An 850–820 Ma LIP dismembered during breakup of the Rodinia supercontinent and destroyed by Early Paleozoic continental subduction in the northern Tibetan Plateau, NW China

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Article history:
Received 11 October 2015
Revised 31 May 2016
Accepted 11 July 2016
Available online 22 July 2016

Keywords:
North Qaidam LIP
Dolerite dike and basalt
Eclogite
Mantle plume
Breakup of Rodinia
Continental subduction

Abstract

Neoproterozoic intraplate magmatism is widely distributed in NW China and generally thought to be related to the breakup of the Rodinia supercontinent. Here we report a fragmented Large Igneous Province (LIP) formed at 850–820 Ma in the northern margin of the Qaidam block, northern Tibetan Plateau (named herein as the “North Qaidam LIP”). The associated rocks have undergone various grades of metamorphism from greenschist to ultrahigh-pressure (UHP) eclogite facies, including the greenschist-facies Yingfeng dolerite dikes and basalts (846–821 Ma), the amphibolite- to HP granulite-facies Aolaoshan meta-volcanic sequence (protolith age of 832 Ma and metamorphic age of 439 Ma), and the North Qaidam UHP eclogites (protolith age of 847–828 Ma and metamorphic age of 440–420 Ma). Geochemical data reveal that they resemble present-day E-MORB/OIB and typical continental flood basalts. These features, together with high potential temperatures ($T_p = 1434–1524^\circ C$) for “primary” magmas, suggest that these basaltic rocks were most likely derived from a mantle plume source and were emplaced in a continental extensional environment.

Their varying metamorphic facies record a range of locations along the underthrust continental slab from near-surface (Yingfeng dolerites/basalts), middle (Aolaoshan amphibolites) to deep (North Qaidam UHP eclogites) sites with depths greater than 120 km. The large spatial distribution (potentially >0.1 Mkm$^2$), short duration (<30 Myr) and intraplate geochemical character suggest that these igneous rocks are remnants of the North Qaidam LIP caused by the upwelling of a mantle plume during 850–820 Ma. We consider that the North Qaidam LIP represents the onset of a protracted break-up history and precedes subsequent multiple episodes of rifting. These Neoproterozoic igneous rocks in the Qaidam block were separated from the contemporaneous magmatic suites over Australia, South China and Tarim by the breakup of Rodinia, and were further destroyed by the subduction of the passive continental margin of the Qaidam block in the Early Paleozoic (440–420 Ma).

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1. Introduction

Large Igneous Provinces (LIPs) are exceptional intraplate igneous events that represent massive crustal emplacement of mafic magmas, generated by processes distinct from normal seafloor spreading and plate convergence (Coffin and Eldholm, 1994; Ernst et al., 2005; Ernst and Jowitt, 2013; Ernst, 2014). Both continental and oceanic LIPs are likely to result from mantle plume heads arriving at the base of lithosphere, and are characterized by their large volume (at least 100,000 km$^3$), short duration (or short duration pulses), and geochemical and/or other affinities consistent with an intraplate tectonic setting (e.g., Richards et al., 1989; Coffin and Eldholm, 1994; Saunders, 2005; Bryan and Ernst, 2008; Ernst et al., 2008; Garfunkel, 2008; Bryan and Ferrari, 2013; Ernst, 2014). Most continental LIPs are dominated by flood basalts or their erosional/deformational remnants, a plumbing system of dikes and sills, and mafic–ultramafic layered
intrusions (e.g., Bryan and Ernst, 2008). A substantial silicic component may be present in some cases, for example Sierra Madre Occidental (e.g., Bryan and Ferrari, 2013). Thick outpourings of flood basalts have been identified on rifted continental margins around the world and are closely connected with the onset of seafloor spreading (e.g., the Greenland traps and North Atlantic Igneous Province for the opening of the North Atlantic, the Deccan traps for the Indian Ocean, and the Paraná–Etendeka traps for the South Atlantic; White and McKenzie, 1989; Courtillot et al., 1999; Bryan and Ernst, 2008). Thus it is proposed that there are causal links between the formation of ancient LIPs and the growth, breakup and cycles of supercontinents, and they are critical for recognizing the episodes of continental breakup and constraining supercontinental reconstructions (White and McKenzie, 1989; Hill et al., 1992; Park et al., 1995; Saunders et al., 1996; Wingate et al., 1998; Courtillot et al., 1999; Li et al., 1999, 2008a; Ernst et al., 2005, 2008; Ernst and Jowitt, 2013).

In the last decades, the amalgamation, breakup and configuration of Rodinia have attracted much attention (e.g. Li et al., 2008a and references therein). It is widely accepted that the assembly of this supercontinent is associated with the worldwide Grenville-age orogeny (1.3–0.9 Ga) which has been recognized within North America, Scandinavia, Australia, South China, India, East Antarctica, Tarim and in the Qilian–Qaidam area (Li et al., 2008a; Song et al., 2012). However, the timing of the onset of the prolonged breakup process has been controversial. The first episode of Neoproterozoic plume activity was identified in light of the ca. 825 Ma mafic dikes and sills, komatiites, mafic–ultramafic intrusions, continental flood basalts (CFBs), and anorogenic granitoids in South China, Tarim and Australia (see Li et al. (2008a) for details). These magmatic events are also correlated to the initial rift phase of the Nanhua rift basin in South China and the Adelaide geosyncline in southeastern Australia (Powell et al., 1994; Preiss, 2000; Wang and Li, 2003; Li et al., 2003a). However, recent geochronological results suggest that the intraplate magmatism related to the breakup of Rodinia may have started earlier, perhaps at 870–850 Ma in South China, Qilian–Qaidam, Africa, India, Australia, the Scottish promontory of Laurentia and the Scandinavian Caledonides (Song et al., 2010 and references therein) or even at ca. 930 Ma in North China and West Africa (Peng et al., 2011; Ernst, 2014). Alternatively, Zhou et al. (2002, 2006a,b) and Wang et al. (2007) speculated that the magmatism of this period was formed in an active continental margin or a collisional orogen around the Yangtze Craton.

It is generally considered that the Qilian–Qaidam block was an integral component of Rodinia, and had a close relationship with South China (Xu et al., 2015 and references therein). In terms of the Grenville-age magmatism and metamorphism, Song et al. (2012) identified the link between the South China, Qilian–Qaidam and Tarim blocks, and named them as the “South-West China United Continent” (Fig. 1a). Nevertheless, the process of separation away from the rest of Rodinia for the Qilian–Qaidam block is still poorly understood due to the sparse intraplate magmatic records, not least because of later fragmentation, erosion, burial and metamorphism related to the Early Paleozoic collisional orogeny.

The North Qaidam ultrahigh-pressure metamorphic (UHPM) belt on the northern Tibetan Plateau is a continental subduction/collisional suture, where the ancient passive continental margin of the Qaidam block was dragged to depths greater than 100 km and was destroyed during the period of 440–420 Ma (Song et al., 2006, 2012, 2014). However, the protoliths of eclogites in the North Qaidam UHPM belt have been controversial, as to whether they represent oceanic crust or continental basalts, which is significant for understanding the tectonic evolution from oceanic subduction to continental subduction-collision (Song et al., 2014 and references therein).

In this paper, we present petrological, geochronological, geochemical and Sm-Nd isotopic data for the Yingfeng dolerite dikes/basalts and the Aolaoshan meta-volcanic rocks in the western extension of the North Qaidam UHPM belt. By combining our data with the previous results on the North Qaidam eclogites and neighboring mafic–ultramafic intrusions, we suggest that these igneous rocks form in the within-plate environment with a mantle plume origin and are remnants of the 850–820 Ma North Qaidam LIP, associated with the initial breakup of Rodinia.

2. Geological setting

The Qaidam block in the northern margin of Qinghai-Tibet Plateau is located between the larger South China, Tarim and North China blocks (Fig. 1a) and is covered with Mesozoic to Cenozoic sedimentary sequences. To its north, the North Qaidam continental-type ultra-high pressure metamorphic (UHPM) belt has a NW-SE trend, and is offset about 400 km by the left-lateral Altyn Tagh Fault. The Quanji block is separated from the North Qaidam UHPM belt by the Wulan–Yuka Fault (Zhang et al., 2001; Li et al., 2003b; Chen et al., 2007, 2009a). This block consists of Archean to Early Proterozoic gneisses, amphibolites and granulites, and is unconformably covered by the less deformed and metamorphosed Neoproterozoic Quanji Group and Cambrian-Ordovician sequences (see Chen et al., 2009a; Fig. 1b). The Qilian block in the north contains Precambrian basement rocks formed from Archean to Neoproterozoic with Grenville-age (1000–900 Ma) intrusions, and has a close affinity with the Yangtze block (Wan et al., 2001, 2006; Lu et al., 2008; Song et al., 2013). Recent studies suggested that the combined Qilian–Qaidam microcontinent was a fragment of the Rodinia supercontinent, and rifted away from southeastern Australia at 600–550 Ma (Xu et al., 2015). Further to the north is the North Qilian oceanic suture zone, which consists of ophiolites, arc volcanic rocks and lawsonite-bearing eclogites and blueschists associated with the oceanic subduction in the Early Paleozoic era (see Song et al., 2013 for details).

The North Qaidam UHPM belt extends discontinuously for over 400 km from Dulan in the southeast, northwestward through Xitieshan and Lüliangshan to Yuka (see Fig. 1b for localities). The lithologies mainly consist of granitic and pelitic gneisses (~80%) with eclogite and garnet peridotite blocks. The granitic and pelitic gneisses recorded a Grenville-age orogenesis at ~1020–900 Ma (Wan et al., 2006; Song et al., 2012, 2014; Zhang et al., 2012, 2015; Yu et al., 2013). Coesite and diamond inclusions have been identified in zircons and garnets from the metapelites, eclogites and garnet peridotites, which suggest that the UHP metamorphism occurred at depths of 100–200 km at 438–420 Ma (Song et al., 2014 and references therein).

3. Occurrence and petrography

Three types/occurrences of the 850–820 Ma volcanic rocks were identified in the North Qaidam region as following: (1) Yingfeng low-grade meta-mafic dikes/basalts, (2) Aolaoshan medium-grade meta-volcanics and (3) eclogite blocks in the North Qaidam UHPM belt associated with continental subduction.

3.1. Yingfeng low-grade meta-mafic dikes/basalts

The Yingfeng mafic dikes and basalts (Site 5 in Fig. 1a) are located at the northwest of the Yuka eclogite-gneiss terrane (Fig. 1b). The Yingfeng mafic rocks mainly occur as sills, dikes and layered basalts (Fig. 2a-b). The dikes dominantly trend in a NNW direction, with lengths ranging from 1 to 3 km and widths from 2 to 5 m. Together with large sills (1 × 5 km), they intrude
Fig. 1. (a) Tectonic framework of continental China showing the distribution of the 850–820 Ma LIP records throughout the inferred South-West China United Continent, involving the South China, Tarim, Qilian-Qaidam blocks (modified by Song et al., 2012). 1: 825–842 Ma Gaojiacun mafic-ultramafic complexes (Zhu et al., 2006); 2: 821 Ma Bikou basalts (Wang et al., 2008); 3: 828 Ma Jinchuan mafic-ultramafic intrusions (Li et al., 2005); 4: 824 Ma Qurqtagh dolerite dikes (Zhang et al., 2009); 5: 820–850 Ma Yingfeng–Aolaoshan dolerite dikes and flood basalts (Lu et al., 2008; this study); 6: 847 Ma CFB protolith of Yuka eclogites (Song et al., 2010); 7: 877 Ma protolith of Xitieshan eclogites (Zhang et al., 2011, 2012); 8: 828–838 Ma protolith of Dulan eclogites (Zhang et al., 2010; Yu et al., 2013); 9: 828 Ma mafic to ultramafic dikes and sills of North Guangxi (Li et al., 1999); 10: 850 Ma Zhenzhushan bimodal volcanic rocks, Wuyi basalts/gabbros, Gangbian alkaline complex and Shenwu dolerite dikes (Li et al., 2008b, 2010a,b; Shu et al., 2011). (b) Geological map of the North Qaidam ultra-high pressure metamorphic (UHPM) belt. (c) Geological sketch map of the Yingfeng and Aolaoshan regions with sample locations.
3.2. Aolaoshan medium-grade meta-volcanics

The Aolaoshan meta-volcanic sequence (Site 5 in Fig. 1a) mainly consists of thick meta-basaltic layers (100–200 m) with rare sedimentary interlayers (Fig. 2c). Thin meta-rhyolite interlayers (white-colored) are occasionally present (Fig. 2d). The mafic rocks underwent amphibolite- to high-pressure granulite facies metamorphism. The analytical method for mineral chemistry and the representative mineral compositions used for \(P-T\) calculations are given in Appendix Table 1. The garnet amphibolite (Q14-87) is chiefly composed of plagioclase, hornblende, garnet and quartz with minor clinopyroxene and biotite (Fig. 3e-f). Rutile occurs as inclusions in garnet. Clinopyroxene occurs as fine-grained crystals around coarse amphibole, suggesting a prograde metamorphism. Application of the garnet-clinopyroxene geothermometer (Ravna, 2000) together with garnet-clinopyroxene-plagioclase-quartz geobarometer (Eckert et al., 1991) give the metamorphic peak condition of \(P = 17–19\) kbar and \(T = 728–825\) °C. The amphibolite (Q14-88) mainly consists of hornblende, plagioclase with minor garnet (Fig. 3d). Garnet-hornblende-plagioclase-quartz thermobarometry (Holland and Blundy, 1994; Dale et al., 2000) yields the \(P-T\) conditions of 705–727 °C and 10–11 kbar.

3.3. Eclogite blocks in N. Qaidam UHPM belt

Eclogites in the three terranes of the North Qaidam UHPM belt (Site 6–8 in Fig. 1a) mainly occur as various sized blocks, layers and boudinaged dikes within granitic and pelitic gneisses. Two types of protoliths of these eclogite blocks have been identified: (1) the Cambrian ophiolite with protolith ages of \(\sim 540–500\) Ma (Zhang et al., 2008; Song et al., 2009), and (2) Neoproterozoic CFB with protolith ages of \(850–820\) Ma (Chen et al., 2009; Song et al.,
The peak metamorphic P–T conditions for both types of eclogites have been estimated in ranges of $P = 2.6–3.5$ GPa and $T = 600–830$ °C, and zircons from these eclogites yielded HP-UHP metamorphic ages ranging from 470 Ma to 420 Ma, indicating a complete orogenic process from oceanic subduction to continental collision (Song et al., 2014 and references herein).

The CFB-type eclogites with protolith ages of 850–820 Ma in Yuka terrane have been described by Song et al. (2010), while those occurred in the Xitieshan and Dulan terranes are shown in Fig. 4. They all occur in large blocks intercalated with granitic and pelitic gneisses. Some eclogite layers are several to tens of meters in thickness and extend for more than 1 km. Most eclogites are fresh, show a medium- to coarse-grained granular texture and have a typical mineral assemblage of garnet, omphacite, rutile and phengite.

### 4. Analytical methods

#### 4.1. In situ zircon U-Pb dating

Zircons were separated by heavy liquid and magnetic techniques. These grains were enclosed in epoxy resin and polished to half of their thickness. The grain mount was imaged in reflected and transmitted light as well as cathodoluminescence (CL) in order to select analysis positions. The CL examination was conducted by a Scanning Electron Microscope (SEM) at Peking University. The grain mount was vacuum-coated with high-purity gold before secondary ion mass spectroscopy (SIMS) U-Pb isotope analyses.

U, Th and Pb isotopic compositions for sample 13MH-18 were analyzed using the Cameca IMS-1280 SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences. The instrument description and analytical procedure are given in Li et al.
U-Th-Pb ratios were determined relative to the standard zircon Plešovice (Šlama et al., 2008) and their absolute abundances were calibrated to standard zircon 91500 (Wiedenbeck et al., 1995). Analyses of the Plešovice standard were interspersed with those of unknown grains. A long-term uncertainty of 1.5% (1σ) for 206Pb/238U measurements of the standard zircons was propagated to the unknowns (Li et al., 2010c), despite that the measured 206Pb/238U error in a specific session is generally 1% (1σ).

Fig. 4. Field photographs and occurrences of eclogites in the North Qaidam UHP belt. (a and b) Layered eclogite blocks in the Yuka terrane. (c and d) Layered eclogite blocks in the Xitieshan terrane. (e and f) Large eclogite blocks in the Dulan terrane.
Correction of common lead was made by measuring non-radiogenic 204Pb. An average Pb of present-day crustal composition (Stacey and Kramers, 1975) was used for the common Pb, assuming that it was largely due to surface contamination introduced during sample preparation. In order to monitor the external uncertainties, the standard Qinghu was alternately analyzed together with other unknown zircons. Seven measurements on the Qinghu zircons for SIMS analyses yield a concordia age of 160.6 ± 0.9 Ma (MSWD = 0.54), which is identical within error to the recommended value of 159.5 ± 0.2 Ma (Li et al., 2013).

Measurements of U-Th-Pb isotopes for sample 13MH-19, 13MH-44, and Q14-77 were carried out on an Agilent-7500a quadrupole inductively coupled plasma-mass spectrometer coupled with a New Wave SS UP193 laser sampler (LA-ICP-MS) at the Geological Lab Center, China University of Geosciences, Beijing (CUGB). A laser spot size of 36 μm, a laser energy density of 8.5 J/cm², and a repetition rate of 10 Hz were applied for analysis. National Institute of Standards and Technology 610 glass and Harvard zircon 91500 (Wiedenbeck et al., 1995) were used as external standards, Si as an internal standard, and zircon standard TEMORA (417 Ma) from Australia (Black et al., 2003) as the secondary standard. The common lead correction was done following Andersen (2002). Analytical details are described in Song et al. (2010). The standard Qinghu zircons give a concordia age of 162.0 ± 0.6 Ma (n = 10, MSWD = 1.4).

Data processing was carried out using the Isoplot/Ex v. 2.49 program (Ludwig, 2001). Uncertainties on individual analyses in the data tables are reported at 1σ level. The weighted mean 206Pb/238U ages are quoted with 95% confidence interval. The Qinghu zircon data for SIMS and LA-ICP-MS are provided in Appendix Table 2.

4.2. Bulk rock major and trace element analyses

The bulk-rock major and trace elements were analyzed at CUGB. Major elements were analyzed using a Leeman Prodigy inductively coupled plasma-optical emission spectroscopy (ICP-OES) instrument with high-dispersion Echelle optics. Based on rock standards AGV-2, GRS-1, and GSR-3 (national geological standard reference material of China), the analytical precisions (1σ) for most major elements (Appendix Table 3) are better than 1% with the exception of TiO₂ (~1.5%) and P₂O₅ (~2.0%). Loss on ignition was determined by placing 1 g of samples in the furnace at 1000 °C for several hours before being cooled in a desiccator and reweighed.

Bulk rock trace element analysis was done on an Agilent-7500a inductively coupled plasma-mass spectrometer (ICP-MS) instrument. Roughly 40 mg of sample powder was dissolved in an equal mixture of subboiling distilled HNO₃ and HF with a Teflon digestion vessel on a hot plate at 285 °C for 48 h using high-pressure bombs to aid digestion/dissolution. The samples were then evaporated to incipient dryness, refluxed with 6 N HNO₃, and heated again to incipient dryness. They were then dissolved in 2 ml of 3 N HNO₃ using high-pressure bombs for a further 24 h to ensure complete digestion/dissolution. After digestion, they were diluted with Milli-Q water (18 MΩ) to a final dilution factor of 2000. Rock standards AGV-2 and GSR-3 were used to monitor the analytical accuracy and precision (Appendix Table 4). Analytical accuracy, as indicated by relative difference between measured and recommended values, is better than 5% for most elements, and better than 10 ~ 15% for Gd and Ta.

4.3. Bulk rock Sr-Nd isotope analyses

The separation and determination of Sm-Nd isotopes were carried out at the Ministry of Education (MOE) Key Laboratory of Orogenic Belts and Crustal Evolution, Peking University. Powders of samples (~300 mg) and standard BCR-2 (~200 mg) were dissolved by using HF + HNO₃ in sealed Teflon capsules and heated on a hot plate for 7 days. REEs were separated using AG50 W cation-exchange columns. Sm and Nd were further purified by passing REE through second PS07 cation-exchange columns, conditioned and eluted with dilute HCl. Sm–Nd isotopic compositions were measured by a VG-AXIOM HR-MC-ICP-MS. Each sample was analyzed in between two determination of the standard solutions (JNdI for Nd). The 147Sm/144Nd ratios were calculated from Sm and Nd contents measured by ICP-MS. The measured 144Nd/146Nd ratios have been normalized to 146Nd/144Nd = 0.7219, and adjusted to JNdI standard = 0.512120. In order to monitor the accuracy and reliability data, the standard BCR-2 was also analyzed together with unknown samples. Four measurements yielded 144Nd/146Nd = 0.512622 ± 14, 0.512624 ± 20, 0.512624 ± 14 and 0.512622 ± 11, which are within error of measurements reported by Weis et al. (2006).

5. Results

5.1. Zircon U-Pb ages

Sample 13MH-18 was collected from a dolerite dike in the Yingfeng region (see locality in Fig. 1c). Zircons selected for SIMS analyses are mostly irregular, tabular and transparent, and have length to width ratios up to 4:1. The results of SIMS-U-Pb analyses are listed in Table 1. Twenty spots of 20 zircons were analyzed and show variable abundance of Th (180–906 ppm), U (196–838 ppm) and high Th/U (0.7–1.2). The common Pb content is low with mostly f206 < 0.1%. All apparent 206Pb/238U ages (824–873 Ma) are concordant within analytical errors and yield a weighted mean age of 845 ± 6 Ma (MSWD = 1.19). This age is comparable with the concordia age of 844 ± 2 Ma (MSWD = 0.26; Fig. 5a). CL images show uniform wide and straight oscillatory zones, and no cores are observed, which is typical for zircons that crystallize from mafic magma (Fig. 5a). Most grains are characterized by a narrow, highly luminescent rim, responding to a later regional thermal event.

Zircons from the dolerite samples (13MH-19 and 13MH-44) also have irregular or fragmented tabular shapes. CL investigations reveal that most grains contain a CL-dark or weak straight oscillatory domain surrounded by a narrow CL-bright overgrowth, which is similar to that of 13MH-18 (Fig. 5b-c). The results of LA-ICP-MS U-Pb analyses are given in Table 2. Twenty spots of 13MH-19 were determined with high Th/U ratios (0.9–1.8). Among these, 19 analyses have consistent apparent 206Pb/238U ages of 832–855 Ma and yield a weighted mean age of 851 ± 5 Ma (MSWD = 0.35), which is consistent with the concordia age of 852 ± 2 Ma (MSWD = 1.2; Fig. 5b). Another zircon grain gives distinctly older 206Pb/238U age (981 ± 11 Ma), indicating that it may be captured from the basement rocks. A total of 10 spots were analyzed on 10 grains for 13MH-44. The apparent 206Pb/238U ages range from 830 Ma to 858 Ma and yield a mean age of 846 ± 6 Ma (MSWD = 1.13; Fig. 5c). These spots are characterized by high Th/U ratios (1.9–4.1). However, some spots are slightly discordant perhaps due to Pb-loss during later metamorphism or deformation. Recently, Lu et al. (2008) also reported a SHRIMP U-Pb age of 821 ± 11 Ma for these mafic dikes. Thus we conclude that Yingfeng dolerite dikes and basaltics formed at 820–850 Ma.

The Aolaoshan meta-ryolite (Q14-77) is interbedded with meta-basalt layers (Fig. 2d). The results of LA-ICP-MS U-Pb analyses are listed in Table 2. The zircons are colorless and subhedral-euhedral with 100–200 μm in length and 50–100 μm in width. Cathodoluminescence (CL) investigations reveal that a few zircon grains contain a CL-bright, oscillatory zoned core surrounded by...
Fig. 5. (a) U-Pb concordia diagram for SIMS analyses of the Yingfeng dolerite (13MH-18). (b-c) U-Pb concordia diagram for LA-ICP-MS analyses of the Yingfeng dolerite (13MH-19 and 13MH-44). (d) U-Pb concordia diagram for LA-ICP-MS analyses of the Aolaoshan meta-rhyolite (Q14-77).

Table 1

In-situ SIMS zircon U-Pb data for the Yingfeng dolerite (13MH-18).

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<th>Th ppm</th>
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<th>206Pb/238U ±1σ (%)</th>
<th>203Pb/238U ±1σ (%)</th>
<th>207Pb/235U ±1σ (%)</th>
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<td>0.1406</td>
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<td>11</td>
<td>406</td>
<td>375</td>
<td>0.92</td>
<td>0.03</td>
<td>0.0668</td>
<td>0.91</td>
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<td>1.75</td>
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<td>12</td>
<td>508</td>
<td>600</td>
<td>1.18</td>
<td>0.03</td>
<td>0.0672</td>
<td>0.68</td>
<td>1.317</td>
<td>1.65</td>
<td>0.1421</td>
</tr>
<tr>
<td>13</td>
<td>396</td>
<td>438</td>
<td>1.10</td>
<td>0.09</td>
<td>0.0674</td>
<td>0.96</td>
<td>1.292</td>
<td>1.79</td>
<td>0.1390</td>
</tr>
<tr>
<td>14</td>
<td>662</td>
<td>687</td>
<td>1.04</td>
<td>0.03</td>
<td>0.0668</td>
<td>0.62</td>
<td>1.336</td>
<td>1.62</td>
<td>0.1450</td>
</tr>
<tr>
<td>15</td>
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<td>341</td>
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<td>0.00</td>
<td>0.0668</td>
<td>0.79</td>
<td>1.289</td>
<td>1.70</td>
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<td>337</td>
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<td>0.04</td>
<td>0.0665</td>
<td>1.14</td>
<td>1.297</td>
<td>1.89</td>
<td>0.1414</td>
</tr>
<tr>
<td>17</td>
<td>233</td>
<td>229</td>
<td>0.98</td>
<td>0.06</td>
<td>0.0661</td>
<td>1.20</td>
<td>1.276</td>
<td>1.92</td>
<td>0.1400</td>
</tr>
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<td>18</td>
<td>402</td>
<td>492</td>
<td>1.22</td>
<td>0.00</td>
<td>0.0678</td>
<td>0.78</td>
<td>1.320</td>
<td>1.69</td>
<td>0.1412</td>
</tr>
<tr>
<td>19</td>
<td>838</td>
<td>906</td>
<td>1.08</td>
<td>0.01</td>
<td>0.0672</td>
<td>0.54</td>
<td>1.303</td>
<td>1.59</td>
<td>0.1407</td>
</tr>
<tr>
<td>20</td>
<td>826</td>
<td>876</td>
<td>1.06</td>
<td>0.00</td>
<td>0.0677</td>
<td>0.54</td>
<td>1.317</td>
<td>1.59</td>
<td>0.1411</td>
</tr>
</tbody>
</table>

f CCS is the percentage of common 206Pb in total 206Pb.
a narrow CL-dark, structureless rim (Fig. 5d). However, most zircons have no cores and show inhomogeneous CL intensities with patchy, banded or structureless patterns, similar to that of rim surrounding inherited cores. A total of 25 spots were analyzed on 25 grains. All the data define a discordant line with an upper-intercept age of 803 ± 38 Ma and a lower-intercept age of 439 ± 4 Ma (Fig. 5d). Seven analyses from inherited cores yield 206Pb/238U ages of 820−849 Ma, combining to a mean age of 832 ± 9 Ma (MSWD = 1.2), which is consistent with the upper-intercept age. These spots are characterized by high Th/U ratios (0.45−0.86). However, 14 spots from the CL-dark domains give a mean 206Pb/238U age of 439 ± 4 Ma (MSWD = 1.6), which is indistinguishable with the lower-intercept age within error. They have low Th/U (0.03−0.16), indicating a metamorphic origin. Another four concordant U-Pb ages (586−744 Ma) are located between upper- and lower-intercept ages. The intermediate Th/U values (0.24−0.46) imply that they may represent mixed ages of core and rim domains. Therefore, we interpret that the weighted mean age of 832 ± 9 Ma represents the protolith age of Aolaoshan meta-volcanic rocks and the age of 439 ± 4 Ma represents the time

Table 2  
In-situ LA-ICP-MS zircon U-Pb data for the Yangfeng dolerites (13M1-19 and 13M1-44) and the Aolaoshan meta-rhyolite (Q14-77).

<table>
<thead>
<tr>
<th>Spot #</th>
<th>Concentration (ppm)</th>
<th>Th/U</th>
<th>Isotopic ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>1M19-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>386 482</td>
<td>1.25</td>
<td>0.06739</td>
</tr>
<tr>
<td>2</td>
<td>259 287</td>
<td>1.11</td>
<td>0.06737</td>
</tr>
<tr>
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<tr>
<td>1M19-44</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1806 6004</td>
<td>3.33</td>
<td>0.06955</td>
</tr>
<tr>
<td>2</td>
<td>1783 3984</td>
<td>2.23</td>
<td>0.06811</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3
Whole-rock major and trace element data for the Yingfeng dolerites/basalts and the Aolaoshan meta-volcanics.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yingfeng dolerites/basalts</th>
<th>Aolaoshan meta-volcanics</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2O</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>Na2O</td>
<td>1.93</td>
<td>1.39</td>
</tr>
<tr>
<td>MgO</td>
<td>7.42</td>
<td>6.89</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>11.84</td>
<td>11.78</td>
</tr>
<tr>
<td>LOI</td>
<td>11.30</td>
<td>9.78</td>
</tr>
<tr>
<td>Na2O</td>
<td>1.93</td>
<td>1.39</td>
</tr>
<tr>
<td>MgO</td>
<td>7.42</td>
<td>6.89</td>
</tr>
</tbody>
</table>

Major elements (wt.%)

Fe2O3 = all Fe calculated as Fe2O3; LOI = loss on ignition; Mg# = 100 × (Mg/(Mg + Fe2O3)); Fe3+/Fe = 0.1.

Table 4
Whole-rock Sm–Nd isotopic data for the Yingfeng dolerites/basalts.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>147Sm/144Nd</th>
<th>143Nd/144Nd</th>
<th>2σ</th>
<th>εNd(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13MH–13</td>
<td>2.41</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>50.824</td>
</tr>
<tr>
<td>13MH–15</td>
<td>4.88</td>
<td>1.39</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>50.824</td>
</tr>
<tr>
<td>13MH–43</td>
<td>2.77</td>
<td>9.11</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>50.824</td>
</tr>
<tr>
<td>13MH–44</td>
<td>4.02</td>
<td>14.03</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>50.824</td>
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<tr>
<td>13MH–57</td>
<td>2.60</td>
<td>7.87</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>50.824</td>
</tr>
</tbody>
</table>

Notes: (1) εNd(T) = ([147Sm/144Nd]/[147Sm/144Nd]CHUR – 1) × 10^6; (2) T = 850 Ma, crystallization age of the Yingfeng dolerite.

5.2. Major and minor elements

Ten samples of the Yingfeng dolerites/basalts and five samples of the Aolaoshan meta-volcanics were analyzed for major- and trace-element data (see sampling localities in Fig. 1c). The results...
are listed in Table 3. They show weak alteration with low loss on ignition (LOI) of 0.3 wt.% to 2.3 wt.%.

In the Yingfeng mafic rocks, there is a uniform and moderate LREE enrichment, with La/N = 1.3, Nb/Th = 12. The low-Ti eclogites from Yuka, Xitieshan and Dulan exhibit a higher Ti content and Mg number (63–71). They exclusively plot within the subalkaline basalt field (Fig. 6a). On the FeOT/MgO vs TiO₂ plot (Fig. 6c), the Yingfeng mafic rocks exhibit a typical tholeiitic trend. Together with the data for eclogites from Yuka, Dulan and Xitieshan in the North Qaidam UHPM belt (Fig. 6b), they can be divided into a high-Ti alkaline group [Ti/Y > 500 and (Sm/Yb)N > 2.5] and a low-Ti tholeiitic group [Ti/Y < 500 and (Sm/Yb)N < 2.5]. The Yingfeng dolerites/basalts belong to the latter group.

The Aolaoshan meta-volcanics mainly consist of basalt (Q14-85/87/89) and rhyolites (Q14-83/84). Sample Q14-85 plots within the subalkaline basalt field, while Q14-87/89 belong to the andesite/basalt field (Fig. 6a). Q14-85 has a less evolved composition compared to Q14-87/89. On the primitive mantle-normalized spider diagram (Sun and McDonough, 1989), the Aolaoshan felsic rocks are characterized by strong LREE-enrichment (LaN/GdN = 13.1 and 8.2) and HREE-depletion (GdN/YbN = 7.2 and 3.0), and no Eu anomalies to significant positive anomalies (ΔEu = 0.93 and 2.33), which may be attributed to residual garnet and plagioclase accumulation, respectively (Fig. 7g).

5.3. Sm-Nd isotopes

Five samples of the Yingfeng dolerites/basalts were analyzed for Sm-Nd isotopes. The results are presented in Table 4. They have consistent 147Sm/144Nd ratios (0.16–0.21) and moderate 146Nd/144Nd ratios (0.512480–0.512904) with initial εNd(T) values (−0.5 ~ +3.8), indicating that they were derived from a time-integrated depleted mantle. All the initial values of Nd isotope for the North Qaidam eclogites were also recalculated at 850 Ma. The high-Ti group of the Yuka eclogites exhibits high and positive εNd(T) values (+4.2 to +5.1). However, the low-Ti eclogites with lower εNd(T) (+1.2 ~ +5.9), which are similar to those of Yingfeng dolerites/basalts, but significantly distinct from the initial Nd isotopic value of contemporaneous depleted mantle [εNd(850 Ma) = +8.1].

6. Petrogenesis

6.1. Effect of alteration on magma compositions

Although the Yingfeng dolerites/basalts and Aolaoshan meta-volcanics have low LOI (0.3–2.3 wt.%), the mobility of major and trace elements still need to be evaluated prior to the discussion on petrogenesis, especially when comparisons are made with the Yuka, Dulan and Xitieshan eclogites. The effects of alteration and metamorphism on major element contents can be monitored by the CIA value [Al₂O₃/(Al₂O₃ + CaO + Na₂O + K₂O)] in molecular
The CIA values of the Yingfeng–Aolaoshan mafic rocks are in a limited range of 34–47%, consistent with those of fresh basalts (CIA = 30–45%; Nesbitt and Young, 1982). The North Qaidam eclogites have relatively variable but similar CIA values (29–49) to those of fresh basalts. The CIA values (~49) of the Aolaoshan felsic rocks also fall within the interval of fresh granitic rocks (CIA = 45–55; Nesbitt and Young, 1982). These recognitions can be also supported by the A-CN-K and A-CNK-FM triangular diagrams (Appendix Fig. 1, Nesbitt and Young, 1989).

Fig. 7. Primitive mantle-normalized incompatible trace element spidergrams and chondrite-normalized REE diagrams for the North Qaidam eclogites, Yingfeng dolerites/basalts and Aolaoshan meta-volcanic rocks. Data for the Yuka eclogites are from Chen et al. (2009b) and Song et al. (2010); the Dulan and Xitieshan eclogites from Zhang et al. (2012) and Yu et al. (2013). The average value of Suxiong alkaline basalts (blue line) in the Kangdian Rift of South China is from Li et al. (2002). The values for Jinchuan dolerites (red lines) are from Li et al. (2005). The low-Ti basalts data for the Deccan LIP (grey domain) are from Melluso et al. (2006). The normalization values are from Sun and McDonough (1989). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
The mobility of trace elements can be assessed by plotting against Zr or CIA values (Li et al., 2008b, 2010b). In the covariance diagrams (Fig. 8), the rare earth elements (REE, such as La and Yb), Y, HFSE (Th, Zr, Hf, Nb, Ta, Ti) and compatible elements (Cr and Ni) show linear relationships with Zr, which indicate they are immobile during later alteration and metamorphism, although the alkaline high-Ti and tholeiitic low-Ti groups show distinct trends. Therefore, we will only use the immobile elements in the following discussion.

6.2. Fractional crystallization

Most of the mafic rocks in North Qaidam show the characteristics of evolved magmas in disequilibrium with primary melts which have Mg# > 72, Cr > 1000 ppm and Ni > 400 ppm (Wilson, 1989; Niu and O’Hara, 2008). Sample 13MH-18 from the Yingfeng dolerites/basalts is least-evolved with high MgO (11.5 wt.%), Mg# (71), and compatible element contents (Cr = 600 ppm and Ni = 178 ppm), and is closest to the composition of picritic magma (MgO = 12 wt.%; Le Bas, 2000). For the Yingfeng–Aolaoshan mafic rocks, the positive correlation between Mg# and compatible elements (Cr and Ni) indicate the fractional crystallization dominantly of olivine and clinopyroxene in magma chambers or en route to the surface (Fig. 9d and f). The linear relationship between CaO/Al₂O₃ and Mg# may be also ascribed to the fractionation of clinopyroxene (Fig. 9b). The slight Eu anomalies (δEu = 0.86–1.15) suggest that plagioclase may not be a major fractionating phase. The Fe-Ti oxides might not have preferentially crystallized in view of
the weak to absent Ti anomalies and the tholeiitic trend, except for Q14-87 and Q14-89 (Fig. 9c and e). Similarly, for the North Qaidam eclogites, the negative correlation (Mg# vs. TiO₂) and positive correlation (Mg# vs. Ni) are consistent with significant crystal fractionation of olivine (Fig. 9c and f), whereas plagioclase is unlikely to be an important fractionating phase on account of the lack of Eu anomalies (Fig. 7).

6.3. Lithospheric contamination and source

The involvement of continental crust and enriched lithospheric mantle would significantly change the LREE/HFSE and HFSE/LILE ratios in primitive parental magmas (Hofmann, 1988). Among the mafic rocks in North Qaidam, the high-Ti eclogites in Yuka show positive HFSE anomalies [(La/Ta)PM = 0.51–0.97; Ti' = 2TiPM/
(Sm\textsubscript{PM} + Tb\textsubscript{PM}) = 0.82–1.76; subscript PM denotes primary mantle-normalized), which imply negligible contamination of crust or enriched SCLM (Fig. 10 a and c). This conclusion is also supported by positive and uniform initial ε\textsubscript{Nd} values (4.7–5.1; see Fig. 10 b and d). However, the low-Ti eclogites in Yuka, Dulan and Xitieshan show relatively varying anomalies in Nb-Ta and diverse initial Nd isotopic values (Fig. 10 a–c), which imply that the crustal contamination plays a role in magma differentiation, although some are not appreciably contaminated. They are similar to the Jinchuan dolerites, which were recognized to involve lithosphere interaction (Li et al., 2005; Fig. 7). The linear relationship of (La/Ta)\textsubscript{PM} vs. (Th/Ta)\textsubscript{PM} (Ingle et al., 2002) indicates the mixing between mantle melts and upper continental crust (Fig. 10 a; Ingle et al., 2002). The quantitative modeling suggests that they may originate from E-MORB source and have experienced a minor crustal assimilation (<4%; Fig. 10 d).

The Yingfeng dolerites/basalts and one Aolaoshan basalt (Q14-85) exhibit weak enrichments in Nb-Ta ([La/Ta]\textsubscript{PM} = 0.59–1.08) and dominantly positive ε\textsubscript{Nd}(T) values (1.0–3.8), which are similar to those of the least-contaminated low-Ti eclogites (Fig. 10 a and b). These characteristics imply that these mafic rocks suffered little, if any, crustal assimilation. Minor assimilation (<8%) may exist given the weak correlation of Th/Nb with ε\textsubscript{Nd}(T) values (Fig. 10 d). It is noted that the Yingfeng dolerites/basalts perhaps experienced heterogeneous source mixing (e.g. mantle plume and depleted asthenosphere mantle) and/or magma mixing (e.g. OIB and E-MORB/N-MORB), in consideration of their relatively high Th/Nb but low La/Sm compared to the high-Ti group (Fig. 10 b and d). On the contrary, samples Q14-87 and Q14-89 of the Aolaoshan basalts are characterized by significant negative HFSE anomalies (Fig. 10 a and c), and have lower Nb/La ratios (0.10–0.14) than that of the upper continental crust (Nb/La = 0.39; Rudnick and Gao, 2003), implying that the Nb-Ta anomalies could not have derived from crustal contamination. Furthermore, the assimilation of crustal materials is unable to cause the obvious negative anomalies in...
Zr-Hf of samples Q14-87/89. Thus we suggest that their depredations in HFSE are most likely inherited from a metasomatized subcontinental lithosphere mantle (SCLM).

It is noteworthy that the low-Ti and high-Ti groups exhibit obviously different Ti/Y and (Sm/Yb)n ratios (Fig. 6 b). In fact, the fractionation of REE may be ascribed to the AFC processes or to the partial melting, including the effects of residual minerals, melting degree and source heterogeneity. On the plot of La/Yb vs. Tb/Yb (Fig. 11), the high-Ti basalts might be generated by the low degree (2–4%) partial melting of a deep garnet-bearing (0–2%) asthenospheric mantle source. However, the higher degree (>4%) of melting occurred in a residual spinel-stable field for the low-Ti group.

For the Aolaoshan rhyolites (Q14-83/84), the distinct evolved trends in most Zr versus major and minor elements plots (Fig. 8) suggest that they may not have formed by AFC processes of the coeval Aolaoshan basaltic magma. The residual of mafic rocks can hardly produce the abnormal low Na2O/K2O ratios (0.26–0.30), MgO contents (0.1–0.2 wt.%), and compatible element concentrations (Cr = 2.5–4.1 ppm and Ni = 2.3–2.4 ppm). The strong REE fractionation and high Sr/Y ratios (52.7–70.9) imply a source with residual garnet (Fig. 7h). However, the residual phases were most likely dominated by plagioclase, because of the low Sr concentrations (195–219 ppm). The Aolaoshan rhyolites are characterized by high K2O/Na2O (3.3–3.8), CaO/Na2O (0.8–0.9) and low Rb/Ba (0.25–0.65), Rb/Sr (0.82–1.11), indicating a potassic, clay-poor greywacke source (Sylvester, 1998). Similarly, the ca. 800 Ma S-type granitoids from the Qilian and South China blocks are characterized by high CaO/Na2O (>0.3), low Rb/Sr (0.48–2.7), low Rb/Ba (0.1–0.7) and negative barium anomalies, and are derived from clay-poor psammitic rocks (Tung et al., 2013 and references herein).

6.4. Tectonic setting

Despite experiencing variable extents of fractional crystallization and involvement of crustal contamination, the high-Ti eclogites from Yuka show OIB-like Nd isotopic compositions and trace element patterns which are comparable with those of the Suxiong alkali basalts (Li et al., 2002; Fig. 7a–b), while the least-contaminated samples of low-Ti group exhibit E-MORB patterns which are similar to those of the Deccan low-Ti basalts (Fig. 7e–h). Among the Yingfeng dolerites/basalts, samples 13MH-13/18/67 are least-evolved, and have the highest MgO contents (9.5–11.5 wt.%), and compatible elements. With these samples, we calculated the compositions of primary magma based on the procedure of Herzberg et al. (2007) and Wang et al. (2009), which are picritic melts and contain 48.4–49.2 wt.% SiO2, 1.0–1.1 wt.% FeO, 8.9–11.2 wt.% MgO and 14.0–17.7 wt.% MnO. In terms of the equation $T_p$ ($^\circ$C) = 1463 + 12.74MgO – 2924/MgO (Herzberg and O’Hara, 2002), the temperature capabilities (1434–1524 $^\circ$C) are obtained, which are higher than that of contemporary ambient MORB-source asthenospheric mantle (1350–1450 $^\circ$C; references in Li et al., 2008b), implying an origin of anomalously hot mantle source. In addition, the North Qaidam mafic rocks are characterized by high Ti/V, mostly >20 for the low-Ti tholeiitic group and >50 for the high-Ti alkaline group, compatible with continental flood basalts and ocean-island basalts, respectively (Fig. 12a; Shervais, 1982). In the discrimination diagrams of Y1/15-La10-Nb8 (Fig. 12b) and Hf/3-Th-Ta (Fig. 12c), the high-Ti eclogites from Yuka are plotted in the within-plate basalt field. However, most mafic rocks of the low-Ti group belong to E-MORB and continental basalts. In contrast, some Dulan/Xitieshan low-Ti eclogites and two of the Aolaoshan basalts (Q14-87/89) are similar to continental back-arc tholeiites and island arc basalts, which might be ascribed to relatively high degree melting (and/or spinel-stable source) and crust/source contamination (see discussion above). Overall, the low-Ti and high-Ti mafic rocks in North Qaidam are likely to form in an intraplate environment related to mantle plume activities, like Emeishan, Siberian, Deccan and other LIPs in the world (Sharma et al., 1992; Hawkesworth et al., 1995; Xu et al., 2001; Melluso et al., 2006; Jowitt and Ernst, 2013; Ernst, 2014).

7. Discussion

7.1. Protoliths of North Qaidam UHPM eclogites: CFBs subducted to depths of ~120 km

Mafic rocks including basalts and associated intrusions can provide the materials for HP/UHP metamorphism during the subduction of oceanic or continental lithosphere. In the last decade, the origin and age of eclogite protoliths in North Qaidam UHPM belt have been studied (Song et al., 2014 and references therein). The eclogite blocks are dominantly derived from the 850–820 Ma CFBs with minor fragments of the 540–500 Ma oceanic crust (e.g., Zhang et al., 2008, 2010; Chen et al., 2009b; Song et al., 2009, 2010; Yu et al., 2013).

Eclogites with protoliths of 850–820 Ma CFBs in the North Qaidam UHPM belt have similar occurrences to the Yingfeng dolerites/basalts and Aolaoshan meta-volcanic rocks (Figs. 2 and 4). Their geochemical characteristics and protolith ages demonstrate that the Yingfeng dolerites/basalts and Aolaoshan layered volcanic rocks could act as the protoliths of the eclogites in the 400-km-long North Qaidam UHPM belt. The Yingfeng gneiss-facies dolerite dikes and layered basalts are indeed remnants of unsubducted CFBs on the continental margin (less than 20 km in depths). The Aolaoshan volcanic sequence, on the other hand, had undergone amphibolite facies to HP granulite facies metamorphism (40–60 km) at ~439 Ma, while most of mafic rocks in the northern margin of the Qaidam Basin were subducted to upper mantle depths (~120 km) and experienced the ultra-high pressure metamorphism (Fig. 13).
7.2. Determination of the 850–820 Ma North Qaidam LIP along the dismembered continental margin of Rodinia

Because of the dismemberment during continental breakup and strong erosion/cover/metamorphism afterwards, the 850–820 Ma mafic–ultramafic igneous rocks are dispersedly preserved in the neighboring blocks, such as Tarim, South China and Australia (Fig. 1a).

In the Longshoushan terrane of the Alxa (Alashan) block (Site 3 in Fig. 1a), the Jinchuan ultramafic–mafic intrusion, which contains the world second-large Cu–Ni sulfide ore, was dated at \(^{24}C\)828 Ma (Li et al., 2005 and references therein). Integrated mineralogical, petrological and geochemical data are consistent with a mantle plume origin (Li et al., 2005). In addition, the Kuluketage dolerite dikes crop out in the northeastern margin of Tarim, and zircon U-Pb SHRIMP analyses yield a similar Neoproterozoic age of 824 ± 9 Ma (Site 4 in Fig. 1a; Zhang et al., 2009). In northwestern Yangtze, the Bikou basalts are mainly tholeiitic in composition and erupted at 821 \(^{24}C\)811 Ma (Site 2 in Fig. 1a). They are likely the remnants of CFBs derived from a \(^{24}C\)825 Ma mantle plume with recycled components and an anomalously hot asthenosphere source \(^{176}C\) hotter than the contemporary ambient MORB source (Wang et al., 2008). In the Kangdian rift of western Sichuan, the V–Ti and Cu–Ni bearing Gaoligou mafic–ultramafic layered intrusions together with the coeval granitoids were formed in an extensional continental rift at 825 ± 12 Ma (Site 1 in Fig. 1a; Zhu et al., 2006). In northern Guangxi, the 825 Ma mafic–ultramafic dikes and sills are identical in age to the 827 Ma Gairdner-Amata dike swarm of central and southeast Australia, thought to be of mantle plume origin (Site 9 in Fig. 1a; Wingate et al., 1998; Li et al., 1999). The intraplate geochemical signatures (E-MORB or OIB) and high mantle potential temperatures (>1480 °C) imply the presence of a Neoproterozoic mantle plume beneath South China (Wang et al., 2009 and references herein). These simultaneous magmatic rocks in South China were termed the Guibei LIP by Ernst et al. (2008). Recently, a large amount of plume-related igneous activities during this period have also been recognized in the eastern segment of the Nanhua rift basin (Site 10 in Fig. 1a), for example the 849 Ma Zhenzhushan bimodal volcanic rocks, the 836–857 Ma Wuyi basalts/gabbros, the 848 Ma Gangbian alkaline complex and the 849 Ma Shenwu dolerite dikes (Li et al., 2008b, 2010a,b; Shu et al., 2011).

The synchronous igneous rocks in North Qaidam extend more than 400 km from the Dulan UHPM terrane in the east to Yingfeng–Aolaoshan region in the west (Fig. 1b). As discussed above, parts of them had been subducted to depths more than 120 km.
(e.g., Yuka, Xitieshan and Dulan eclogites), some were metamorphosed at middle-lower crust level (e.g., the Aolaoshan amphibolites), and others remained at surface or shallow crustal levels with greenschist-facies metamorphism at most (e.g., the Yingfeng dolerites/basalts), as illustrated in Fig. 13b. By using the simple “lithosphere bending model” and assuming 350 km bending radius of continental lithosphere like Himalaya (Leech et al., 2005), the arc length and radian from shallow to deep locations can reach to 270 km and 0.775, respectively. The subducted LIP component would occupy an area of 270 × 400 km² on the rifted passive continental margin of the Qaidam block. Consequently, we speculate that the 850–820 Ma North Qaidam LIP must have an areal extent of >100,000 km², the minimum dimension criterion considered for the standard LIPs (Coffin and Eldholm, 1994; Bryan and Ernst, 2008; Ernst, 2014), provided that the concurrent magmatic records in the adjacent blocks are also taken into account.

The dismembered 850–820 Ma LIP records in Tarim, South China, Qilian–Qaidam and even Australia, like other well-known reconstructed LIPs in the world (e.g., Paraná–Etendeka, North Atlantic Igneous Province, Deccan, Karoo, etc), may provide strong evidence for that these blocks have close affinities before being separated. Actually, the Grenville-age orogenic belt extends from the Yangtze block in the east, via Qaidam–Qilian in the middle, and to Tarim in the west, in favor of the proposal of the “South-West China United Continent” (Song et al., 2012; Fig. 1a).

In addition, the latest Neoproterozoic continental rift basalts (~600 Ma) in the North Qilian Orogen and central-southeastern Australia also support a link of the Qilian–Qaidam block between SE Australia and South China during the final breakup of Rodinia (Xu et al., 2015). The abundance and planar distribution of coeval (850–820 Ma) igneous rock associations from deep to shallow on the surface, including mafic to ultramafic sills and intrusions (Jinchuan, Gaogia,mat), dikes and flood basalts (Yingfeng, Bikou, Kuluketage, Gairdner-Amata), are consistent with the features of LIPs induced by a superplume (Ernst et al., 2005, 2008).

### 7.3. Tectonic evolution from supercontinental breakup to continental collision and subduction

In general, the formation and evolution of most LIPs are temporally and spatially associated with continental breakup and opening of oceanic basins, although the Siberian and Emeishan LIPs seem to correlate with aborted rifting (Richards et al., 1989; White and McKenzie, 1989; Coffin and Eldholm, 1994; Courtillot et al., 1999; Saunders, 2005; Ernst et al., 2005). Fig. 14 illustrates the dynamic evolution process from an ascending mantle superplume and the formation of LIP (pre-rift phase; Fig. 14a), subsequently to the formation of rift basin and passive margin (synrift phase; Fig. 14b), and then to the seafloor spreading (Fig. 14c) and the final subduction of oceanic–continental lithosphere (Fig. 14d–e).

(a) An ascending mantle plume which arrived at the base of lithosphere could melt by adiabatic decompression/high potential temperature and cause the lithosphere (metasomatized SCLM and lower crust) to melt by conductive heating, which rapidly produced a large amount of igneous rocks (flood basalts, mafic dikes/sills, layered mafic–ultramafic intrusions, anorogenic granitoids) to form the 850–820 Ma LIP. Like most continental LIPs (Afro-Arabian, North Atlantic Igneous Province, Deccan, Paraná, Karoo and Central Atlantic Magmatic Province), the pre-rift magmatism also occurred at Tarim, South China, Qilian–Qaidam and SE Australia during the breakup of Rodinia (Fig. 14a). The North Qaidam LIP mainly consists of the 844–821 Ma Yingfeng–Aolaoshan dolerite dikes and flood basalts, the 850–820 Ma CFB protolith of the North Qaidam eclogites, and the 828 Ma Jinchuan ultramafic intrusions-dolerite dikes. It represents a dismembered LIP (originally >100,000 km² in area) along the passive continental margin. Other contemporaneous plume-related magmatic records in South China, Tarim and

![Fig. 13.](attachment:fig13.png) (a) The peak metamorphic P–T conditions of North Qaidam eclogites, Aolaoshan garnet amphibolites, and Yingfeng dolerites/basalts. P–T boundaries of various metamorphic facies [greenschist (GS), amphibolite (AM), granulite (GR), medium temperature eclogite-high pressure granulite (EC–HPG), blueschist (BS), amphibole–epidote eclogite (Amp/Ep–EC), amphibole lawsonite eclogite (Amp/Lw–EC), lawsonite eclogite (Lw–EC), and amphibole eclogite (Amp–EC)] are according to Brown (2009). (b) The speculative distribution of the 850–820 Ma LIP along the subducted continental margin of the Qilian-Qaidam block. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Australia include the 825 Ma Gairdner dike swarms, the 824 Ma Quruqtagh dolerite dikes, the 825 Ma Gaojiacun mafic–ultramafic intrusions and the 821 Ma Bikou continental flood basalts, and so on. All these rocks are products of the 850–820 Ma superplume, which marks the beginning of a protracted fragmentation process.

(b) The precursory uplift and doming induced by upwelling of a hot and buoyant plume head were followed by the subsidence and extension of thinned continental lithosphere (Fig. 14b), which led to the unconformable contact of sequences and formed rift basins, and further rifted passive continental margins with seaward-dipping reflector sequences (Fig. 14c). The former is ascribed to the continent-scale unroofing and rapid erosion (Li et al., 1999). The latter process was characterized by major rift phase that peaked starting at ca. 820 Ma and included the later prolonged, multi-staged (820–800 Ma, 790–760 Ma and perhaps ca. 600 Ma) volcanism in the Australia, South

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**Fig. 14.** Tectonic model showing a complete evolution from supercontinent breakup in the Neoproterozoic, to sea-floor spreading, oceanic and continental subduction/collision in the Early Paleozoic.
Acknowledgements

We are grateful to X.H. Li and his laboratory group for helping with the zircon dating. This study was supported by the Major State Basic Research Development Program (2015CB885601), Basic geological survey program of China Geological Survey (1212011121258) and National Natural Science Foundation of China (Grant Nos. 41372060, 41572040, 41130314).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2016.07.007.

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