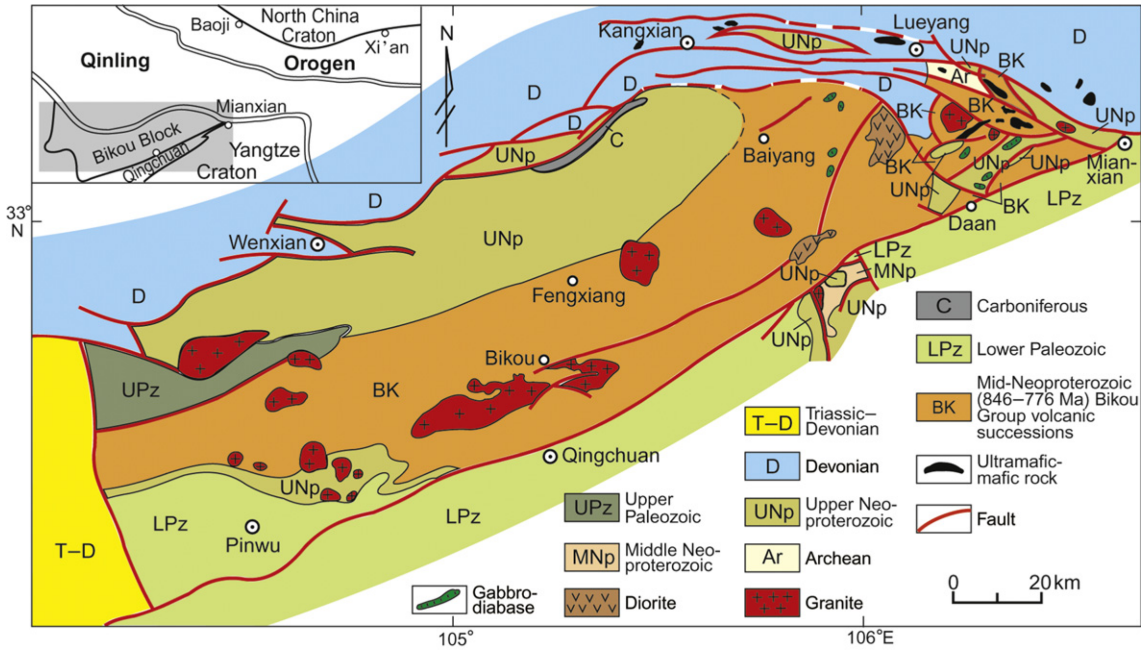

Figure 3 Sketch map showing the distribution of the Mid-Neoproterozoic (846–776 Ma) Bikou Group volcanic successions in the Bikou Block from the northwestern margin of the Yangtze Craton (modified after Xia et al., 2007a).

the Sugaitebulake Formation in the Aksu-Kapin area, and Xu et al. (2009) also obtained a U-Pb SHRIMP age of 615 Ma for the Zhamoketi volcanic Unit in the Kuluketage area.

Besides the Neoproterozoic bimodal volcanic rocks, there are three types of Neoproterozoic intrusions in the Tarim Craton, which include ca. 824–630 Ma mafic dyke swarms (Chen et al., 2004; Zhang et al., 2009; Zhu et al., 2011), ca. 833–760 Ma ultramafic-mafic intrusions (Li et al., 1999a; Zhang et al., 2007, 2011b), and ca. 820–744 Ma alkaline granites (Guo et al., 2005; Zhang et al., 2007). These 840–630 Ma Neoproterozoic igneous events well documented in the Tarim Craton were also interpreted as being related to mantle plume activities during the break-up of the supercontinent Rodinia (Zhang et al., 2007, 2009, 2011b; Zhu et al., 2011). Furthermore, Zhang et al. (2010)

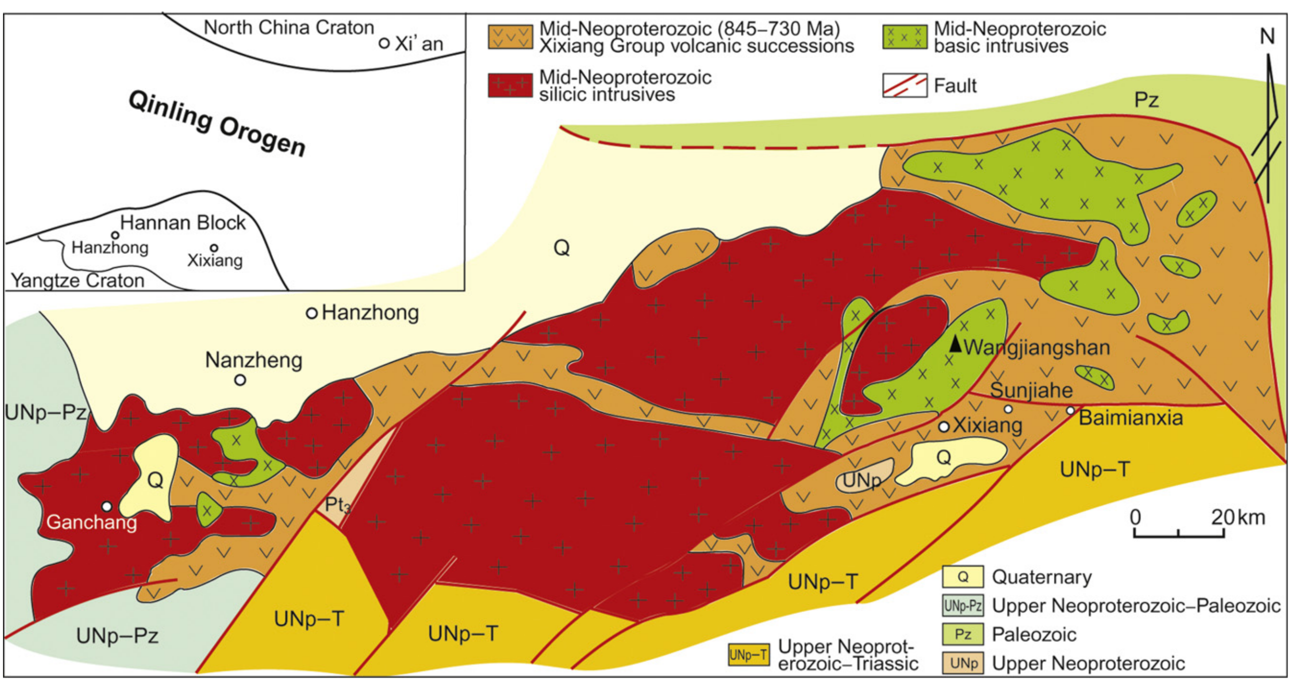

Figure 4 Sketch map showing the distribution of the Mid-Neoproterozoic (845–730 Ma) Xixiang Group volcanic successions in the Hannan Block from the northern margin of the Yangtze Craton (modified after Xia et al., 2009b).

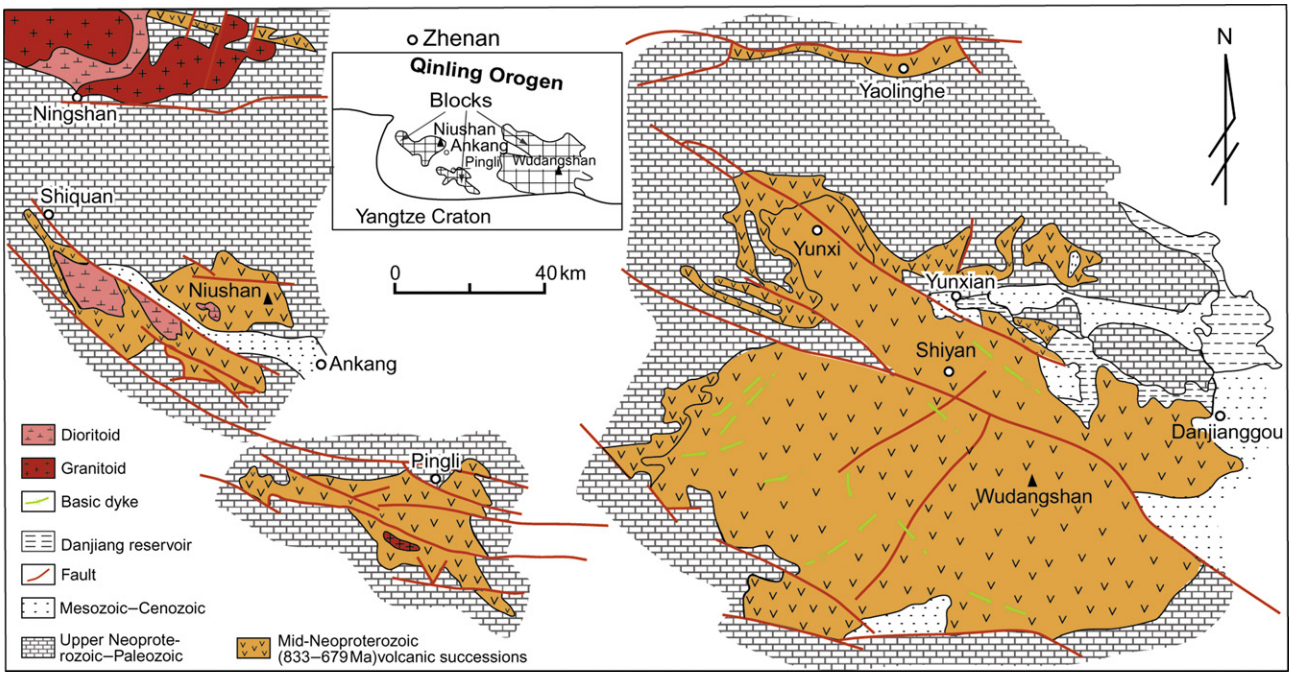

Figure 5 Sketch map showing the distribution of the Mid-Neoproterozoic (833–679 Ma) volcanic successions in the Niushan, Pingli and Wudangshan blocks from the South Qinling Orogen (modified after Xia et al., 2008a).

recently reported that Neoproterozoic rifting-related mafic dykes (802 ± 9 Ma, U-Pb SHRIMP zircon age) and basalts are also distributed in the southern margin of the Tarim Craton.

In addition to abovementioned studies, Song et al. (2010) recently reported that the Yuka eclogites with the protolith ages (U-Pb SHIMP zircon ages) of 847–848 Ma, occurring in the northern margin of the Qaidam Block of northwestern China, have protoliths similar to most typical continental flood basalts with a mantle plume origin. They inferred that the Qaidam Block is probably one of the fragments of the Rodinia supercontinent with a volcanic-rifted passive margin.

2.2. Bikou, Hannan, Niushan, Pingli and Wudangshan blocks in central China

2.2.1. Bikou Block

The Bikou Group volcanic succession occurs on the Bikou Precambrian Block, which is situated in northwestern margin of the Yangtze Craton (Figs. 1 and 3). The Neoarchean Yudongzhi Group makes up the underlying basement of the Bikou Group volcanic succession, which in turn is angular- or parallel-unconformably covered by Upper Neoproterozoic strata (Fig. 9). The Bikou Group volcanic rocks with U-Pb SHRIMP zircon ages of 846–776 Ma (Yan et al., 2003, 2004a,b) and 811–821 Ma (Wang et al., 2008) were formed during the Middle Neoproterozoic. The volcanic succession comprises a thick pile of basic volcanic rocks, subordinate silicic and minor intermediate volcanic rocks (Fig. 7b). Some researchers considered that this volcanic suite formed in an arc setting (Yan et al., 2003, 2004a,b) even though they advocated the view that the Yangtze Craton collided with the Cathaysian Block at the end of the Grenville orogeny to form the South China Block. However, others considered that this volcanic suite erupted in an intracontinental rift setting (Xia et al., 1996a, 1999, 2001, 2007a; Xu et al., 2001, 2002) or proposed that the basalts of this volcanic suite are likely the remnants of Mid-Neoproterozoic continental flood basalts that formed in response to a mantle plume starting ca. 825 Ma during the break-up of the supercontinent Rodinia (Wang et al., 2008).

2.2.2. Hannan Block

The Hannan Precambrian Block (i.e., the Hannan–Micangshan uplift; Ling et al., 2003), where the Xixiang Group volcanic rocks and the Tiechuanshan Formation volcanic succession are developed, is located in the northern margin of the Yangtze Craton (Figs. 1, 4 and 9). The Xixiang Group is made up of the Sunjiahe Formation with U-Pb LA-ICP-MS zircon ages of 845–826 Ma (Xia et al., 2009b) and U-Pb TIMS zircon ages of 839–821 Ma (Zhao et al., 2006), the Dashigou Formation with U-Pb LA-ICP-MS zircon ages of 803–776 Ma (Xia et al., 2009b), the Baimianxia Formation with a U-Pb LA-ICP-MS zircon age of 730 Ma (Xia et al., 2009b), and the Tiechauanshan Formation with a U-Pb TIMS zircon age of 817 ± 5 Ma (Ling et al., 2003) (Fig. 9). These Middle Neoproterozoic (845–730 Ma) volcanic rocks unconformably overlie the Paleoproterozoic Houhe Group, and are in turn unconformably covered by Sinian (Late Neoproterozoic) strata (Fig. 9). The Xixiang Group volcanic succession consists of predominantly basic volcanic rocks, subordinate silicic and small amounts of intermediate volcanic rocks (Fig. 7c), and the Tiechuanshan Formation displays a bimodal distribution of basic and silicic rocks (Ling et al., 2003).

There have been two different explanations concerning the tectonic setting of these volcanic rocks. The first opinions suggested that they were formed in an intracontinental rift setting and are most likely related to the proposed mantle plume that led to the rifting–break-up of the Rodinia supercontinent (Xia et al., 1996a,b, 2001, 2009b; Xu et al., 2001). The second view deemed that the Xixiang volcanic suite has the properties of arc volcanic rocks (Lai et al., 2001, 2003; Ling et al., 2002b, 2003) and that the

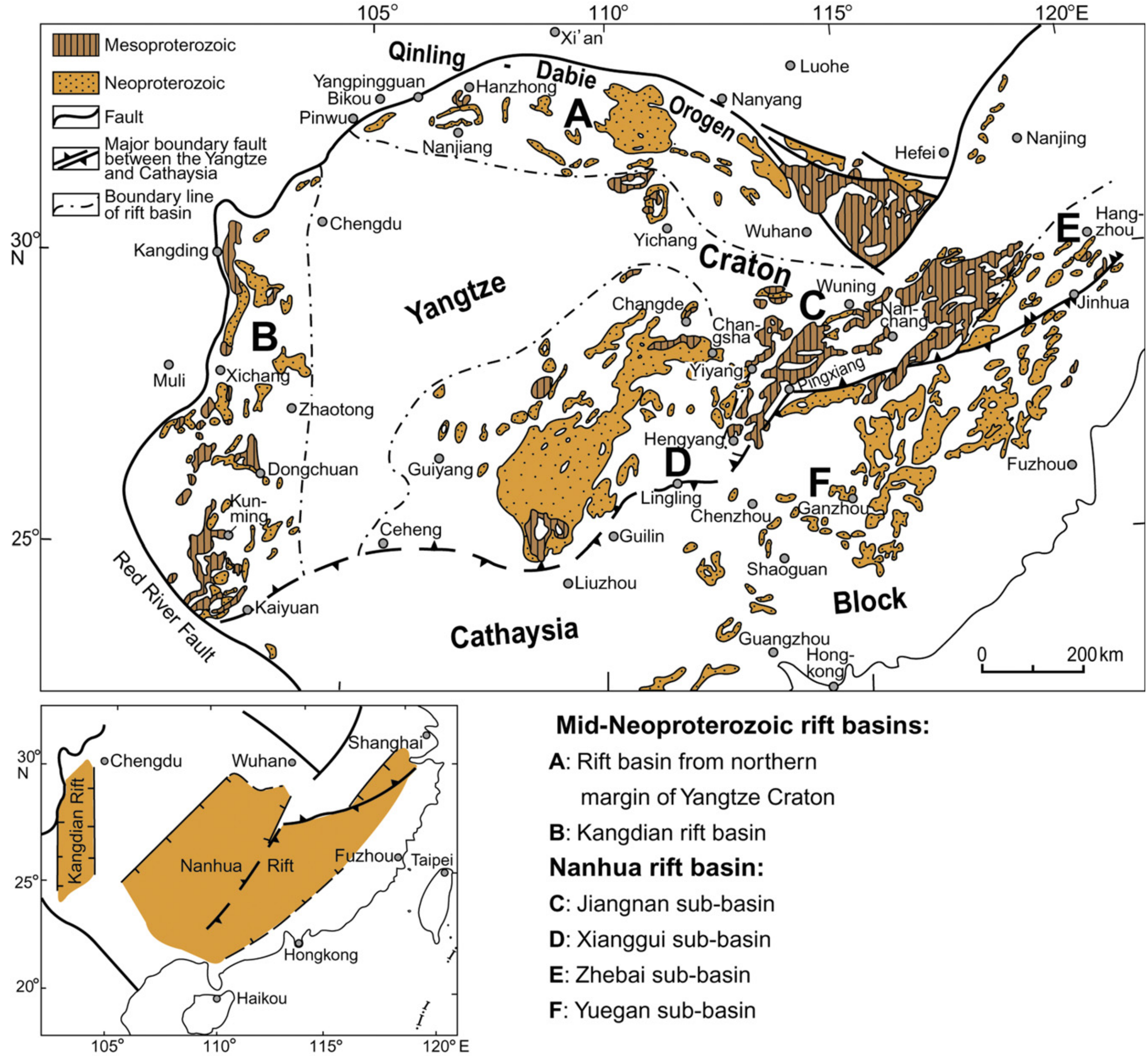

Figure 6 Sketch map showing the distribution of Mid-Neoproterozoic rift basins in South China and neighboring areas (modified after Wang, 2000; Wang and Li, 2003; Wang and Pan, 2009; Wang et al., 2001; and Li and Li, 2007).

Tiechuanshan assemblage was formed within continental rifting caused by plume activity (Ling et al., 2003).

2.2.3. Niushan, Pingli and Wudangshan blocks

The Niushan, Pingli and Wudangshan Precambrian blocks are situated in the southern Qinling orogenic belt to the north of the Yangtze Craton (Figs. 1 and 5; Zhang et al., 2001). On these three blocks occur the Mid-Neoproterozoic Yaolinghe Group, Yunxi Group, Wudangshan Group volcanic rocks and basic dyke swarms. Recent geochronological studies have reported a series of isotopic age data that include U-Pb LA-ICP-MS zircon ages of 833–752 Ma for the volcanic rocks of the Wudangshan Group (Ling et al., 2007), a U-Pb LA-ICP-MS zircon age of 783 Ma for the volcanic rocks of the Yunxi Group (Xia et al., 2008a), and U-Pb TIMS zircon ages of 808–746 Ma (Li et al., 2003a) and U-Pb LA-ICP-MS zircon ages of 800–679 Ma for the volcanic rocks of the Yaolinghe Group (Ling et al., 2007) (Fig. 9). A bimodal distribution based on SiO_2 content of basic and silicic rocks with small amounts of intermediate rocks has been uncovered for the Mid-Neoproterozoic volcanic successions (Fig. 7d). These volcanic successions unconformably overlie the Paleoproterozoic Douling Group, and are in turn covered by Sinian (Late Neoproterozoic) strata (Fig. 9). There have been many different opinions concerning the geological setting of these Mid-Neoproterozoic volcanic successions. Some have considered them to be the products of an intracontinental rift-related volcanism (Li et al., 2003a; Xia et al., 1996a, 2001, 2008a; Xu et al., 2001; Zhang et al., 1999a,b). Others have proposed that the Yaolinghe Group volcanic suite, distributed in the Zhenan and Yaolinghe areas and the Wudangshan Group volcanic rocks

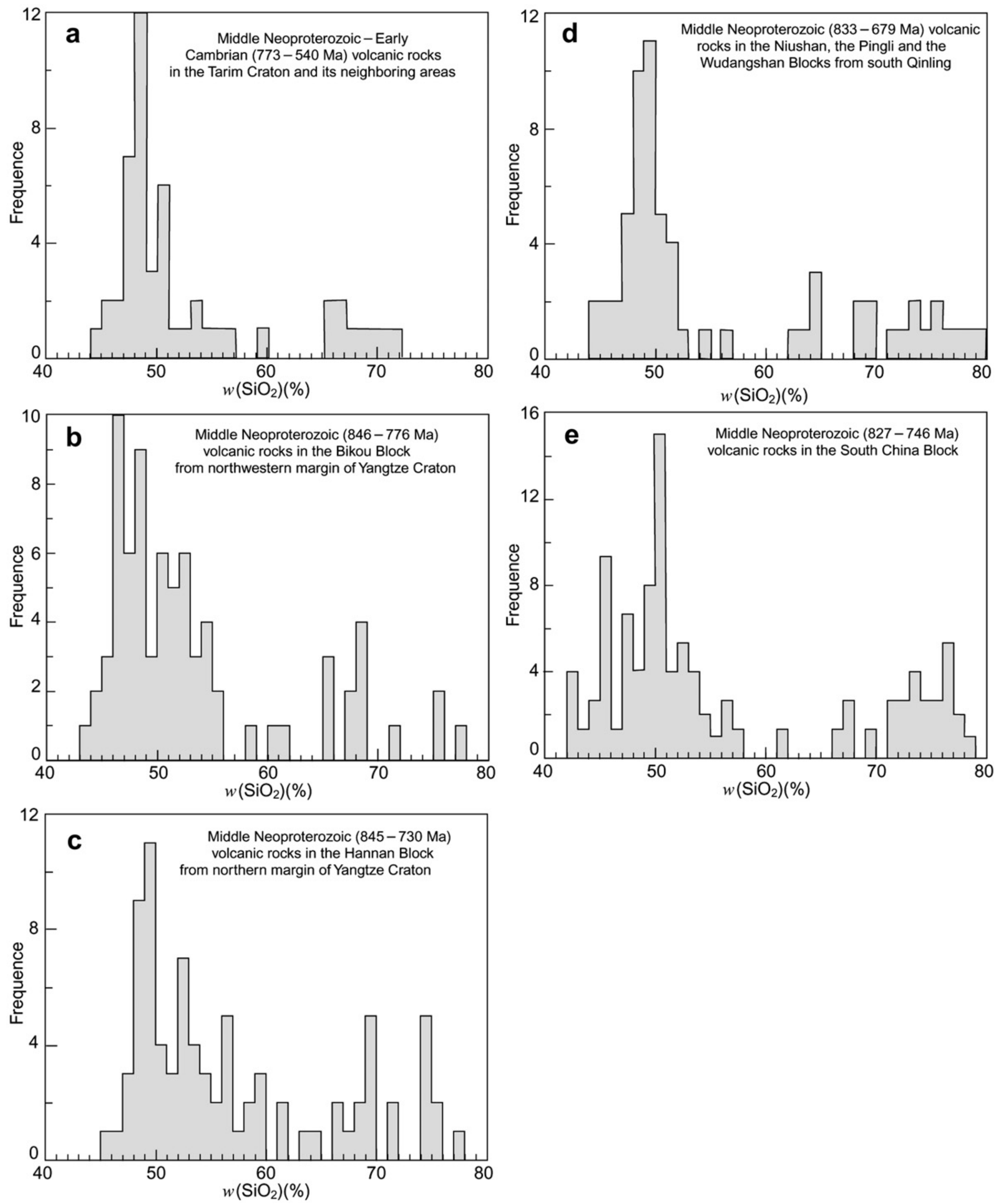

Figure 7 $w(SiO_2)$ content data histograms of Mid−Late Neoproterozoic−Early Cambrian rift-related volcanic rocks in (a) the Tarim Craton and its neighboring areas, (b) the Bikou Block from the northwestern margin of the Yangtze Craton, (c) the Hannan Block from the northern margin of Yangtze Craton, (d) the Niushan, Pingli and Wudangshan blocks from the South Qinling Orogen, and (e) the South China Block. Data sources: (a): Jiang et al., 2001; Xu et al., 2005; Xia et al., 2007c; Wang et al., 2010; Zhang et al., 2010; (b): Xia et al., 1996a, 1999, 2007a; Xu et al., 2001, 2002; Yan et al., 2003, 2004a,b; Wang et al., 2008; (c): Xia et al., 1996a,b, 2001, 2009b; Ling et al., 2002b, 2003; Lai et al., 2001, 2003; (d): Xia et al., 1991, 1996a; Zhang et al., 1999a,b; Ling et al., 2002a,c; Su et al., 2006; Zhang et al., 2002; (e): Xu, 1994; Jin et al., 1997; Tang and Zhou, 1997; Tang et al., 1997, 1998; Zhao et al., 1997, 1999; Chen et al., 1998; Ge et al., 2000; Li et al., 2001, 2002a,b, 2005a,c, 2008a,b; Wang et al., 2003b, 2007; Zhou et al., 2003, 2007; Lu and Gu, 2007.

developed in the Wudangshan area, were formed in an island-arc setting, whereas the Yaolinghe Group volcanic suite and basic dyke swarms, occurring in the Wudangshan area, were formed in a continental rift (Ling et al., 2002a,c; Su et al., 2006).

2.3. Yangtze Craton and Cathaysia Block

The Yangtze Craton and Cathaysia Blocks are located in southern China (Figs. 1 and 6). It is thought that the Early Neoproterozoic

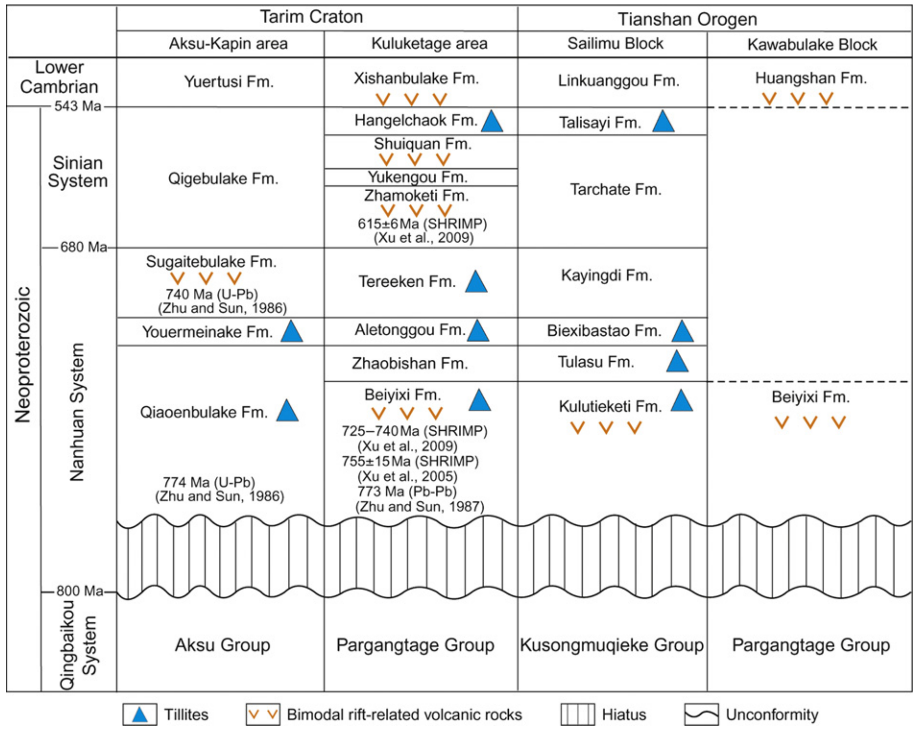

Figure 8 Stratigraphic division and correlation of Neoproterozoic strata in the Tarim Craton and its neighboring areas (modified after Gao et al., 1985, 1993; Gao and Chen, 2003; Xu et al., 2005, 2009; Zhu and Sun, 1986, 1987).

(ca. 1.0–0.9 Ga) Sibao orogeny, belonging to part of the global Grenvillian-aged orogenic events associated with the assembly of Rodinia, resulted in the amalgamation of the Yangtze Craton and Cathaysia Block and the formation of a unified South China Block (Wang, 2000; Wang and Li, 2003; Li et al., 2002a,c, 2006, 2009a; Ye et al., 2007). A major upwelling and partial melting event during the Middle Neoproterozoic led to the development of the Kangdian and Nanhua rift basins (Wang, 2000; Wang et al., 2001; Wang and Li, 2003; Fig. 6). The latter can be divided into four sub-basins: Jiangnan, Xianggui, Zhebai, and Yuegan (Fig. 6).

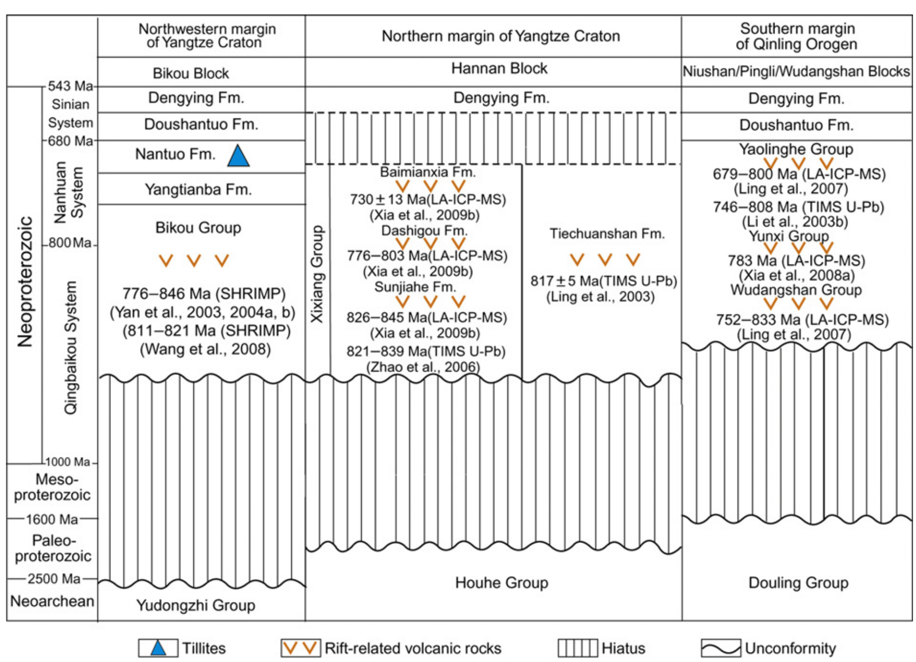

Figure 9 Stratigraphic division and correlation of Neoproterozoic strata in the Bikou Block (northwestern margin of Yangtze Craton), the Hannan Block (northern margin of Yangtze Craton), the Niushan, Pingli and Wudangshan blocks from the South Qinling Orogen (modified after Yan et al., 2003, 2004a,b; Wang et al., 2008; Ling et al., 2003, 2007; Zhao et al., 2006; Li et al., 2003b; Xia et al., 2007a, 2008a, 2009b).

The oldest rock unit in the Yangtze Craton is the Kongling Complex, consisting of Archean to Paleoproterozoic high-grade metamorphic tonalite, trondhjemite and granodiorite gneisses, amphibolites and metamorphic supercrustal rocks (e.g., Qiu et al., 2000). Despite Archean inherited zircons being identified from various rock types in Proterozoic and younger rocks, the oldest known crystalline basement rocks in the Cathaysia Block are the granitic rocks and amphibolites of ca. 1.8 Ga in southwestern Zhejiang and northwestern Fujian provinces (e.g., Li, 1997; Li and Li, 2007).

The Mid-Neoproterozoic (827–746 Ma) bimodal (basic–silicic, Fig. 7e) volcanic rocks are distributed widely in the abovementioned rift basins. These volcanic successions unconformably overlie the Early Neoproterozoic basement and are covered by Late Neoproterozoic strata (Fig. 10). The isotopic geochronology results (see Fig. 10) reveal that the lower age limit for the volcanism in South China during the middle stage of the Neoproterozoic should be less than 830 Ma, while the upper limit may be as young as 740 Ma. The Neoproterozoic global glacial events occurred also on the South China Block during the late stage of the Mid-Neoproterozoic and resulted in the glacial deposits of the Chang'an Formation and a vast continental ice sheet in South China (Wang, 2000, 2005; Wang et al., 2001; Wang and Li, 2003; Fig. 10). The tectonic interpretations of the above widespread volcanic rocks differ greatly. One group (Li et al., 1999b, 2003b, 2008c, 2009b; Li et al., 2002a,b, 2005a,b,c, 2006, 2008a,b; Wang et al., 2007, 2008, 2009; Zhou et al., 2002a, 2007) considered that these Mid-Neoproterozoic rocks originated in intraplate volcanism, which was related to mantle plume activities and continental rifting during the break-up of Rodinia. Especially, the identification of the Yiyang komatiitic basalts exposed in the central South China Block was regarded as the first solid petrological evidence for the proposed ca. 825 Ma mantle plume (Wang et al., 2007). On the contrary, others have argued that most of the Mid-Neoproterozoic igneous rocks were products of orogenesis in either collisional (Li, 1999; Zhao and Cawood, 1999; Wang et al., 2003b, 2004, 2006) or arc settings (Munteanu and Wilson, 2009; Zhou et al., 2002b,c, 2003, 2004, 2006a,b).

The crucial evidences used for arc/collision models are the variable arc-like geochemical signatures in some basaltic rocks and granitoids (Zhou et al., 2002b,c, 2003, 2004, 2006a,b; Wang et al., 2003b, 2004, 2006). However, it has been attested that geochemical characters of granitoids should not be simplistically used for discriminating tectonic regimes because their geochemistry is reflective of their sources, as well as the melting and crystallization histories, not their tectonic environments into which they intrude (Forst et al., 2001; Forst and Forst, 2008). Although basaltic magmas are generally thought to be more reliable for constraining their tectonic settings, the practice of simplistically using some arc-like geochemical signatures to discriminate between continental intraplate basalts and arc basalts should also be used cautiously (Duncan, 1987; Wang et al., 2008, 2009 and references therein). This is because contamination by continental crust or lithosphere can impart subduction-type signatures (e.g., low Nb, low Ta and low Ti) and lead to the

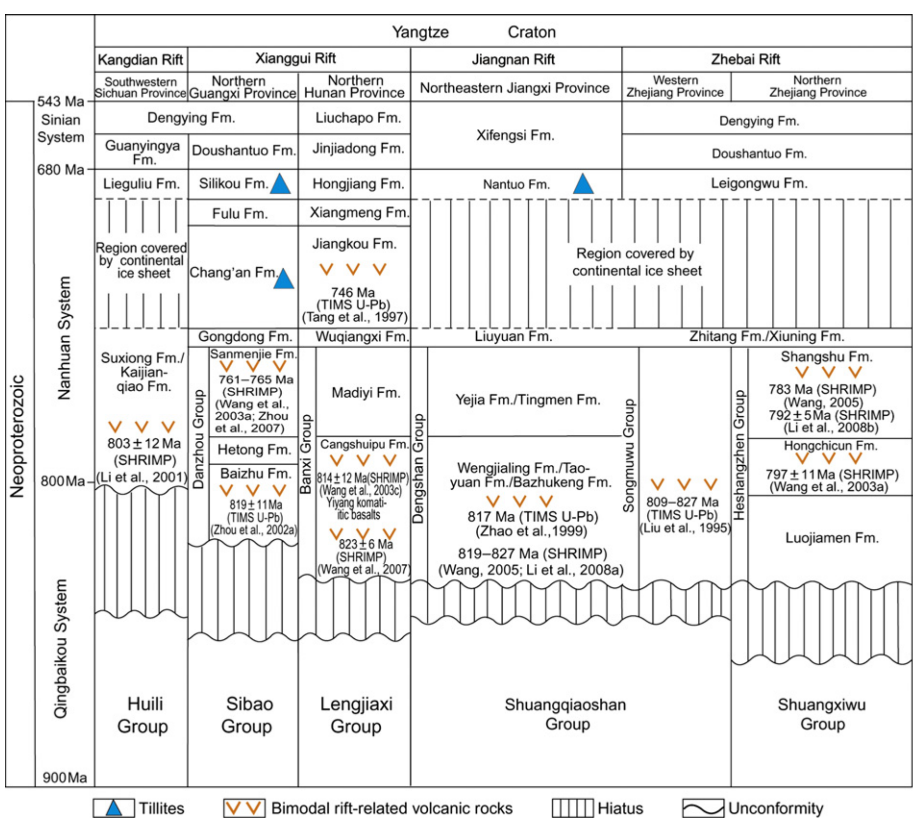

Figure 10 Stratigraphic division and correlation of the Neoproterozoic strata in South China (modified after Li et al., 2001, 2008a,b; Liu et al., 1995; Tang et al., 1997; Wang, 2000, 2005; Wang and Li, 2003; Wang and Pan, 2009; Wang et al., 2001, 2003a, 2007; Zhao et al., 1999; Zhou et al., 2002a, 2007).

misidentification of contaminated continental intraplate basalts as arc related (Ernst et al., 2005; Xia et al., 2007b, 2008b). We will further discuss this further below.

In summary, a large regional correlation indicates that the large-scale volcanic activities on the Qaidam Block (848−847 Ma), the Bikou Block (846−776 Ma), the Hannan Block (845−730 Ma), the Niushan, Pingli and Wudangshan blocks (833−679 Ma), and the South China Block (827−746 Ma) occurred approximately at a same time, whereas those in the Tarim Craton and on neighboring blocks took place later (773−540 Ma).

3. Classification of the Mid−Late Neoproterozoic basic lavas in China

It must be pointed out that the Mid−Upper Neoproterozoic and Lower Cambrian rift-related volcanic rocks in China date from ca. 850−550 Ma and have been altered to various degrees after their eruption, judging from petrographic observations and relatively high LOI in some samples. This process may have changed the concentration of the mobile elements such as K, Na, Rb, Ba, and Sr. Thus, the samples with LOI higher than 5% were excluded, and we cannot utilize the TAS classification diagram in identifying the volcanic rock types. Instead, here we use the SiO_2 versus Nb/Y diagram (Winchester and Floyd, 1977) and the FeO_T/MgO versus SiO_2 diagram (Miyashiro, 1975). On the other hand, age correction of measured $^{87}Sr/^{86}Sr$ ratios involves Rb concentrations. For these reasons, emphasis is placed on immobile elements such as REEs, HFSEs (high field strength elements: Zr, Hf, Nb, Ta, P), Th, Y, Ti, Fe, and Mg, and $\varepsilon_{Nd}(t)$ in the following petrogenesis discussion.

3.1. Tarim Craton and neighboring blocks

According to Ti/Y ratios, the Mid−Late Neoproterozoic−Early Cambrian basic lavas in the Tarim Craton and its neighboring blocks can be divided into two major magma types: high-Ti/Y (HT, Ti/Y > 500) and low-Ti/Y (LT, Ti/Y < 500) basalts (Fig. 11a). Ti/Y, rather TiO_2, is used as a discriminator of magma types, because TiO_2 contents generally increase during fractional crystallization, but Ti/Y does not vary much (Peate et al., 1992). On the basis of Nb/La ratios (index of crustal contamination, Kieffer et al., 2004), the HT and LT lavas can be further divided into HT1 (Nb/La > 0.85) and HT2 (Nb/La ≤ 0.85) lavas, and LT1 (Nb/La > 0.85) and LT2 (Nb/La ≤ 0.85) lavas, respectively (Fig. 11a) (Data sources are as in Fig. 7). All of the LT1 lavas and two HT1 samples, consisting of alkali basalt, belong to the alkaline series and most of LT2 lavas and one HT1 sample, consisting of basalt, basaltic andesite, and minor alkali basalt, belong to the tholeiitic series except four LT2 samples that belong to the alkaline series (Fig. 12a, b).

3.2. Bikou Block

By virtue of the Ti/Y ratios, the 846−776 Ma Bikou Group basic lavas on the Bikou Block can also be divided into two major magma types: high-Ti/Y (HT, Ti/Y > 500) and low-Ti/Y (LT, Ti/Y < 500) basalts (Fig. 11b). In reference to Nb/La ratios, the LT lavas can be further divided into LT1 (Nb/La > 0.85) and LT2 (Nb/La ≤ 0.85) subtypes (Fig. 11b) (Data sources are as in Fig. 7). They consist of basalt, basaltic andesite and minor alkali basalt; most belong to the tholeiitic series except one LT1 and three HT samples that belong to the alkaline series (Fig. 12c, d).

3.3. Hannan Block

All of the 845−730 Ma Xixiang Group and Tiechuanshan Formation basic lavas in the Hannan Block have lower Ti/Y ratios (<500) (Fig. 11c), that so they can be incorporated into the low-Ti/Y (LT, Ti/Y < 500) magma type. In terms of Nb/La ratios, these LT lavas can be further divided into LT1 (Nb/La > 0.85) and LT2 (Nb/La ≤ 0.85) subtypes (Fig. 11c) (Data sources are as in Fig. 7). They comprise basalt and minor basaltic andesite; all of them belong to the tholeiitic series (Fig. 12e, f).

3.4. Niushan, Pingli and Wudangshan blocks

In terms of Ti/Y ratios, the 833−679 Ma basic lavas from the Niushan, Pingli and Wudangshan blocks can be also divided into two major magma types: high-Ti/Y (HT, Ti/Y > 500) and low-Ti/Y (LT, Ti/Y < 500) basalts (Fig. 11d). Moreover, available data permit a further subdivision of the HT and LT groups into HT1 (Nb/La > 0.85) and HT2 (Nb/La ≤ 0.85), and LT1 (Nb/La > 0.85) and LT2 (Nb/La ≤ 0.85) subtypes, respectively (Fig. 11d), on the grounds of Nb/La ratios (Data sources are as in Fig. 7). The HT rocks consist of alkali basalt and minor basalt; most of them belong to the alkaline series except two HT samples that belong to the tholeiitic series (Fig. 12g, h). The LT rocks consist of basalt and minor basaltic andesite; they too belong to the tholeiitic series (Fig. 12g, h).

3.5. South China Block

By virtue of tholeiitic Ti/Y ratios, the 827−746 Ma basic lavas form the South China Block can be also divided into two major magma types: high-Ti/Y (HT, Ti/Y > 500) and low-Ti/Y (LT, Ti/Y < 500) basalts (Fig. 11e). In reference to Nb/La ratios, these HT and LT basalts can be further divided into HT1 (Nb/La > 0.85) and HT2 (Nb/La ≤ 0.85), and LT1 (Nb/La > 0.85) and LT2 (Nb/La ≤ 0.85) subtypes, respectively (Fig. 11e) (Data sources are as in Fig. 7). They consist of basalt, alkali basalt and minor basaltic andesite, basanite; most of the LT lavas belong to the tholeiitic series except one LT1 samples that belong to the alkaline series and most of the HT lavas belong to the alkaline series except two HT samples that belong to the tholeiitic series (Fig. 12i, j).

To sum up, most of the Mid−Late Neoproterozoic basic lavas from the China belong to the tholeiitic series, a part of which consists of the alkaline rocks.

4. Relative contribution of mantle and crust in basic magma generation

Throughout the world, most of the continental rift-related volcanic series can be linked to the asthenospheric mantle (or mantle plumes). However, all of Earth's continental rift-related volcanic rocks show compositional evidence for the involvement of continental lithosphere, including crust and continental lithospheric mantle (CLM), in at least part of their eruptive sequences. We can use the erupted basic lavas to test models of the interactions between the asthenosphere (or plume) and the lithospheric cap for the Mid−Late Neoproterozoic basic lavas in China.

4.1. Evidence for asthenosphere (or plume) involvement

Nb/La ratio is a reliable trace element index of crustal contamination (Kieffer et al., 2004). The Mid−Late Neoproterozoic HT1

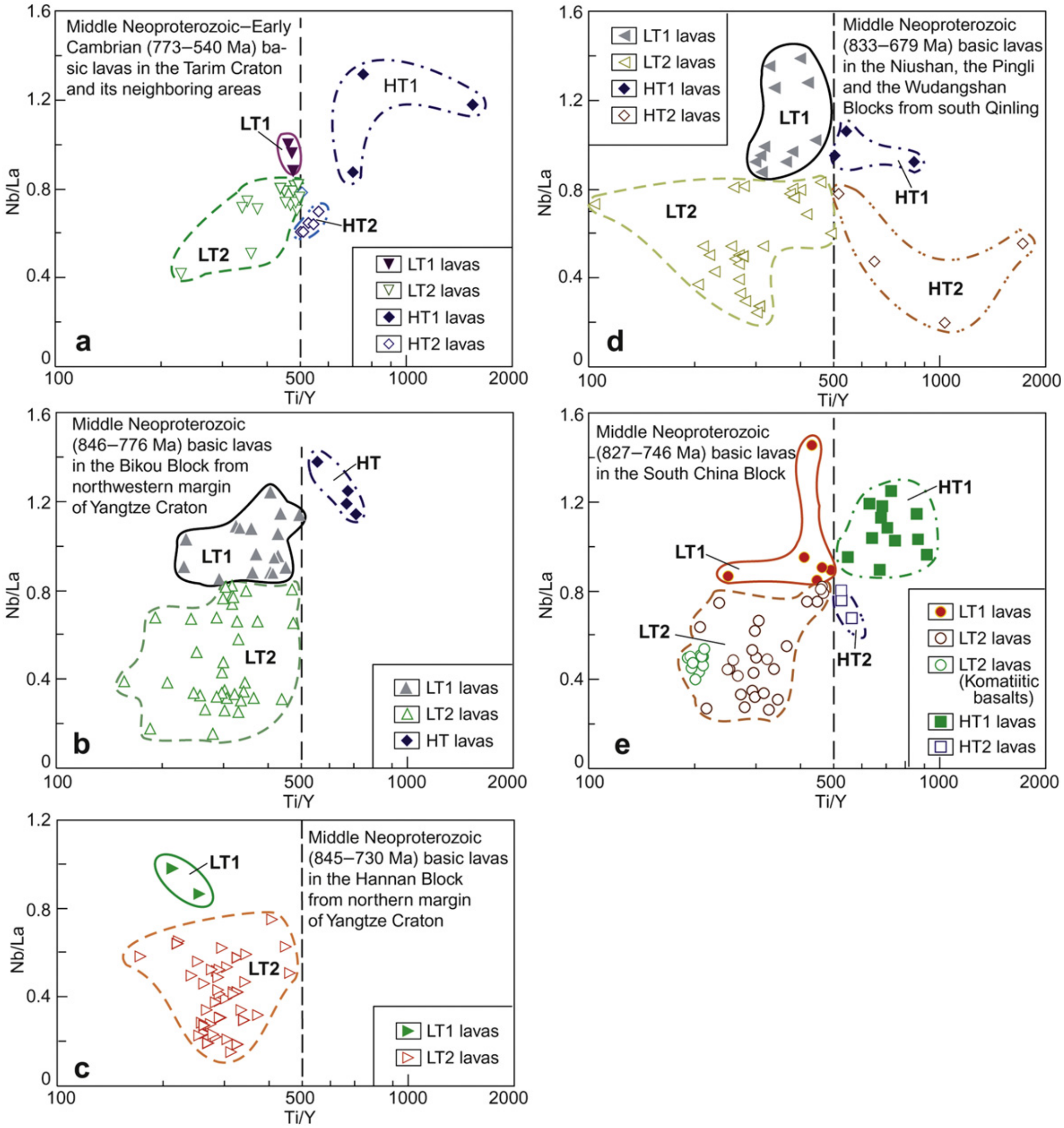

Figure 11 Classification of Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas ($w(SiO_2) \leq 56\%$) in (a) the Tarim Craton and its neighboring areas, (b) the Bikou Block from the northwestern margin of the Yangtze Craton, (c) the Hannan Block from the northern margin of the Yangtze Craton, (d) the Niushan, Pingli and Wudangshan blocks from the South Qinling Orogen, and (e) the South China Block in terms of Ti/Y versus Nb/La. Data sources are as in Fig. 7.

and LT1 lavas from the China have high Nb/La ratios (>0.85) indicating their uncontaminated and slightly contaminated natures (Fig. 11). The majority of HT1 and LT1 lavas exhibit element ratios that overlap with the field of oceanic island basalts (OIB) (Fig. 13). They show "humped" trace element patterns (i.e., absence of negative Nb, Ta and Ti anomalies) that are very similar to OIB except for weakly negative Ta anomaly in minor samples (Fig. 14a, c, e, g, i) (Data sources are as in Fig. 7). These suggest that the HT1 and LT1 lavas may have had some common source and/or process with the OIB.

The variations of $\varepsilon_{Nd}(t)$ values of the Mid–Late Neoproterozoic basic lavas are closely related to the degrees of contamination by continental crust or lithosphere. It can be seen from Fig. 15 that: (1) uncontaminated and slightly contaminated samples (i.e., HT1 and LT1 lavas) constantly exhibit moderate positive $\varepsilon_{Nd}(t)$ values (+1 to +9); (2) strongly contaminated samples (i.e., HT2 and LT2 lavas) are characterized by lower to negative $\varepsilon_{Nd}(t)$ values (−11 to +5). Certain samples with high Nb/La ratios show high $\varepsilon_{Nd}(t)$ (2–6) and low $^{87}Sr/^{86}Sr(t)$ values (0.704–0.705) (Data sources are as in Fig. 7), thus likely reflecting the isotopic signature of the least-contaminated plume component.

Condie (2003, 2005) suggested that it is possible to characterize some of the isotopic mantle domains with four immobile incompatible element ratios: Nb/Th, Zr/Nb, Zr/Y and Nb/Y. These HFSE ratios have the advantage that they do not change with time as isotopic ratios do, and neither are they affected by secondary alteration. As Condie (2005) suggested the Zr-Y-Nb relationships (Fig. 16) can separate plume from non-plume basaltic sources. On

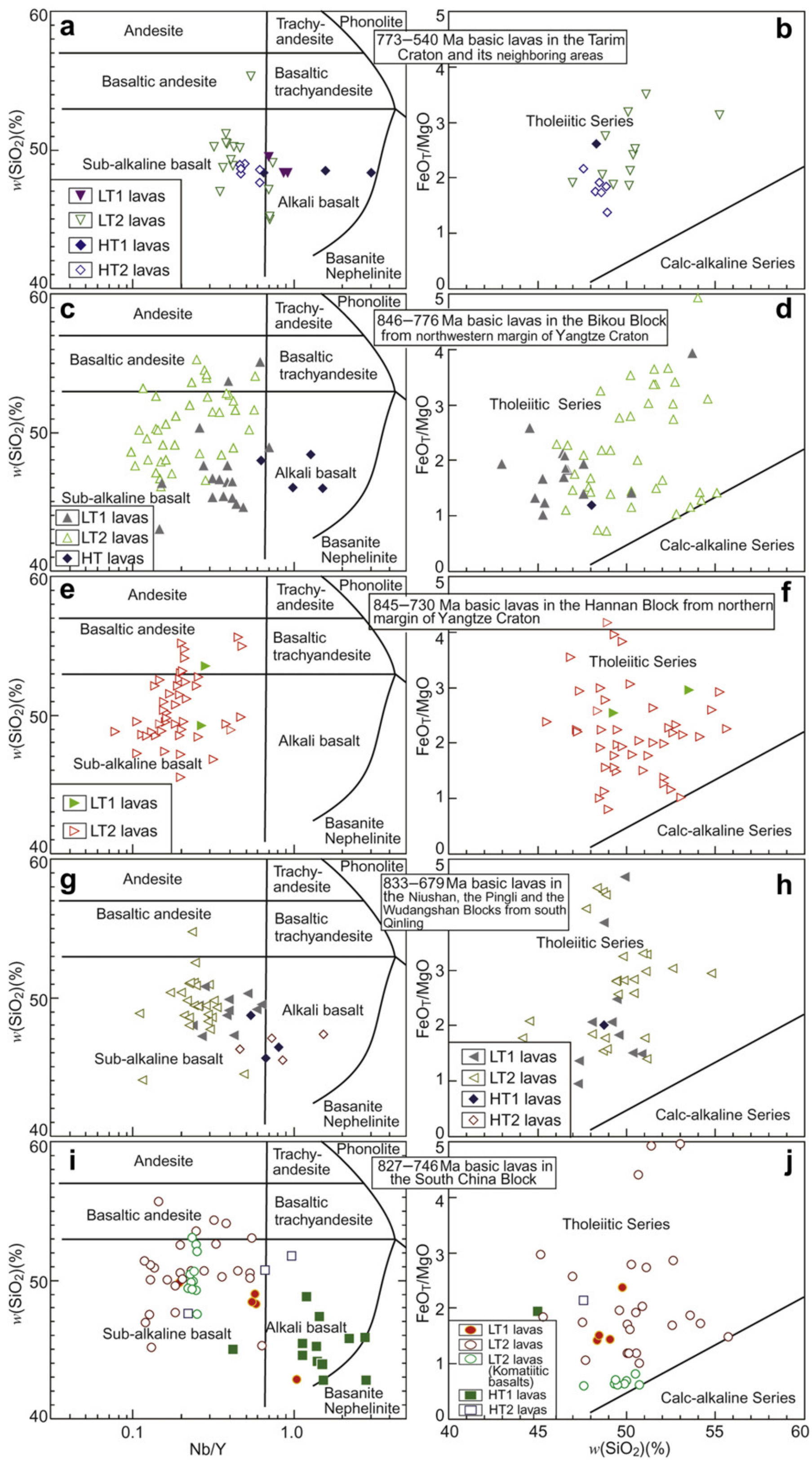

Figure 12 (a)(c)(e)(g)(i) $w(SiO_2)$ versus Nb/Y diagrams (after Winchester and Floyd, 1977) and (b)(d)(f)(h)(j) FeOT/MgO versus $w(SiO_2)$ diagrams (after Miyashiro, 1975) for Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas ($w(SiO_2) \leq 56\%$) from China. Fig. 12b, d, f, h, j show the sub-alkaline volcanic rocks as plotted in Fig. 12a, c, e, g, i respectively. Data sources are as in Fig. 7.

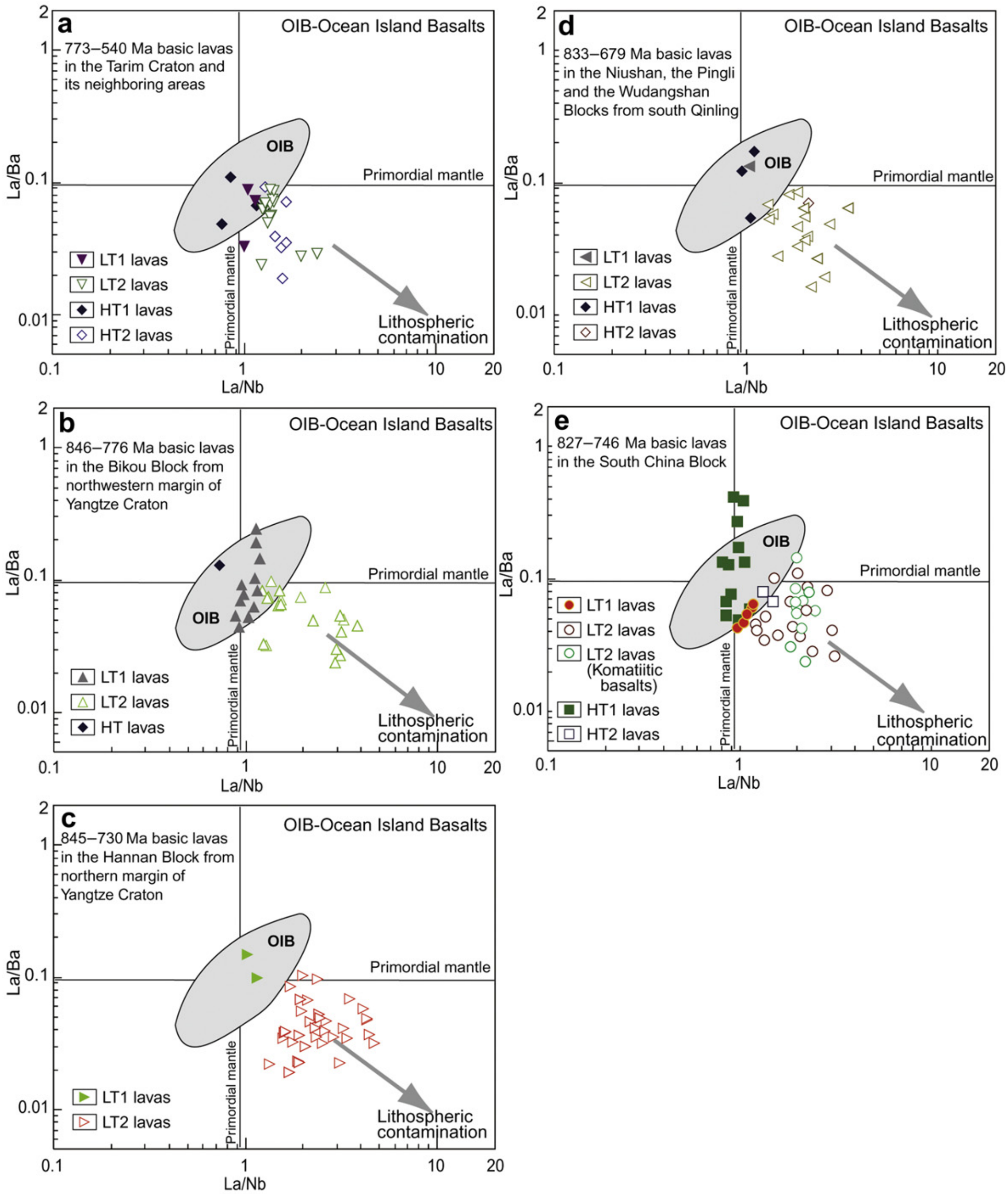

Figure 13 La/Ba versus La/Nb plots for Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas ($w(SiO_2) \leq 56\%$) in (a) the Tarim Craton and its neighboring areas, (b) the Bikou Block from the northwestern margin of the Yangtze Craton, (c) the Hannan Block from the northern margin of the Yangtze Craton, (d) the Niushan, Pingli and Wudangshan blocks from the South Qinling Orogen, and (e) the South China Block. The dispersion to higher La/Nb and lower La/Ba ratios may represent the effects of crustal contamination. Field for oceanic island basalts (OIB) is after Fitton et al. (1991) and Fitton (1995). Data sources are as in Fig. 7.

the Zr/Y-Nb/Y diagram (Fig. 16), basalts plotting below the ΔNb line come from either a shallow depleted source (DM), or they represent plume-derived basalts that have been contaminated by continental crust or/and subcontinental lithosphere. In addition, the Zr-Y-Nb relationships also provide useful geochemical fingerprints to distinguish basalts derived from a plume head source (e.g., Oceanic Plateau Basalts) and basalts derived from a plume tail source (e.g., Oceanic Island Basalts).

Fig. 16 clearly shows that most Mid–Late Neoproterozoic uncontaminated and slightly contaminated LT1 basalts from China plot above the ΔNb line in the mantle plume field defined by the deep depleted plume component (DEP) and the primitive mantle component (PM). This is consistent with the aforementioned major and trace element and isotope geochemical evidence for plume-derived basalts of LT1 lavas. Another feature, suggested by Fig. 16, is the presence of a significant contribution of a recycled

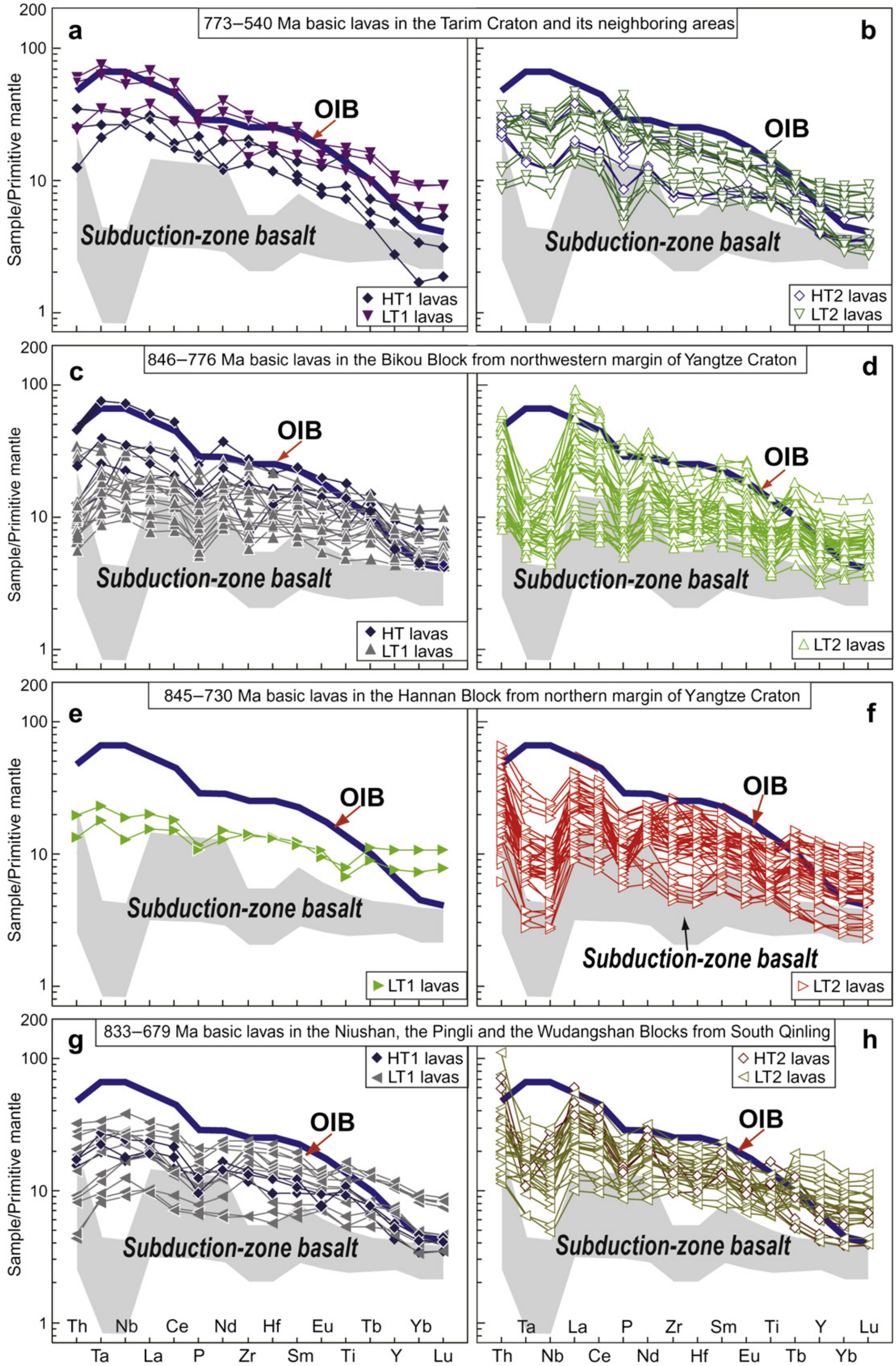

Figure 14 Primitive mantle (after Sun and McDonough, 1989) normalized incompatible trace-element spider diagrams for Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas ($w(SiO_2) \leq 56\%$) in (a, b) the Tarim Craton and its neighboring areas, (c, d) the Bikou Block from the northwestern margin of the Yangtze Craton, (e, f) the Hannan Block from the northern margin of the Yangtze Craton, (g, h) the Niushan, Pingli and Wudangshan blocks from the South Qinling Orogen, and (i, j) the South China Block.

Patterns for oceanic island basalts (OIB) are from Sun and McDonough (1989). The shaded area shows the range for subduction-zone basalts, with the lower and upper limits being defined by "average" low-K and high-K basalts, respectively (Tatsumi and Eggins, 1995). Data sources are as in Fig. 7.

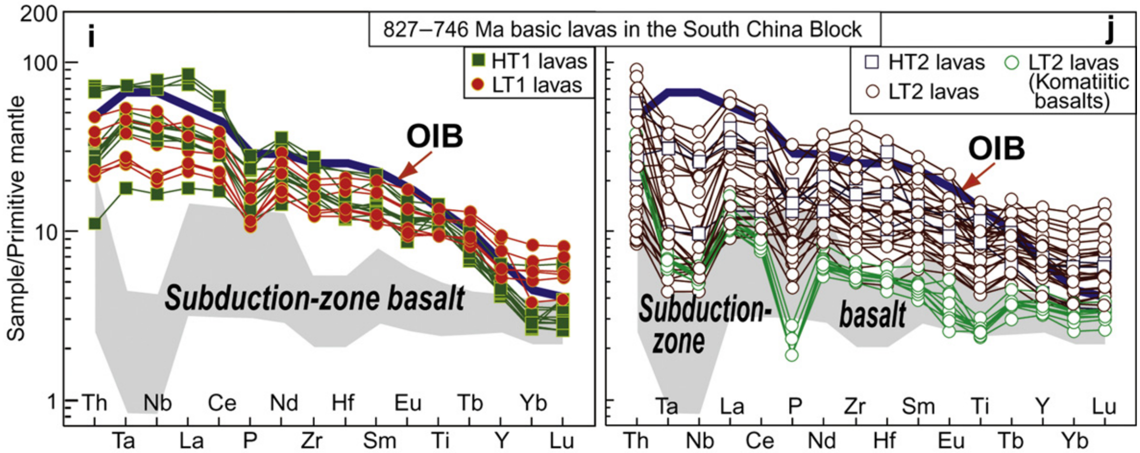

Fig. 14 (continued)

mantle component (REC) for the uncontaminated and slightly contaminated HT and HT1 lavas from the Tarim Craton, the Bikou, South China, and the Niushan, the Pingli and the Wudangshan blocks, respectively. All these indicate that the LT1 lavas might be derived from a plume head and the HT and HT1 lavas might be derived from a plume tail.

4.2. Lithospheric signature: CLM or crustal contamination

The HT2 and LT2 lavas are characterized by low Nb/La ($\leq$0.85; Fig. 11), high large-ion lithophile element concentrations and pronounced negative Nb, Ta, Zr, Hf and Ti anomalies (Fig. 14b, d, f, h, j) suggesting that components other than a plume must have been involved in the generation and evolution of the Mid–Late Neoproterozoic basic lavas from China (Data sources are as in Fig. 7). The most likely components are from the lithosphere. There are still debates regarding the method by which the lithosphere contributes to magma generation. Either contamination of plume-derived magmas by lithosphere-derived melts (Arndt et al., 1993) or whole-scale melting of the subcontinental lithospheric mantle (CLM, Gallagher and Hawkesworth, 1992; Hooper et al., 1995; Hawkesworth et al., 1995; Rogers et al., 1995) or melt-rock reaction resulting from the infiltration of plume-derived magmas into the lithosphere in a process related to the thermo-mechanical erosion of the lithosphere mantle (Macdonald et al., 2001) has been proposed. We adopt the third opinion of Macdonald et al. (2001) in this study.

Incompatible elements such as La or Ba should increase relative Nb if basaltic magma is contaminated by lithospheric material, which usually has high La/Nb, Ba/Nb and low La/Ba (Weaver and Tarney, 1984; Wedepohl, 1995). Fig. 13 displays the variations of La/Nb against La/Ba for the Mid–Late Neoproterozoic basic lavas from China, in comparison with the field of OIB (Fitton et al., 1991; Fitton, 1995). Majority of HT2 and LT2 lavas have higher La/Nb and lower La/Ba ratios indicative of the influence of crustal or/and subcontinental lithospheric component.

The Mid–Late Neoproterozoic HT2 and LT2 lavas from China are characterized by lower to negative $\varepsilon_{Nd}(t)$ (−11 to +5) (Fig. 15) and variable $^{87}Sr/^{86}Sr(t)$ (0.704–0.712) (Data sources are as in Fig. 7). These may be related to the contamination of an older continental lithosphere and the HT2 and LT2 lavas are lithospherically contaminated continental basalts derived from the asthenosphere or plume. It must be pointed out that although both of lithospheric contamination and slab-derived fluid and/or melts could lead to low Nb/La ratios, only the former could yield significantly negative $\varepsilon_{Nd}(t)$ values.

It can be seen from Fig. 16 that most HT2 and LT2 lavas fall into the field defined by the enriched component (EN), and they represent plum-derived basalts that have been contaminated by continental crust or/and subcontinental lithosphere. This is also consistent with the aforesaid conclusions obtained on major and trace element and isotope geochemical studies.

Some chemical and isotopic composition of the HT2 and LT2 lavas may inherit that of the CLM. However, as already mentioned, the Mid–Upper Neoproterozoic rift-related volcanic rocks are widespread on the Precambrian continental blocks in China. Thus, it is difficult to imagine that such a large volume of magma was generated by melting of the lithospheric mantle alone, which has been stable for a long time period in a non-convective state. The thermomechanic model suggests that only a small amount of melts can be produced from the lithospheric mantle by conduction of heat from mantle plume (McKenzie and Bickle, 1988; Arndt and Christensen, 1992). Generation of the Mid–Late Neoproterozoic basalts from China due to melting of the subcontinental lithospheric mantle is considered as unlikely although a contribution from the subcontinental lithospheric mantle cannot be excluded.

In summary, the generation of large amount of the Mid–Late Neoproterozoic basalts from China is likely confined to convective asthenosphere or plume. The geochemical variation of the HT2 and LT2 lavas can therefore be accounted for by lithospheric contamination of plume-derived magmas.

5. Discrimination of tectonic setting for the Mid–Late Neoproterozoic basaltic rocks in China

As mentioned above on geologic background, there have been two different opinions concerning the geological setting of the Mid–Upper Neoproterozoic volcanic rocks in China: products of intraplate volcanism, and formed in either collisional or arc settings. Recent geological studies indicate that by ca. 900 Ma all the present major known Precambrian continental blocks in northwestern, central and southern China, such as the Tarim Craton and its adjacent blocks and the Yangtze Craton and the Cathaysia Block and their neighboring blocks, had aggregated to

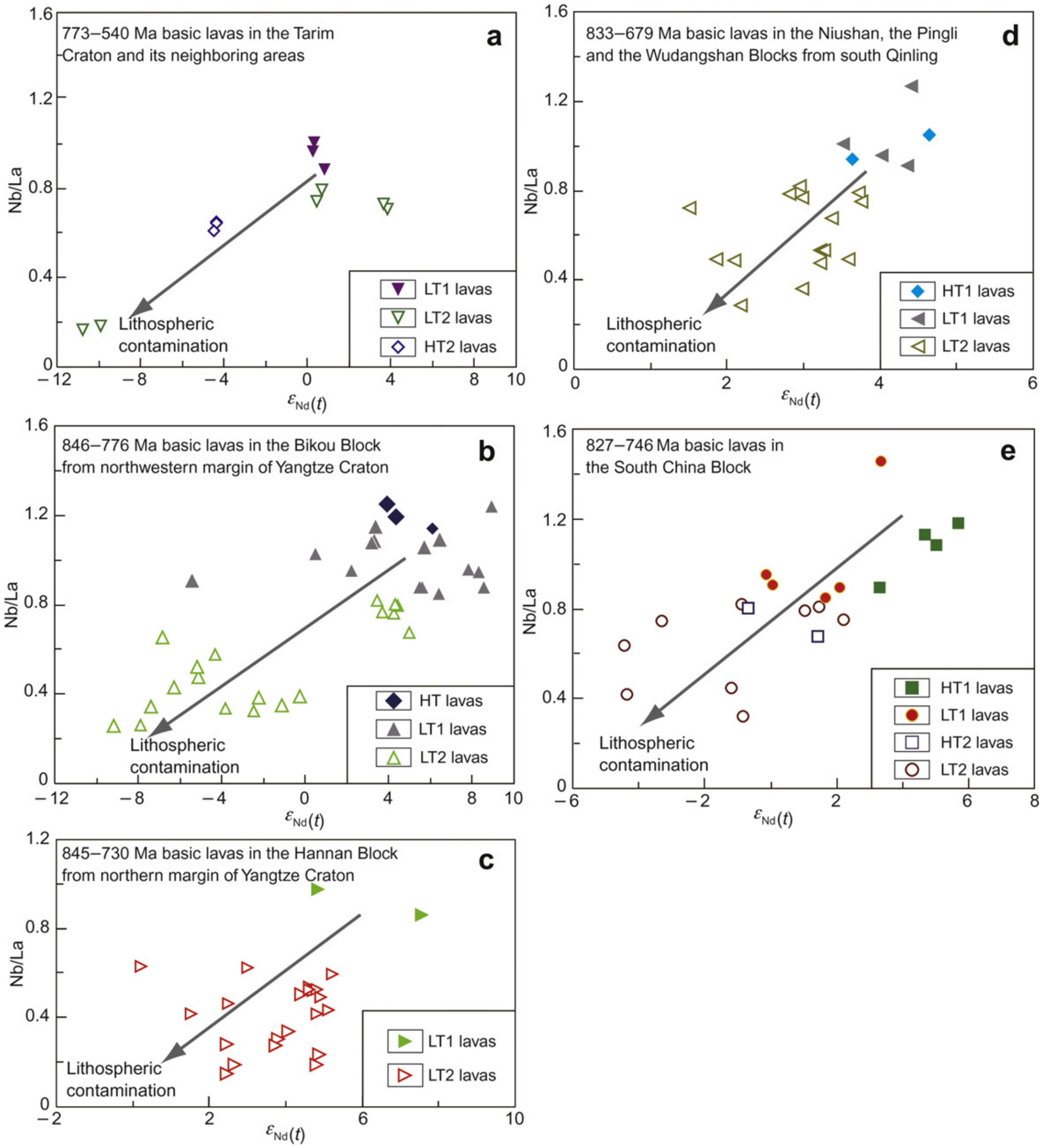

Figure 15 Nb/La versus $\varepsilon_{Nd}(t)$ diagrams for Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas ($w(SiO_2) \le 56\%$) in (a) the Tarim Craton and its neighboring areas, (b) the Bikou Block from the northwestern margin of the Yangtze Craton, (c) the Hannan Block from the northern margin of the Yangtze Craton, (d) the Niushan, Pingli and Wudangshan blocks from the South Qinling Orogen, and (e) the South China Block. Data sources are as in Fig. 7.

form part of the Rodinia supercontinent (Li et al., 2008c). Evidences for ca. 900 Ma orogenic events include the ca. 920–880 Ma arc volcanics and ophiolite obduction in the eastern Sibao Orogen of South China (Li et al., 2005b, 2009a), and the ca. 1048–933 Ma granites (Shu et al., 2011) and the ca. 1.1–0.9 Ga tectonothermal event recorded in the Xinditaga Group (Zhang et al., 2011a) in the Kuluketage area of the Tarim Craton. The former is the time when the Cathaysia (part of Laurentia) collided with the Yangtze plate and the latter may also be the time when the Tarim joined Australia (Li et al., 2008c). Thus, all the abovementioned major known continental blocks from China were in an intraplate setting during the Mid-Neoproterozoic period.

Geochemical studies can be used to discriminate the tectonic settings for volcanic rocks. Here, it must be pointed out that "contamination by continental crust or lithosphere can impart subduction-type signatures (e.g., low Nb, low Ta and low Ti) and lead to the misidentification of contaminated continental basalts as arc related" (Ernst et al., 2005; Xia et al., 2007b, 2008b). When we utilize Zr/Y-Zr diagram, it can be seen that most of the Mid–Late Neoproterozoic basic lavas from China plot in the within-plate basalts (WPB) field (Fig. 17a). In contrast, when several geochemical diagrams (Fig. 17b–d) using Nb, Ta or Ti as discriminating factors are utilized, it can be observed that uncontaminated and slightly contaminated samples (i.e., HT1 and

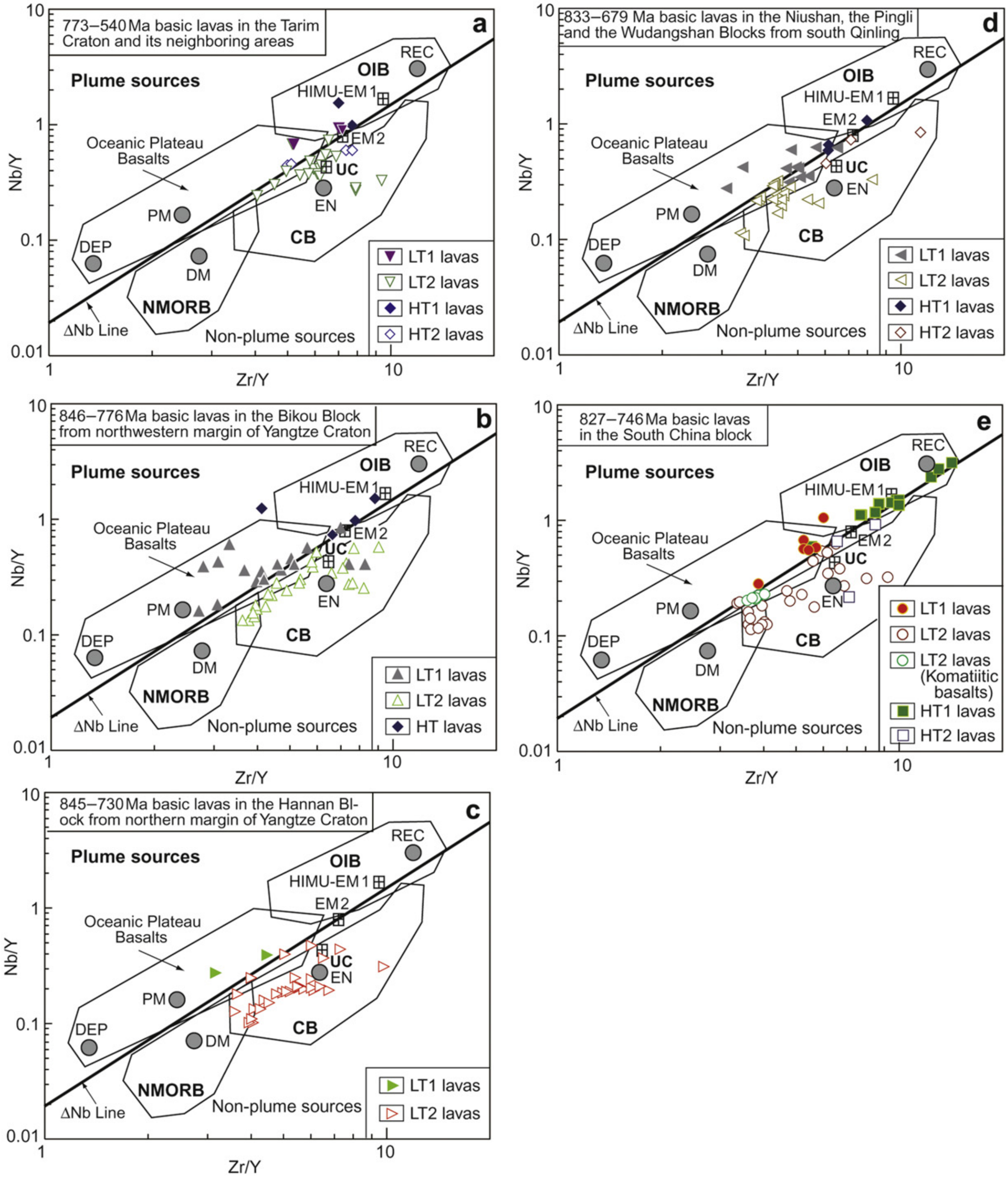

Figure 16 Zr/Y versus Nb/Y diagrams (diagrams after Condie, 2005) for Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas ($w(SiO_2) \leq 56\%$) in (a) the Tarim Craton and its neighboring areas, (b) the Bikou Block from the northwestern margin of the Yangtze Craton, (c) the Hannan Block from the northern margin of the Yangtze Craton, (d) the Niushan, Pingli and Wudangshan blocks from the South Qinling Orogen, and (e) the South China Block.

Abbreviations: UC – upper continental crust; CB – contaminated (by continental crust or/and subcontinental lithosphere) basalts; PM – primitive mantle; DM – shallow depleted mantle; HIMU – high-μ (U/Pb) source; EM1 and EM2 – enriched mantle sources; OIB – oceanic island basalt; DEP – deep depleted mantle; EN – enriched component; REC – recycled component. Data sources are as in Fig. 7.

LT1 lavas with Nb/La > 0.85) still plot in the WPB field, but the plots of all other contaminated samples (i.e. HT2 and LT2 lavas with Nb/La ≤ 0.85) displace toward lower Nb, Ta or Ti and into the island-arc field. In this case, we cannot regard the lithospherically contaminated basic lavas as arc related. Besides, although the HT2 and LT2 lavas, which generally belong to the tholeiitic series (Fig. 12), are characterized by low Nb/La ratios (≤0.85) and depletions in Nb, Ta and Ti (Fig. 14b, d, f, h, j), their concentrations of incompatible trace elements are conspicuously higher than those of subduction-zone basalts (Fig. 14b, d, f, h, j). The HT2 and LT2 lavas cannot be regarded, therefore, as volcanic arc basalts, and they are lithospherically contaminated continental

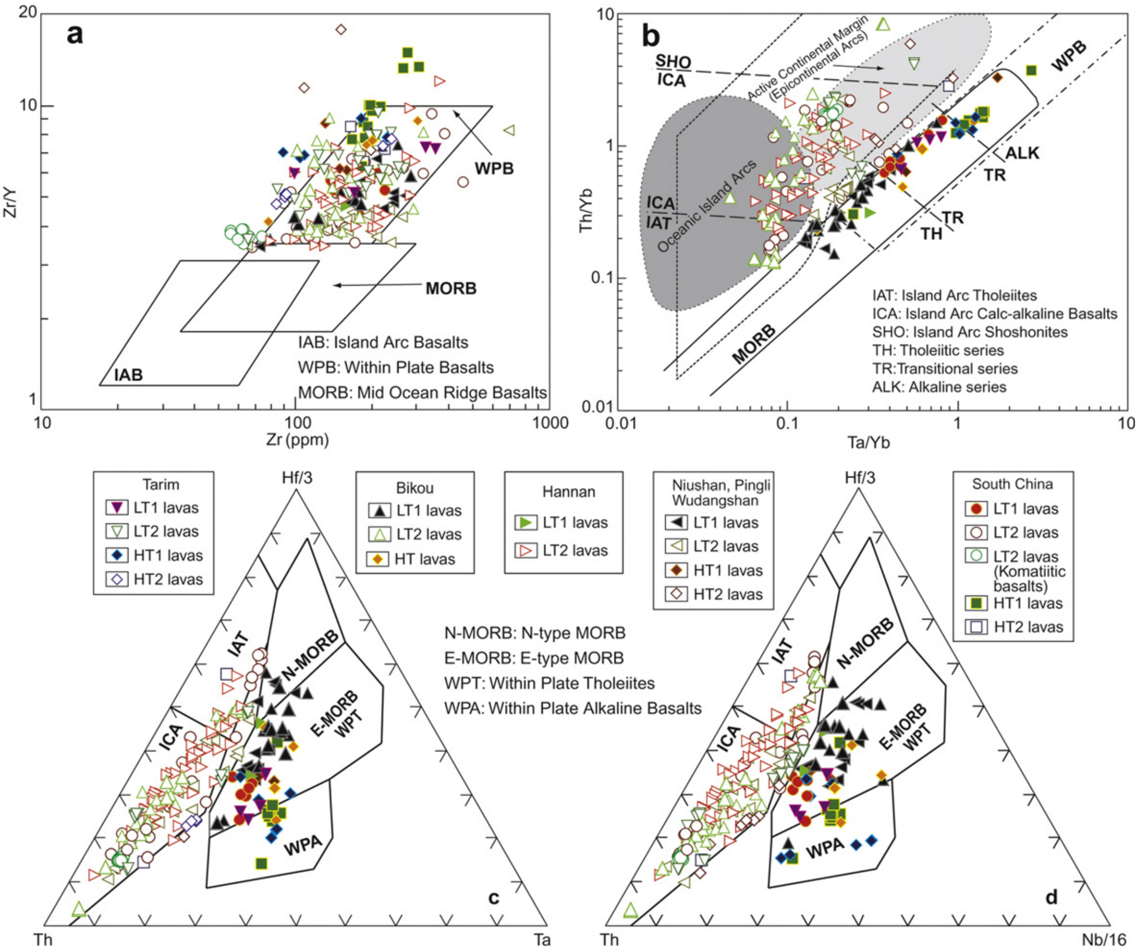

Figure 17 Tectonic setting of Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas ($w(SiO_2) \leq 56\%$) from China. (a) Zr/Y versus Zr diagram (after Pearce, 1982); (b) Th/Yb versus Ta/Yb diagram (after Pearce, 1982); (c) Hf/3-Th-Ta diagram (after Wood, 1980); (d) Hf/3-Th-Nb/16 diagram (after Wood, 1980). Data sources are as in Fig. 7.

basalts. Thus, the Mid–Late Neoproterozoic basic lavas from China did indeed erupt in an intracontinental rift setting based on geochemical discrimination. This is consistent with the geological evidence for an intracontinental rift setting.

In addition, as already mentioned, the variations of $\varepsilon_{Nd}(t)$ values of the Mid–Late Neoproterozoic basic lavas from China are closely related to the degrees of contamination by continental crust or lithosphere. Fig. 15 shows that: (1) uncontaminated and slightly contaminated samples (i.e., HT1 and LT1 lavas) constantly exhibit moderate positive $\varepsilon_{Nd}(t)$ values (+1 to +9); (2) strongly contaminated samples (i.e., HT2 and LT2 lavas) are characterized by lower to negative $\varepsilon_{Nd}(t)$ values (−11 to +5). The lower to negative $\varepsilon_{Nd}(t)$ values of HT2 and LT2 lavas may be related to the contamination of an older continental lithosphere. The above characteristics of variations of $\varepsilon_{Nd}(t)$ values also demonstrate that the Mid–Late Neoproterozoic basic lavas from China were formed in an intracontinental rift setting rather than in an island-arc setting.

6. Melting conditions and source characteristics

REEs such as La, Gd and Yb are particularly useful, because their relative abundances are strongly dependent on the degree of partial melting and nature of aluminous phase (spinel or garnet) in the mantle source. Here, we adopt the REE modeling of Reichow et al. (2005, Fig. 18), to illustrate the depth and degree of melting necessary to account for the variation in REE ratios of the Mid–Late Neoproterozoic basic lavas from China, and to constrain whether spinel or garnet was present in the source.

The data of Mid–Late Neoproterozoic basic lavas from China form positive arrays on the diagrams of La/Yb versus Gd/Yb (Fig. 18) (Data sources are as in Fig. 7). The $Gd/Yb_{(BSE)}$ ratio in the Mid–Late Neoproterozoic basic lavas from China varies only slightly (1–5), whereas $La/Yb_{(BSE)}$ displays much higher variation (2–30). Large variations in La/Yb can be related to changes in the degree of partial melting, fractional crystallization and to crustal contamination, or a combination of these. Melts parental to the HT2 and LT2 lavas were contaminated by continental lithosphere, which has a strong influence on the La/Yb ratio but minor effects on Gd/Yb. Therefore, we use only the uncontaminated and slightly contaminated samples (i.e., HT1 and LT1 lavas) for discussion.

Fig. 18 shows that the LT1 lavas lie within the garnet–spinel transition zone or are superimposed on the modeled partial melting trend defined by garnet peridotite with an initial bulk silicate earth (BSE) source composition at 3 GPa or lie within the garnet stability field at 3–4 GPa with degrees of melting being in the range of 5%–30%, and the HT1 lavas lie within the garnet stability field at 3–4 GPa or are superimposed on the modeled

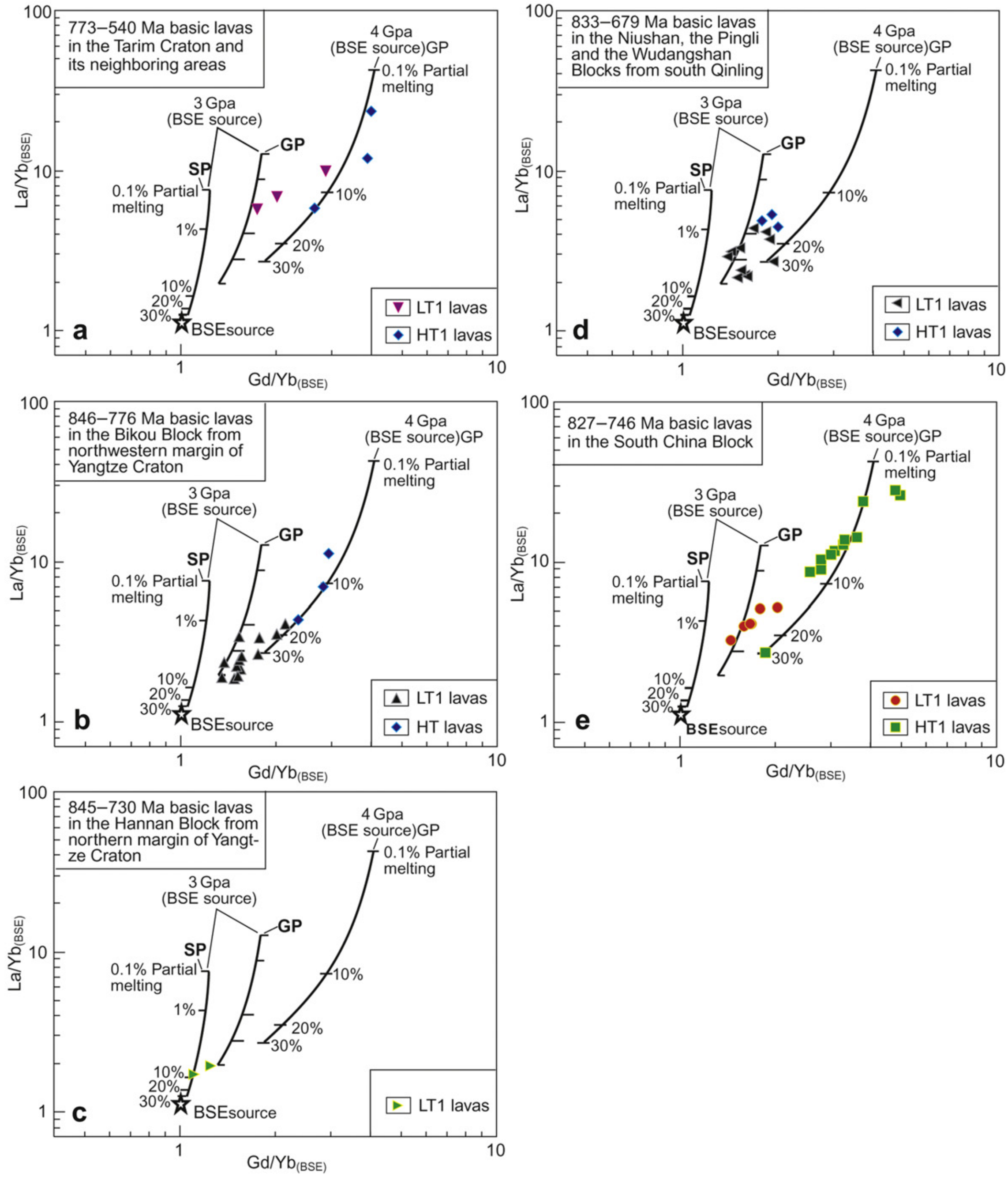

Figure 18 La/Yb versus Gd/Yb [normalized to bulk silicate earth (BSE): McDonough and Sun, 1995] plots of Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas ($w(SiO_2) \leq 56\%$) in (a) the Tarim Craton and its neighboring areas, (b) the Bikou Block from the northwestern margin of the Yangtze Craton, (c) the Hannan Block from the northern margin of the Yangtze Craton, (d) the Niushan, Pingli and Wudangshan blocks from the South Qinling Orogen, and (e) the South China Block.
The trend lines are non-modal batch melting curves calculated by Reichow et al. (2005) for an initial BSE (bulk silicate earth) source. Bulk distribution coefficients were calculated by Reichow et al. (2005) using mineral proportions for garnet peridotite (GP) at 3 and 4 GPa after Walter (1998) and spinel peridotite (SP) at 3 GPa given by McKenzie and O'Nions (1991). Distribution coefficients used for the REE are from Hanson (1980) and Hart and Dunn (1993). Partial melting of the BSE source for garnet peridotite and spinel peridotite is indicated by the trend lines (GP) and (SP), respectively. Data sources are as in Fig. 7.

partial melting trend defined by garnet peridotite with BSE source composition at 4 GPa and degrees of melting <20%.

All of these indicate that the HT1 lavas were generated at a larger depth by lower degrees of partial melting from the mantle plume, and the LT1 lavas were, in contrast, derived by higher degrees of partial melting at shallower levels.

7. Implications for rifting and break-up of Rodinia supercontinent

The Mid–Late Neoproterozoic intracontinental rift-related volcanism that occurred on several Precambrian continental

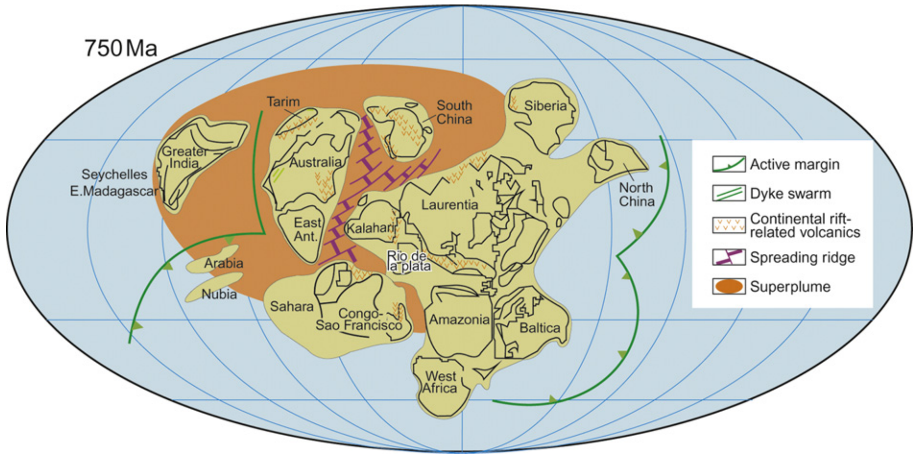

Figure 19 Cartoon diagram showing the break-up of Rodinia at ca. 750 Ma (modified after Li et al., 2008c).

blocks from China is comparable with the synchronous rift-related volcanism on other Rodinian continents including Australia, Laurentia, South Korea, India and the Seychelles (e.g., Parrish and Scammell, 1988; Heaman et al., 1992; Su et al., 1994; Zhao et al., 1994; Fetter and Goldberg, 1995; Park et al., 1995; Lee et al., 1998, 2003; Bhushan, 2000; Preiss, 2000; Frimmel et al., 2001; Ashwal et al., 2002; Li et al., 1999b, 2002a,b,c, 2003b, 2005a,b,c, 2006, 2008a,b,c, 2009b; Ling et al., 2003; Shellnutt et al., 2004; Song et al., 2010; Wang et al., 2007, 2008, 2009; Wang et al., 2010; Xu et al., 2005; Xia et al., 1996a,b, 2002, 2007a,b,c, 2008a, 2009a,b; Zhang et al., 1999a,b; Zhang et al., 2010). This global intraplate volcanism has commonly been attributed to mantle plumes or a mantle superplume (e.g., Heaman et al., 1992; Zhao et al., 1994; Park et al., 1995; Li et al., 1999b, 2003b, 2005a, 2006, 2008a,b,c, 2009b; Frimmel et al., 2001; Shellnutt et al., 2004; Song et al., 2010; Wang et al., 2007, 2008, 2009; Wang et al., 2010; Xia et al., 2007a,c, 2008a, 2009a,b; Zhang et al., 2010) that caused rifting and the final break-up of the supercontinent Rodinia.

Available data reveal that the Mid–Late Neoproterozoic rift-related volcanic activities in China can be divided into two stages: the first stage from ca. 848 Ma to 679 Ma mainly occurred in Qaidam and the South China Block and neighboring blocks and the second stage from ca. 773 Ma to 540 Ma mainly took place in Tarim Craton and adjacent blocks.

The rift-related volcanic successions of the first stage in Qaidam and South China are also found in Australia (Zhao et al., 1994; Wingate et al., 1998), India (Radhakrishna and Mathew, 1996), Kalahari (Frimmel et al., 2001), Arabian–Nubian terranes (Stein and Goldstein, 1996; Teklay et al., 2002) and Laurentia (Su et al., 1994; Aleinikoff et al., 1995; Fetter and Goldberg, 1995). Li et al. (2008c) suggested that by ca. 750 Ma, the western half of Rodinia may have started to break apart (Fig. 19). The pulse of volcanism at the end of the first stage may be interpreted as representing the break-up and opening of a wide ocean, first between Australia–East Antarctica and South China, and then between South China and Laurentia.

In the rift-related volcanic successions of the second stage, the Early Cambrian basic volcanic units in northeastern Tarim may correlate with the Early Cambrian Kalkarindji basalts in central and northern Australia (Li et al., 1996, 2008c; Evins et al., 2009), which may be interpreted as representing the separating between Australia and Tarim.

Thus, the break-up of Rodinia occurred diachronously (Li et al., 2008c). The Mid–Late Neoproterozoic rift-related volcanism from China is the response to rifting and break-up of Rodinia, and is also the precursor of the opening of the global Early Paleozoic Ocean.

8. Summary and conclusions

Mid–Late Neoproterozoic volcanic rocks are widespread on several Precambrian continental blocks in China, which had aggregated to form part of the Rodinia supercontinent by ca. 900 Ma. These volcanic rocks consist mainly with huge volumes of basic rocks and variable amounts of silicic volcanics, with small amounts or an absence of intermediate rocks that display a compositional bimodality. Although the tectonic affiliations of these volcanics are still controversial, our studies demonstrate that they were formed in an intracontinental rift setting rather than in an island-arc setting.

On the basis of petrogeochemical data, the rift-related basic lavas can be classified into two major magma types: HT ($Ti/Y > 500$) and LT ($Ti/Y < 500$). According to Nb/La ratios, the HT and LT lavas can be further divided into HT1 ($Nb/La > 0.85$) and HT2 ($Nb/La \leq 0.85$), and LT1 ($Nb/La > 0.85$) and LT2 ($Nb/La \leq 0.85$) lavas, respectively. The predominant geochemical signatures of these studied volcanic magmas are inferred to be derived from deep-seated mantle plumes. The available elemental and Sr-Nd isotope data suggest that geochemical variation of the HT2 and LT2 lavas can be accounted for by lithospheric contamination of plume-derived magmas, whereas the parental magmas of the HT1 and LT1 lavas have not undergone pronounced lithospheric contamination during their ascent.

The Mid–Late Neoproterozoic rift-related volcanism in China was part of global rift-related volcanism during the rifting and break-up of Rodinia supercontinent. The break-up of Rodinia occurred diachronously. The rift-related volcanic activities at the end of the Mid-Neoproterozoic coincided temporally with the breaking apart of Australia–East Antarctica, South China and Laurentia. The Early Cambrian rift-related volcanism is interpreted as having occurred during and to be a proxy for the separation of Australia and Tarim.

Acknowledgments

The constructive reviews of two anonymous reviewers greatly improved an early version of the manuscript. This research benefited from financial support from the Land and Resources Survey Project of China (Grants # 1212010611804, 121201120133) and the National Natural Science Foundation of China (Grant # 40472044). Dr. Susan Turner (Brisbane) assisted with English.

References

Aleinikoff, J.N., Zartman, R.E., Walter, M., Rankin, D.W., Lyttle, P.T., Burton, W.C., 1995. U-Pb ages of metarhyolites of the Catoctin and Mount Rogers formations Central and Southern Appalachians: evidence for two pulses of Lapetan rifting. American Journal of Science 295, 428−454.

Arndt, N.T., Christensen, U., 1992. The role of lithospheric mantle in continental flood volcanism: thermal and geochemical constraints. Journal of Geophysical Research 97, 10967−10981.

Arndt, N.T., Czamanske, G.K., Wooden, J.L., Fedorenko, V.A., 1993. Mantle and crustal contributions to continental flood volcanism. Tectonophysics 223, 39−52.

Ashwal, L.D., Demaiffe, D., Torsvik, T.H., 2002. Petrogenesis of Neoproterozoic granitoids and related rocks from the Seychelles: the case for an Andean-type arc origin. Journal of Petrology 43, 45−83.

Bhushan, S.K., 2000. Malani rhyolites—a review. Gondwana Research 3, 65−77.

Chen, D.F., Pan, J.M., Xu, W.X., Che, G.Q., Chen, X.P., 1998. Geochemistry of Sinian basalts from South China and its tectonic setting. Acta Petrologica Sinica 14, 343−350 (in Chinese with English abstract).

Chen, Y., Xu, B., Zhan, S., Li, Y., 2004. First mid-Neoproterozoic paleomagnetic results from the Tarim Basin (NW China) and their geodynamic implications. Precambrian Research 133, 271−281.

Condie, K.C., 2003. Incompatible element ratios in oceanic basalts and komatiites: tracking deep mantle sources and continental growth rates with time. Geochemistry Geophysics Geosystems 4 (1), 1005.

Condie, K.C., 2005. High field strength element ratios in Archean basalts: a window to evolving sources of mantle plumes? Lithos 79, 491−504.

Duncan, A.R., 1987. The Karoo igneous province − a problem area for inferring tectonic setting from basalt geochemistry. Journal of Volcanology and Geothermal Research 32, 13−34.

Ernst, R.E., Buchan, K.L., Campbell, I.H., 2005. Frontiers in large igneous province research. Lithos 79, 271−297.

Evins, L.Z., Jourdan, F., Phillips, D., 2009. The Cambrian Kalkarindji Large Igneous Province: extend and characteristics based on new $^{40}Ar/^{39}Ar$ and geochemical data. Lithos 110, 294−304.

Fetter, A.H., Goldberg, S.A., 1995. Age and geochemical characteristics of bimodal magmatism in the Neoproterozoic Grandfather Mountain Rift Basin. Journal of Geology 103, 313−326.

Fitton, J.G., 1995. Coupled molybdenum and niobium depletion in continental basalts. Earth and Planetary Science Letters 136, 715−721.

Fitton, J.G., James, D., Leeman, W.P., 1991. Basic magmatism associated with the late Cenozoic extension in the western United States: compositional variations in space and time. Journal of Geophysical Research 96, 13693−13711.

Forst, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Forst, C.D., 2001. A geochemical classification for granitic rocks. Journal of Petrology 42, 2033−2048.

Forst, B.R., Forst, C.D., 2008. On charnockites. Gondwana Research 13, 30−44.

Frimmel, H.E., Zartman, R., Späth, E., 2001. The Richtersveld igneous complex, South Africa: U-Pb zircon and geochemical evidence for the beginning of Neoproterozoic continental breakup. Journal of Geology 109, 493−508.

Gallagher, K., Hawkesworth, C.J., 1992. Dehydration melting and the generation of continental flood basalts. Nature 358, 57−59.

Gao, Z.J., Chen, J.B., Lu, S.N., Peng, C.W., Qin, Z.Y., 1993. The Precambrian Geology in Northern Xinjiang. Geological Publishing House, Beijing, 171 pp (in Chinese with English abstract).

Gao, Z.J., Chen, K.Q., 2003. The Nanhua System of Xinjiang and some geological issues of Nanhua System in China. Geological Survey and Research 26, 8−14 (in Chinese with English abstract).

Gao, Z.J., Wang, W.Y., Peng, C.W., Li, Y.A., Xiao, B., 1985. Sinian System in Xinjiang, China. Xinjiang People's Publishing House, Urumqi, 173 pp (in Chinese with English abstract).

Ge, W.C., Li, X.H., Li, Z.X., Zhou, H.W., Wang, J., Lee, C.Y., 2000. "Longsheng ophiolite" in North Guangxi revised. Acta Petrologica Sinica 16, 111−118 (in Chinese with English abstract).

Guo, Z.J., Yin, A., Bobinson, A., Jia, C.Z., 2005. Geochronology and geochemistry of deep-drill-core samples from the basement of the central Tarim basin. Journal of Asian Earth Sciences 25, 45−56.

Hanson, G.N., 1980. Rare earth elements in petrogenetic studies of igneous systems. Annual Review of Earth and Planetary Sciences 8, 371−406.

Hart, S.R., Dunn, T., 1993. Experimental cpx/melt partitioning of 24 trace elements. Contributions to Mineralogy and Petrology 113, 1−8.

Hawkesworth, C., Turner, S., Gallagher, K., Hunter, A., Bradshaw, T., Rogers, N., 1995. Calc-alkaline magmatism, lithospheric thinning and extension in the Basin and Range. Journal of Geophysical Research 100, 10271−10286.

Heaman, L.M., LeCheminant, A.N., Rainbird, R.H., 1992. Nature and timing of Franklin igneous events, Canada: implications for a Late Proterozoic mantle plume and the breakup of Laurentia. Earth and Planetary Science Letters 109, 117−131.

Hooper, P.R., Bailey, D.G., McCarley Holder, G.A., 1995. Tertiary calc-alkaline magmatism associated with lithospheric extension in the Pacific Northwest. In: Smith, E.I., Metcalf, R.V. (Eds.), Magmatism and Extension. Journal of Geophysical Research vol. 100, 10303−10319.

Jiang, C.Y., Wu, W.K., Li, L.C., Mu, Y.M., Bai, K.Y., Zhao, X.N., 2001. The Phanerozoic Tectonic Evolution in Eastern Segment of South Tianshan. Geological Publishing House, Beijing, 160 pp (in Chinese).

Jin, W.S., Zhao, F.Q., Wang, Z.W., Gan, X.C., 1997. Geochemical characteristics of rocks of the Xuefengi stratigraphic units, in the Xiangqiangui area. Hunan Geology 16, 78−84 (in Chinese with English abstract).

Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Yirgu, G., Ayalew, D., Weise, D., Jerram, D.A., Keller, F., Meugniot, C., 2004. Flood and shield basalts from Ethiopia: magmas from the African superswell. Journal of Petrology 45, 793−834.

Lai, S.C., Li, S.Z., Zhang, G.W., 2003. Tectonic setting of the volcano-sedimentary rock association from Xixiang Group, Shaanxi province: volcanic rock geochemistry constraints. Acta Petrologica Sinica 19, 143−152 (in Chinese with English abstract).

Lai, S.C., Yang, R.Y., Zhang, G.W., 2001. Tectonic setting and implication of the Sunjiahe volcanic rocks, Xixiang Group, in south Qinling. Chinese Journal of Geology 36, 295−303 (in Chinese with English abstract).

Lee, K.S., Chang, H.W., Park, K.H., 1998. Neoproterozoic bimodal volcanism in the central Ogcheon belt, Korea: age and tectonic implication. Precambrian Research 89, 47−57.

Lee, S.R., Cho, M., Cheong, C.S., Kim, H., Wingate, M.T.D., 2003. Age, geochemistry, and tectonic significance of Neoproterozoic alkaline granitoids in the northwestern margin of the Gyeonggi massif, South Korea. Precambrian Research 122, 297−310.

Li, H.K., Lu, S.N., Chen, Z.H., Xiang, Z.Q., Zhou, H.Y., Hao, G.J., 2003a. Zircon U-Pb geochronological study of the Yaolinghe Group from the southern Qinling orogen. Chinese Science Bulletin 22, 775−781 (in Chinese with English abstract).

Li, W.X., Li, X.H., Li, Z.X., 2005a. Neoproterozoic bimodal magmatism in the Cathaysia Block of South China and its tectonic significance. Precambrian Research 136, 51−66.

Li, W.X., Li, X.H., Li, Z.X., 2008a. Mid-Neoproterozoic volcanic rocks from the Guangfeng rift succession, South China: U-Pb zircon age, geochemistry, Nd isotope and tectonic significance. Geological Magazine 145, 475−489.

Li, X.H., 1997. Timing of the Cathaysia block formation: constraints from SHRIMP U-Pb zircon geochronology. Episodes 20, 188−192.

Li, X.H., 1999. U-Pb zircon ages of granites from the southern margin of the Yangtze Block: timing of Neoproterozoic Jinning: orogeny in SE

China and implications for Rodinia Assembly. Precambrian Research 97, 43−57.

Li, X.H., Li, W.X., Li, Z.X., Liu, Y., 2008b. 850−790 Ma bimodal volcanic and intrusive rocks in northern Zhejiang, south China: a major episode of continental rift magmatism during the breakup of Rodinia. Lithos 102, 341−357.

Li, X.H., Li, W.X., Li, Z.X., Lo, C.H., Wang, J., Ye, M.F., Yang, Y.H., 2009a. Amalgamation between the Yangtze and Cathaysia Blocks in South China: constraints from SHRIMP U-Pb zircon ages, geochemistry and Nd-Hf isotopes of the Shuangxiwu volcanic rocks. Precambrian Research 174, 117−128.

Li, X.H., Li, W.X., Li, Z.X., Wang, J., 2005b. Formation of the South China Block: evidence from Sibaoan orogenic magmatism. In: Wingate, M.T.D., Pisarevsky, S.A. (Eds.), Supercontinent and Earth Evolution Symposium. Geological Society of Australia, Fremantle, p. 86 (Abst. 81).

Li, X.H., Li, Z.X., Sinclair, J.A., Li, W.X., Carter, G., 2006. Revisiting the "Yanbian Terrane": implications for Neoproterozoic tectonic evolution of the western Yangtze Block, South China. Precambrian Research 151, 14−30.

Li, X.H., Li, Z.X., Zhou, H., Liu, Y., Kinny, P.D., 2002a. U-Pb zircon geochronology, geochemistry and Nd isotopic study of Neoproterozoic bimodal volcanic rocks in the Kangdian Rift of South China: implications for the initial rifting of Rodinia. Precambrian Research 113, 135−154.

Li, X.H., Qi, C.S., Liu, Y., Liang, X.R., Tu, X.L., Xie, L.W., Yang, Y.H., 2005c. Petrogenesis of the Neoproterozoic bimodal volcanic rocks along the western margin of the Yangtze block: new constraints from Hf isotopes and Fe/Mn ratios. China Science Bulletin 50, 2481−2486.

Li, X.H., Zhou, H.W., Li, Z.X., Liu, Y., 2002b. Petrogenesis of Neoproterozoic bimodal volcanics in western Sichuan and its tectonic implications: geochemical and Sm-Nd isotopic constraints. Chinese Journal of Geology 37, 264−276 (in Chinese with English abstract).

Li, X.H., Zhou, H.W., Li, Z.X., Liu, Y., Kinny, P., 2001. Zircon U-Pb age and petrochemical characteristics of the Neoproterozoic bimodal volcanics from western Yangtze block. Geochemica 30, 315−322 (in Chinese with English abstract).

Li, Y.J., Jia, C.Z., Hu, S.L., Huang, Z.B., Zen, Q., Tuan, Z.J., 1999a. The ^{40}Ar-^{39}Ar isotopic age of Wajilitag gabbro in Tarim basin and its geological significance. Acta Petrologica Sinica 15, 594−599 (in Chinese with English abstract).

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vermikovsky, V., 2008c. Assembly, configuration, and breakup history of Rodinia: a synthesis. Precambrian Research 168, 179−210.

Li, Z.X., Li, X.H., 2007. Formation of the 1300 km-wide intra-continental orogen and post-orogenic magmatic province in Mesozoic South China: a flat-slab subduction model. Geology 35, 179−182.

Li, Z.X., Li, X.H., Kinny, P.D., Wang, J., 1999b. The breakup of Rodinia: did it start with a mantle plume beneath South China? Earth and Planetary Science Letters 173, 171−181.

Li, Z.X., Li, X.H., Kinny, P.D., Wang, J., Zhang, S., Zhou, H., 2003b. Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze craton, South China and correlations with other continents: evidence for a mantle superplume that broke up Rodinia. Precambrian Research 122, 85−109.

Li, Z.X., Li, X.H., Wang, X.C., 2009b. The South China piece in the Rodinian puzzle: a reply to the comment by Munteanu and Wilson. Precambrian Research 171, 77−79.

Li, Z.X., Li, X.H., Zhou, H., Kinny, P.D., 2002c. Grenville-aged continental collision in South China: new SHIMP U-Pb zircon results and implications for Rodinia configuration. Geology 30, 163−166.

Li, Z.X., Zhang, L., Powell, C.M., 1996. Positions of the East Asian cratons in the Neoproterozoic supercontinent Rodinia. Australian Journal of Earth Science 43, 593−604.

Ling, W.L., Cheng, J.P., Wang, X.H., 2002a. Geochemical features of the Neoproterozoic igneous rocks from the Wudang region and their implications for the reconstruction of the Jinning tectonic evolution along the South Qinling orogenic belt. Acta Petrologica Sinica 18, 25−36 (in Chinese with English abstract).

Ling, W.L., Gao, S., Ouyang, J.P., Zhang, B.R., Li, H.M., 2002b. Time and tectonic setting of the Xixiang Group: constraints from zircon U-Pb geochronology and geochemistry. Science in China (Series D) 32, 101−112 (in Chinese).

Ling, W., Gao, S., Zhang, B., Li, H., Liu, Y., Cheng, J., 2003. Neoproterozoic tectonic evolution of the northwestern Yangtze Craton, South China: implications for amalgamation and break-up of the Rodinia Supercontinent. Precambrian Research 122, 111−140.

Ling, W.L., Ren, B.F., Duan, R.C., 2007. Zircon U-Pb isotopic geochronology of Wudangshan Group, Yaolinghe Group and basic intrusions and its geological significance. Chinese Science Bulletin 52, 1445−1456 (in Chinese with English abstract).

Ling, W.L., Wang, X.H., Cheng, J.P., 2002c. Recognition and significance of Zhen'an arc-volcanic suite, South Qinling orogenic belt. Geochimica 31, 222−229 (in Chinese with English abstract).

Liu, B.G., Zheng, G.C., Chen, S.M., 1995. The breakup of the Songmuwu Group in western Zhejiang: evidence from isotope dating. Geological Review 41, 457−461 (in Chinese with English abstract).

Lu, C.Z., Gu, M.G., 2007. Definition of Neoproterozoic bimodal volcanic rocks in the south of Hangzhou and its tectonic significance. Geology in China 34, 565−571 (in Chinese with English abstract).

Macdonald, R., Rogers, N.W., Fitton, J.G., Black, S., Smith, M., 2001. Plume−lithosphere interaction in the generation of the basalts of the Kenya rift, east Africa. Journal of Petrology 42, 877−900.

McDonough, W.F., Sun, S.S., 1995. The composition of the Earth. Chemical Geology 120, 223−253.

McKenzie, D., Bickle, M.J., 1988. The volume and composition of melt generated by extension of the lithosphere. Journal of Petrology 29, 625−679.

McKenzie, D., O'Nions, R.K., 1991. Partial melt distributions from inversion of rare earth element concentrations. Journal of Petrology 32, 1021−1091.

Miyashiro, A., 1975. Classification, characteristics and origin of ophiolites. Journal of Geology 83, 249−281.

Munteanu, M., Wilson, A., 2009. The South China piece in the Rodinian puzzle. A comment on "Assembly, configuration, and break-up history of Rodinia: a synthesis by Li et al. (2008) [Precambrian Res. 160, 179−210]. Precambrian Research 171, 74−76.

Park, J.K., Buchan, K.L., Harlan, S.S., 1995. A proposed giant radiating dyke swarm fragmented by the separation of Laurentia and Australia based on paleomagmatism of ca. 780 Ma mafic intrusions in western North America. Earth and Planetary Science Letters 132, 129−139.

Parrish, R.R., Scammell, R.J., 1988. The age of the Mount Copeland syenite gneiss and its metamorphic zircons, Monashee Complex, southeastern Columbia, Radiogenic age and isotopic studies: report 2. Geological Survey Canada Paper 882, 21−28.

Pearce, J.A., 1982. Trace element characteristics of lavas from destructive plate boundaries. In: Thorps, R.S. (Ed.), Andesites. John Wiley and Sons, New York, pp. 525−548.

Peate, D.W., Hawkesworth, C.J., Mantovani, M.S.M., 1992. Chemical stratigraphy of the parana lavas (south America): classification of magma-types and their spatial distribution. Bulletin of Volcanology 55, 119−139.

Preiss, W.V., 2000. The Adelaide Geosyncline of South Australia and its significance in Neoproterozoic continental reconstruction. Precambrian Research 100, 21−63.

Qiu, Y.M., Gao, S., McNaughton, N.J., Groves, D.J., Ling, W., 2000. First evidence of >3.2 Ga continental crust in the Yangtze craton of South China and its implications for Archean crustal evolution and Phanerozoic tectonics. Geology 28, 11−14.

Radhakrishna, T., Mathew, J., 1996. Late Precambrian (850−800 Ma) palaeo-magnetic pole for the south Indian shield from the Harohalli alkaline dykes: geotectonic implications for Gondwana reconstructions. Precambrian Research 80, 77−87.

Reichow, M.K., Saunders, A.D., White, R.V., Al'Mukhamedov, A.I., Medvedev, A.Ya, 2005. Geochemistry and petrogenesis of basalts from the West Siberian Basin: an extension of the Permo-Triassic Siberian Traps, Russia. Lithos 79, 425–452.

Rogers, N.W., Hawkesworth, C.J., Ormerod, D.S., 1995. Late Cenozoic basaltic magmatism in the Western Great Basin, California and Nevada. Journal of Geophysical Research 100, 10287–10301.

Shellnutt, J.G., Dostal, J., Keppie, J.D., 2004. Petrogenesis of the 723 Ma Coronation sills, Amundsen basin, Arctic Canada: implications for the breakup of Rodinia. Precambrian Research 129, 309–324.

Shu, L.S., Deng, X.L., Zhu, W.B., Ma, D.S., Xiao, W.J., 2011. Precambrian tectonic evolution of the Tarim Block, NW China: new geochronological insights from the Quruqtagh domain. Journal of Asian Earth Sciences 42, 774–790.

Song, S.G., Su, Li., Li, X.H., Zhang, G.B., Niu, Y.L., Zhang, L.F., 2010. Tracing the 850-Ma continental flood basalts from a piece of subducted continental crust in the North Qaidam UHPM belt, NW China. Precambrian Research 183, 805–816.

Stein, M., Goldstein, S.L., 1996. From plume head to continental lithosphere in the Arabian–Nubian shield. Nature 382, 773–778.

Su, C.Q., Hu, J.M., Li, Y., Liu, J.Q., 2006. The existence of two different tectonic attributes in Yaolinghe Group in South Qinling region. Acta Petrologica et Mineralogica 25, 287–298 (in Chinese with English abstract).

Su, Q., Golberg, S.A., Fullagar, P.D., 1994. Precise U-Pb zircon ages of Neoproterozoic plutons in the southern Appalachian Blue Ridge and their implications for the initial rifting of Laurentia. Precambrian Research 68, 81–95.

Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Special Publications. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins, vol. 42. Geological Society, London, pp. 313–346.

Tang, H.F., Li, W.X., Zhou, X.M., 1998. Comparison of Neoproterozoic volcanic-sedimentary rocks from the Zhejiang–Jiangxi–Anhui border area. Acta Geologica Sinica 72, 34–41 (in Chinese with English abstract).

Tang, H.F., Zhou, X.M., 1997. Geochemical constraints to the petrogenesis of two types of basalts from eastern Jiangnan ancient land. Science in China (Series D) 27, 306–311 (in Chinese).

Tang, X.S., Huang, J.Z., Guo, L.Q., 1997. Hunan Banxi Group and its tectonic environment. Hunan Geology 16, 219–226 (in Chinese with English abstract).

Tatsumi, Y., Eggins, S.M., 1995. Subduction Zone Magmatism. Blackwell Science, Cambridge, 211 pp.

Teklay, M., Kröner, A., Mezger, K., 2002. Enrichment from plume interaction in the generation of Neoproterozoic arc rocks in northern Eritrea: implications for crustal accretion in the southern Arabian–Nubian Shield. Chemical Geology 184, 167–184.

Walter, M.J., 1998. Melting of garnet peridotite and the origin of komatiite and depleted lithosphere. Journal of Petrology 39, 29–60.

Wang, F., Wang, B., Shu, L.S., 2010. Continental tholeiitic basalt of the Akesu area (NW China) and its implication for the Neoproterozoic rifting in the north Tarim. Acta Petrologica Sinica 26, 547–558 (in Chinese with English abstract).

Wang, J., 2000. Neoproterozoic Rifting History of South China: Significance to Rodinia Breakup. Geological Publishing House, Beijing, 146 pp (in Chinese with English abstract).

Wang, J., 2005. New advances in the study of "the Nanhuaan System"—with particular reference to the stratigraphic division and correlation of the Nanhuaan System, South China. Geological Bulletin of China 24, 491–495 (in Chinese with English abstract).

Wang, J., Li, X.H., Duan, T.Z., Liu, D.Y., Song, B., Li, Z.X., Gao, Y.H., 2003a. Zircon SHRIMP U-Pb dating for the Cangshuipu volcanic rocks and its implications for the lower boundary age of the Nanhua strata in South China. Chinese Science Bulletin 48, 1663–1669.

Wang, J., Li, Z.X., 2003. History of Neoproterozoic rift basins in South China: implications for Rodinia break-up. Precambrian Research 122, 141–158.

Wang, J., Liu, B.J., Pan, G.T., 2001. Neoproterozoic rifting history of south China: significance to Rodinia breakup. Journal of Mineralogy and Petrology 21, 135–145 (in Chinese with English abstract).

Wang, J., Pan, G.T., 2009. Neoproterozoic South China Palaeocontinents: an overview. Acta Sedimentologica Sinica 27, 818–825 (in Chinese with English abstract).

Wang, X.C., Li, X.H., Li, W.X., Li, Z.X., 2007. Ca. 825 Ma komatiitic basalts in South China: first evidence for >1500 °C mantle melts by a Rodinian mantle plume. Geology 35, 1103–1106.

Wang, X.C., Li, X.H., Li, W.X., Li, Z.X., 2009. Variable involvements of mantle plumes in the genesis of mid-Neoproterozoic basaltic rocks in South China: a review. Gondwana Research 15, 381–395.

Wang, X.C., Li, X.H., Li, W.X., Li, Z.X., Liu, Y., Yang, Y.H., Liang, X.R., Tu, X.L., 2008. The Bikou basalts in northwestern Yangtze Block, South China: remains of 820–810 Ma continental flood basalts? Geological Society of America Bulletin 120, 1478–1492.

Wang, X.L., Zhou, J.C., Qiu, J.S., Gao, J.F., 2003b. Geochemistry of the Meso-Neoproterozoic volcanic-intrusive rocks from Hunan province and its petrogenic significance. Acta Petrologica Sinica 19, 49–60 (in Chinese with English abstract).

Wang, X.L., Zhou, J.C., Qiu, J.S., Gao, J.F., 2004. Geochemistry of the Meso- to Neoproterozoic basic-acid rocks from Hunan Province, South China: implications for the evolution of the western Jiangnan orogen. Precambrian Research 135, 79–103.

Wang, X.L., Zhou, J.C., Qiu, J.S., Zhang, W.L., Liu, X.M., Zhang, G.L., 2006. LA-ICP-MS U-Pb zircon geochronology of the Neoproterozoic igneous rocks from Northern Guangxi, South China: implications for tectonic evolution. Precambrian Research 145, 111–130.

Weaver, B.L., Tarney, J., 1984. Empirical approach to estimating the composition of the continental crust. Nature 310, 575–577.

Wedepohl, K.H., 1995. The composition of the continental crust. Geochimica et Cosmochimica Acta 59, 1217–1232.

Winchester, J.A., Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology 20, 325–343.

Wingate, M.T.D., Campbell, I.H., Compston, W., Gibson, G.M., 1998. Ion microprobe U-Pb ages for Neoproterozoic basaltic magmatism in south-central Australia and implications for the breakup of Rodinia. Precambrian Research 87, 135–159.

Wood, D.A., 1980. The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of British Tertialy volcanic province. Earth and Planetary Science Letters 50, 11–30.

Xia, L.Q., Xia, Z.C., Li, X.M., Ma, Z.P., Xu, X.Y., 2008a. Petrogenesis of the Yaolinghe Group, Yunxi Group, Wudangshan Group volcanic rocks and basic dyke swarms from eastern part of South Qinling Mountains. Northwestern Geology 41, 1–29 (in Chinese with English abstract).

Xia, L.Q., Xia, Z.C., Li, X.M., Ma, Z.P., Xu, X.Y., 2009a. Mid-Neoproterozoic rift-related volcanic rocks in South China: geological records of rifting and break-up of the Supercontinent Rodinia. Northwestern Geology 42, 1–33 (in Chinese with English abstract).

Xia, L.Q., Xia, Z.C., Ma, Z.P., Xu, X.Y., Li, X.M., 2009b. Petrogenesis of volcanic rocks from Xixiang Group in middle part of South Qinling Mountains. Northwestern Geology 42, 1–37 (in Chinese with English abstract).

Xia, L.Q., Xia, Z.C., Ren, Y.X., Peng, L.G., Zhang, C., Yang, J.H., Wang, X.A., Li, Z.P., Han, S., Huang, Z.X., 1991. Marine Volcanic Rocks from Qilian and Qinling Mountains. China University of Geosciences Press, Wuhan, 304 pp (in Chinese with English abstract).

Xia, L.Q., Xia, Z.C., Xu, X.Y., 1996a. Properties of middle-late Proterozoic volcanic rocks in South Qinling and the Precambrian continental break-up. Science in China (Series D) 39, 256–265.

Xia, L.Q., Xia, Z.C., Xu, X.Y., 1996b. The confirmation of continental flood basalt of the Proterozoic Xixiang Group in South Qinling and its geological implications. Geological Review 42, 513–522 (in Chinese with English abstract).

Xia, L.Q., Xia, Z.C., Xu, X.Y., 2001. The middle-late Proterozoic volcanic rocks in South Qinling and tectonic implication. In: Zhang, G.W., Zhang, B.R., Yuan, X.C. (Eds.), Qinling Orogenic Belt and Continental Dynamics. Science Press, Beijing, pp. 629–654 (in Chinese).

Xia, L.Q., Xia, Z.C., Xu, X.Y., Li, X.M., Ma, Z.P., 2007a. Petrogenesis of the Bikou Group volcanic rocks. Earth Science Frontiers 14, 84−101 (in Chinese with English abstract).

Xia, L.Q., Xia, Z.C., Xu, X.Y., Li, X.M., Ma, Z.P., 2007b. The discrimination between continental basalt and island arc basalt based on geochemical method. Acta Petrologica et Mineralogica 26, 77−89 (in Chinese with English abstract).

Xia, L.Q., Xia, Z.C., Xu, X.Y., Li, X.M., Ma, Z.P., 2008b. Relative contributions of crust and mantle to the generation of the Tianshan Carboniferous rift-related basic lavas, northwestern China. Journal of Asian Earth Sciences 31, 357−378.

Xia, L.Q., Xia, Z.C., Xu, X.Y., Li, X.M., Ma, Z.P., Wang, L.S., 2007c. Magmatism in the Tianshan. Chinese Earth Publishing House, Beijing, 350 pp (in Chinese).

Xia, L.Q., Zhang, G.W., Xia, Z.C., Xu, X.Y., Dong, Y.P., Li, X.M., 2002. Constraints on the timing of opening and closing of the Tianshan Paleozoic oceanic basin: evidence from Sinian and Carboniferous volcanic rocks. Geological Bulletin of China 21, 55−62 (in Chinese with English abstract).

Xia, Z.C., Xia, L.Q., Xu, X.Y., 1999. The nature and formation environment of volcanic rocks series of the Bikou Group. Geological Review 45 (Supp.), 681−688 (in Chinese with English abstract).

Xu, B., Jian, H., Zou, H., Zhang, L., Liu, D., 2005. U-Pb zircon geochronology and geochemistry of Neoproterozoic volcanic rocks in the Tarim Block of northwestern China: implications for the breakup of Rodinia supercontinent and Neoproterozoic glaciations. Precambrian Research 136, 107−123.

Xu, B., Xiao, S.H., Zou, H.B., Chen, Y., Li, Z.X., Song, B., Liu, D.Y., Zhou, C.M., Yuan, X.L., 2009. SHRIMP zircon U-Pb age constraints on Neoproterozoic Qurugtagh diamictites in NW China. Precambrian Research 168, 247−258.

Xu, B.T., 1994. Nd and Sr isotopic geochemistry of Presinian volcanic rocks in Northwestern Zhejiang Province. Geology of Zhejiang 10, 45−50 (in Chinese with English abstract).

Xu, X.Y., Xia, Z.C., Xia, L.Q., 2001. Proterozoic intraplate volcanic rocks in south Qinling Mountains and their tectonic implications. Acta Petrologica et Mineralogica 20, 255−262 (in Chinese with English abstract).

Xu, X.Y., Xia, Z.C., Xia, L.Q., 2002. Volcanic cycles of the Bikou Group and their tectonic implications. Geological Bulletin of China 21, 478−485 (in Chinese with English abstract).

Yan, Q.R., Hanson, A.D., Wang, Z.Q., Druscheke, P.A., Yan, Z., Wang, T., Liu, D.Y., Song, B., Jian, P., Zhou, H., Jiang, C.F., 2004a. Neoproterozoic subduction and rifting on the Northern margin of the Yangtze plate, China: implications for Rodinia reconstruction. International Geology Review 46, 817−832.

Yan, Q.R., Hanson, A.D., Wang, Z.Q., Yan, Z., Druschke, P.A., Wang, T., Liu, D.Y., Song, B., Jiang, C.F., 2004b. Geochemistry and tectonic setting of the Bikou volcanic terrane on the northern margin of the Yangtze plate. Acta Petrologica et Mineralogica 23, 1−11 (in Chinese with English abstract).

Yan, Q.R., Wang, Z.Q., Hanson, A.D., Druschke, P.A., Yan, Z., Liu, D.Y., Jian, P., Song, B., Wang, T., Jiang, C.F., 2003. SHRIMP age and geochemistry of Bikou volcanic terrane: implication for Neoproterozoic tectonics on the north margin of the Yangtze craton. Acta Geologica Sinica 77, 479−490.

Ye, M.F., Li, X.H., Li, W.X., Liu, Y., Li, Z.X., 2007. SHRIMP zircon U−Pb geochronological and whole-rock geochemical evidence for an early Neoproterozoic Sibaaoan magmatic arc along the southeastern margin of the Yangtze Block. Gondwana Research 12, 144−156.

Zhang, C.L., Li, H.K., Santosh, M., Li, Z.X., Wang, H.Y., Ye, H.M., 2011a. Precambrian evolution and cratonization of the Tarim Block, NW China: petrology, geochemistry, Nd-isotopes and U-Pb zircon geochronology from Archean gabbro−TTG−potassic granite suite and Paleoproterozoic metamorphic belt. Journal of Asian Earth Sciences. doi:10.1016/j.jseaes.2011.05.018.

Zhang, C.L., Li, X.H., Li, Z.X., Lu, S.N., Ye, H.M., Li, H.M., 2007. Neoproterozoic ultramafic−mafic−carbonatite complex and granitoids in Quruqtagh of northeastern Tarim Block, western China: geochronology, geochemistry and tectonic implications. Precambrian Research 152, 149−169.

Zhang, C.L., Li, Z.X., Li, X.H., Ye, H.M., 2009. Neoproterozoic mafic dyke swarms at the northern margin of the Tarim Block, NW China: age, geochemistry, petrogenesis and tectonic implications. Journal of Asian Earth Sciences 35, 167−179.

Zhang, C.L., Yang, D.S., Wang, H.Y., Dong, Y.G., Ye, H.M., 2010. Neoproterozoic mafic dykes and basalts in the southern margin of Tarim, northwest China: age, geochemistry and geodynamic implications. Acta Geologica Sinica 84, 549−562.

Zhang, C.L., Yang, D.S., Wang, H.Y., Takahashi, Y., Ye, H.M., 2011b. Neoproterozoic mafic−ultramafic layered intrusion in Quruqtagh of northeastern Tarim Block, NW China: two phases of mafic igneous activity with different mantle sources. Gondwana Research 19, 177−190.

Zhang, C.L., Zhou, D.W., Jin, H.L., 1999a. Study on the Sr, Nd, Pb and O isotopes of basic dyke swarms in the Wudang block and basic volcanics of the Yaolinhe Group. Acta Petrologica Sinica 15, 430−437 (in Chinese with English abstract).

Zhang, C.L., Zhou, D.W., Liu, Y.Y., 1999b. Geochemistry of basic dykes in Wudangshan block and their tectonic significance. Geochimica 28, 126−135 (in Chinese with English abstract).

Zhang, G.W., Zhang, B.R., Yuan, X.C., 2001. Qinling Orogenic Belt and Continental Dynamics. Science Press, Beijing, 855 pp (in Chinese).

Zhang, Z.Q., Zhang, G.W., Tang, S.H., 2002. Isotopic Geochronology of Metamorphic Strata in South Qinling Mountains. Geological Publishing House, Beijing, 256 pp (in Chinese).

Zhao, F.Q., Jin, W.S., Gan, X.C., 1997. Geochemistry of the volcanics in Dengshan Group and Songmuwu Group from NE Jiangxi province and NW Zhejiang province. Progress in Precambrian Research 20, 51−57 (in Chinese with English abstract).

Zhao, F.Q., Jin, W.S., Gan, X.C., 1999. Geology, geochemistry and geochronology of the Neoproterozoic volcanic rocks from the Huaishan and their forming tectonic setting and origin. In: Qian, X.L., You, Z.D. (Eds.), Symposium of 30th International Geological Congress, vol. 17. Geological Publishing House, Beijing, pp. 81−91 (in Chinese).

Zhao, F.Q., Zhao, W.P., Zuo, Y.C., Li, Z.H., Xue, K.Q., 2006. U-Pb geochronology of Neoproterozoic magmatic rocks in Hanzhong, southern Shaanxi, China. Geological Bulletin of China 25, 383−388 (in Chinese with English abstract).

Zhao, G.C., Cawood, P.A., 1999. Tectonothermal evolution of the Mayuan assemblage in the Cathaysia Block: implications for Neoproterozoic collisional-related assembly of the South China Craton. American Journal of Science 299, 309−339.

Zhao, J.X., McCulloch, M.T., Korsch, R.J., 1994. Characterisation of a plume-related approximately 800 Ma magmatic event and its implications for basin formation in central-southern Australia. Earth and Planetary Science Letters 121, 349−367.

Zhou, H.W., Li, X.H., Wang, H.R., 2002a. Zircon U-Pb age of basic volcanic rocks of Yingyangguan Group from Guangxi province and its geological significance. Geological Review 48 (Supp.), 22−25 (in Chinese with English abstract).

Zhou, J.B., Li, X.H., Ge, W.C., Li, Z.X., 2007. Age and origin of middle Neoproterozoic mafic magmatism in southern Yangtze Block and relevance to the break-up of Rodinia. Gondwana Research 12, 184−197.

Zhou, J.C., Wang, X.L., Qiu, J.S., Gao, J.F., 2003. Lithogeochemistry of Meso- and Neoproterozoic mafic-ultramafic rocks from northern Guangxi. Acta Petrologica Sinica 19, 9−18 (in Chinese with English abstract).

Zhou, J.C., Wang, X.L., Qiu, J.S., Gao, J.F., 2004. Geochemistry of Meso-Neoproterozoic mafic-ultramafic rocks from northern Guangxi, China: arc or plume magmatism? Geochemical Journal 38, 139−152.

Zhou, M.F., Kennedy, F., Sun, A.K., Malpas, M., Lesher, J., 2002b. Neoproterozoic arc-related mafic intrusions along the northern margin of South China: implication for the accretion of Rodinia. Journal of Geology 110, 611−618.

Zhou, M.F., Ma, Y., Yan, D.P., Xia, X., Zhao, J.H., Sun, M., 2006a. The Yanbian Terrane (Southern Sichuan Province, SW China):

a Neoproterozoic arc assemblage in the western margin of the Yangtze Block. Precambrian Research 144, 19−38.

Zhou, M.F., Yan, D.P., Kennedy, A.K., Li, Y., Ding, J., 2002c. SHRIMP U-Pb zircon geochronological and geochemical evidence for Neoproterozoic arc-magmatism along the western margin of the Yangtze Block, South China. Earth and Planetary Science Letters 196, 51−67.

Zhou, M.F., Yan, D.P., Wang, C.L., Qi, L., Kennedy, A., 2006b. Subduction-related origin of the 750 Ma Xuelongbao adakitic complex (Sichuan Province, China): implications for the tectonic setting of the giant Neoproterozoic magmatic event in South China. Earth and Planetary Science Letters 248, 286−300.

Zhu, J.C., Sun, W.P., 1986. Approach of deagenetic age and evolution of metamorphic rocks of middle Tianshan. Xinjiang Geology 4, 47−52 (in Chinese with English abstract).

Zhu, J.C., Sun, W.P., 1987. Geochronology study of Sinian system for Tianshan region, Xinjiang. Xinjiang Geology 5, 55−61 (in Chinese with English abstract).

Zhu, W.B., Zheng, B.H., Shu, L.S., Ma, D.S., Wan, J.L., Zheng, D.W., Zhang, Z.Y., Zhu, X.Q., 2011. Geochemistry and SHRIMP U-Pb zircon geochronology of Korla mafic dykes: constrains on the Neoproterozoic continental breakup in the Tarim Block, northwest China. Journal of Asian Earth Sciences 42, 791−804.