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

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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 ≤ 0.85), and LT1 (Nb/La > 0.85) and LT2 (Nb/La ≤ 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.
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,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; Muntau and Wilson, 2009; Yan et al., 2003, 2004a,b; Zhou et al., 2002b,c, 2003, 2004, 2006a,b).
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 (SiO₂/C₂O₅ 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 Saillimu Block of the Tianshan, and are unconformably overlain by Lower Cambrian strata (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., 2005; Xia et al., 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.

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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)
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 SHRIMP 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 Tiechuanxian 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 (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
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 SiO₂ 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 Paleo-proterozoic 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 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).
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
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, 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).

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**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).

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**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 supracrustal 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, 2008a, 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
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 SiO2 versus Nb/Y diagram (Winchester and Floyd, 1977) and the FeO/FeMgO versus SiO2 diagram (Miyashiro, 1975). On the other hand, age correction of measured 87Sr/86Sr 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 εNd(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 TiO2, is used as a discriminator of magma types, because TiO2 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 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) lavas, 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 HT 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
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 \( \varepsilon_{\text{Nd}}(t) \) 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 \( \varepsilon_{\text{Nd}}(t) \) values (+1 to +9); (2) strongly contaminated samples (i.e., HT2 and LT2 lavas) are characterized by lower to negative \( \varepsilon_{\text{Nd}}(t) \) values (−11 to +5). Certain samples with high Nb/La ratios show high \( \varepsilon_{\text{Nd}}(t) \) (2−6) and low \(^{87}\text{Sr}/^{86}\text{Sr}(t) \) 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.
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 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 ($w(\text{SiO}_2) \leq 56\%$) 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.
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 (<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 magma by lithosphere-derived melts (Arndt et al., 1999) 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 thermomechanical erosion of the lithospheric 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 Barney, 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 (Fitch et al., 1991; Fitch, 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 εNd(t) (−11 to +5) (Fig. 15) and variable 87Sr/86Sr(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 basals 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 εNd(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 plume-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 thermomechanical 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 Christiansen, 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
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 15** Nb/La versus $\varepsilon_{Nd}(t)$ diagrams for Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas (wt(SiO$_2$) ≤ 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.
\[ \text{LT1 lavas with Nb/La > 0.85) still plot in the WPB field, but the plots of all other contaminated samples (i.e. HT2 and LT2 lavas with Nb/La \leq 0.85) displace toward lower Nb, Ta or Ti and into the island-arc field. In this case, we cannot regard the lithospherically contaminated basic lavas as arc related. Besides, although the HT2 and LT2 lavas, which generally belong to the tholeiitic series (Fig. 12), are characterized by low Nb/La ratios (\leq 0.85) and depletions in Nb, Ta and Ti (Fig. 14b, d, f, h, j), their concentrations of incompatible trace elements are conspicuously higher than those of subduction-zone basalts (Fig. 14b, d, f, h, j). The HT2 and LT2 lavas cannot be regarded, therefore, as volcanic arc basalts, and they are lithospherically contaminated continental...} \]

Figure 16  Zr/Y versus Nb/Y diagrams (diagrams after Condie, 2005) for Mid–Late Neoproterozoic–Early Cambrian rift-related basic lavas (w(SiO2) \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, Pingle 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-\(\mu\) (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.
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 $\varepsilon_{\text{Nd}}(t)$ 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 $\varepsilon_{\text{Nd}}(t)$ values (+1 to +9); (2) strongly contaminated samples (i.e., HT2 and LT2 lavas) are characterized by lower to negative $\varepsilon_{\text{Nd}}(t)$ values (−11 to +5). The lower to negative $\varepsilon_{\text{Nd}}(t)$ values of HT2 and LT2 lavas may be related to the contamination of an older continental lithosphere. The above characteristics of variations of $\varepsilon_{\text{Nd}}(t)$ 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 HT1 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
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
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; Evans 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 ≤ 0.85), and LT1 (Nb/La > 0.85) and LT2 (Nb/La ≤ 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.

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