AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL074717

Key Points:

- $\delta^{18}O$ depleted rhyolite from the Malani Igneous Suites (MIS) in NW India
- Significant shift from magmatism with mantle-like $\delta^{18}O$-$\varepsilon_{Hf(t)}$ values to low ^{18}O but juvenile magmatism at 800–780 Ma
- Similar tectono-thermal transition occurred in NW India, south China, and Madagascar at 800–780 Ma

Supporting Information:

- Supporting Information S1
- Table S1
- Data S1
- Data S2
- Data S3
- Data S4

Correspondence to:
W. Wang,
wwz@cug.edu.cn

Citation:
Wang, W., Cawood, P. A., Zhou, M.-F., Pandit, M. K., Xia, X.-P., & Zhao, J.-H. (2017). Low-$\delta^{18}O$ rhyolites from the Malani igneous suite: A positive test for south China and NW India linkage in Rodinia. *Geophysical Research Letters*, *44*, 10,298–10,305. https://doi.org/10.1002/2017GL074717

Received 29 JUN 2017
Accepted 29 SEP 2017
Accepted article online 9 OCT 2017
Published online 30 OCT 2017

Low-$\delta^{18}O$ Rhyolites From the Malani Igneous Suite: A Positive Test for South China and NW India Linkage in Rodinia

Wei Wang[1,2], Peter A. Cawood[3,4], Mei-Fu Zhou[2], Manoj K. Pandit[5], Xiao-Ping Xia[6], and Jun-Hong Zhao[1]

[1]State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences, China University of Geosciences, Wuhan, China, [2]Department of Earth Sciences, University of Hong Kong, Hong Kong, [3]School of Earth, Atmosphere and Environment, Monash University, Melbourne, Victoria, Australia, [4]Department of Earth Sciences, University of St Andrews, St Andrews, UK, [5]Department of Geology, University of Rajasthan, Jaipur, India, [6]Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China

Abstract The Malani igneous suite (MIS) in NW India represents one of the best preserved silicic large igneous provinces. Voluminous silicic lavas of the MIS erupted between ~780–750 Ma. Zircon grains from rhyolite and dacite lavas have oxygen isotopic compositions that include depleted ($\delta^{18}O$ = 4.12 to −1.11‰) and enriched ($\delta^{18}O$ = 8.23–5.12‰) signatures. The low-$\delta^{18}O$ zircon grains have highly radiogenic Hf isotopic compositions ($\varepsilon_{Hf(t)}$ = +13.0 to +3.6), suggesting high-temperature bulk cannibalization of upper level juvenile mafic crust as an essential mechanism to produce the low-$\delta^{18}O$ felsic magma. Xenocrystic zircon grains in dacites have high $\delta^{18}O$ and low $\varepsilon_{Hf(t)}$ values for magmas older than 800 Ma, reflecting a dramatic transition in tectono-thermal regime in NW India during 800–780 Ma. A synchronous transition also occurred in south China and Madagascar, suggesting a spatially linked geodynamic system. NW India and south China together with Madagascar and the Seychelles lay either along the periphery of Rodinia or outboards of the supercontinent with the age of convergent plate margin magmatism coinciding with breakup of the supercontinent.

1. Introduction

The ~780–750 Ma Malani igneous suite (MIS), NW India, is a Precambrian silicic large igneous province that has an estimated extent of 55,000 km^2 and a thickness of 3–7 km (Kilaru et al., 2013; Pareek, 1981). Geological conditions required to generate such voluminous felsic magma include high rates of magma production, migration, and accumulation, but details are poorly known and controversial (Ashwal et al., 2013; Sharma, 2005). The affinities and tectonic setting of the MIS play a crucial role in the reconstruction of the Rodinia supercontinent, as it forms part of a pulse of activity linking Madagascar, Seychelles, NW India, and south China. However, the MIS and coeval magmatism in south China was thought to be either the product of a mantle plume (Kochhar, 2001; Li et al., 1999) that favor an internal location for south China within the Rodinia supercontinent (Li et al., 2008) or a product of the overall subduction setting (Ashwal et al., 2013; Ashwal et al., 2002; Zhou et al., 2006). In the later model, south China together with NW India, the Seychelles, and Madagascar was suggested to be located in an external location within the supercontinent or on a separate tectonic plate off the supercontinent (Cawood et al., 2013, 2017; Li et al., 2008; Merdith et al., 2017; Zhou et al., 2006).

Magmatic rocks with zircon $\delta^{18}O$ lower than the mantle value (+5.3‰; Valley et al., 1998) are rare as they require large quantities of meteoric water for high-temperature exchange (Smithies et al., 2015; Valley et al., 2005). The maximum depth, at which water circulation and the hydrothermal O-isotopic exchange can occur effectively, is within the upper ~10 km of crust, limited by the brittle-ductile transition (Menzies et al., 2014). Therefore, the low-$\delta^{18}O$ silicic volcanic rocks can provide precise information on magmatism and uppermost crustal processes (Bindeman et al., 2012; Smithies et al., 2015). Besides, low-$\delta^{18}O$ silicic magmas are also significant for understanding caldera and/or rift tectonic settings on account of their close association such as the Holocene Iceland magmatism, which was considered to be generated by partial melting of crust that is hydrothermally altered in shallow (rift) environments and with diverse $\delta^{18}O$ values (Bindeman et al., 2012).

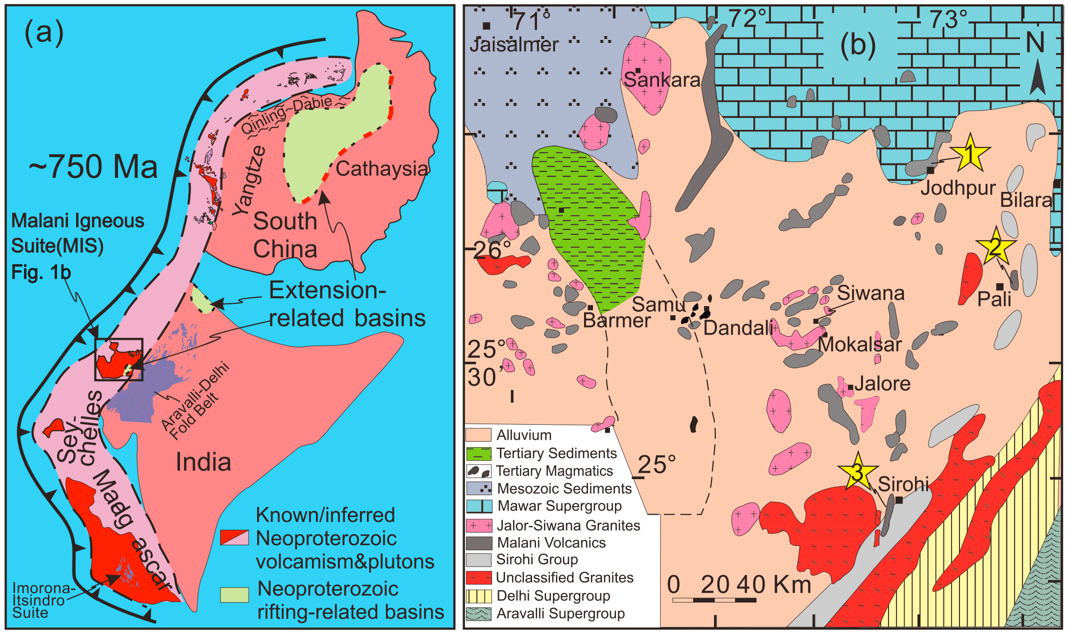

Figure 1. (a) The proposed linkage among Madagascar, Seychelles, NW India, and south China (after Zhou et al., 2006; Ashwal et al., 2013); (b) the outcrop pattern of the extrusive and intrusive phases of the Malani igneous suite (adapted from Roy & Jakhar, 2002). The symbol with number represents the location of sampling. 1: Jodhpur rhyolite; 2: Punagarh dacite; and 3: Sindreth rhyolite.

Zircon grains with low-to-negative $\delta^{18}O$ values are reported from the Neoproterozoic protolith of the Mesozoic Sulu-Dabie metamorphic rocks, in Neoproterozoic volcanic rocks in Qinling orogenic belt, and in the Tonian-aged Imorona-Itsindro Suite in central Madagascar (Archibald et al., 2016; Chen et al., 2011; Fu et al., 2013; Liu & Zhang, 2013; Zheng et al., 2007). The generation of these low-$\delta^{18}O$ magmas is considered to be related to a rift setting coinciding with the breakup of Rodinia supercontinent. Therefore, existence of low-$\delta^{18}O$ magma in the MIS must be evaluated to understand the tectonic affinity of the MIS and possible paleogeographic association among south China, NW India, and Madagascar in Rodinia.

In this paper we report, for the first time, low-$\delta^{18}O$ isotopic compositions of zircon from felsic volcanic rocks from the MIS. These low-$\delta^{18}O$ rhyolites in NW India can be genetically linked to synchronous ^{18}O-depleted igneous rocks in south China, the Seychelles, and Madagascar (Archibald et al., 2016; Harris & Ashwal, 2002; Zhang & Zheng, 2013). We have evaluated and discussed the ^{18}O values in combination with radiogenic isotopic data to propose a close linkage among these blocks, which we argue, lay along a convergent plate margin, that is, along the periphery of Rodinia.

2. The MIS and Sampling

The MIS is located to the west of the Proterozoic Aravalli-Delhi Fold Belt in NW India. It overlies the Precambrian Delhi Supergroup and Erinpura Granite, and in turn is overlain by the late Neoproterozoic to Cambrian Marwar sedimentary rocks (Pandit et al., 2001; Roy & Jakhar, 2002). The MIS covers an area of more than 55,000 km^2; however, actual outcrops of MIS lithologies occupy less than 15% of the area, largely due to Quaternary sand cover. The MIS display cyclic sequences of tuff and rhyolite in the Jodhpur area (Figure 1), and basaltic lava in association with felsic volcanic (rhyolitic tuff and dacite) and sedimentation in small linear basins around Sirohi and Pali, where they are known as the Sindreth and Punagarh groups, respectively (Figure 1).

In this study, rhyolites from the Sirohi (Sindreth Group) and Jodhpur areas and dacites from the Pali area (Punagarh Group) were collected for in situ zircon U-Pb, Hf, and O-isotopic analyses. Rhyolites are porphyritic with phenocrysts of tabular plagioclase, K-feldspar, and embayed quartz. Groundmass comprises either fine-grained quartz, feldspar and amphibole, or predominantly devitrified glass. The Punagarh dacite

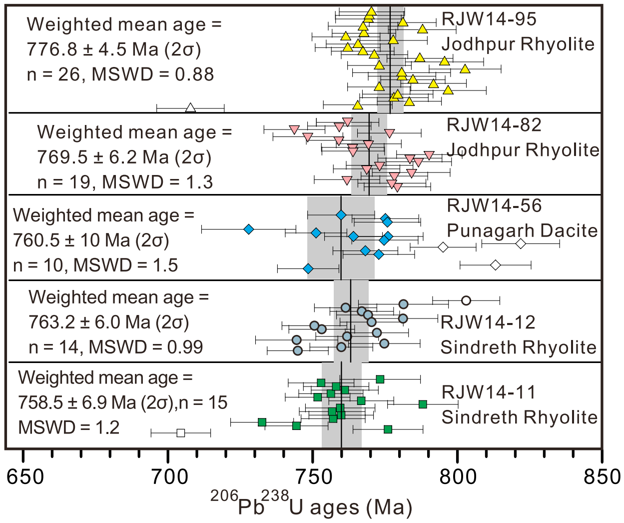

Figure 2. $^{206}Pb/^{238}U$ ages of the dated Malani rhyolites and dacite. The points represent individual SIMS spot analyses with 1σ error bars. The vertical solid bars are U-Pb weighted mean ages, with shaded areas representing a 95% confidence interval. Zircon ages not used in the weighed mean age calculation, which are suspected for being antecrysts or xenocrysts, are indicated by open shape.

consists of K-feldspar and plagioclase phenocrysts, quartz, oxide minerals and chlorite, and fine-grained groundmass of quartz, feldspar, and amphibole.

3. Analytical Methods and Results

Zircon was separated using standard density and magnetic procedures first, and then handpicked under a microscope. In situ zircon U-Pb ages and O isotope analysis were measured using the Cameca IMS-1280 SIMS equipped in Institute of Geology and Geophysics (for O isotopes analyses), and Guangzhou Institute of Geochemistry (for U-Th-Pb analysis), Chinese Academy of Science. Zircon Lu-Hf isotopes were measured using a Neptune Plus multicollector–inductively coupled plasma–mass spectrometry, coupled to an ArF Excimer Laser ablation system, housed at the FocuMs (Jupu) analysis lab, Nanjing China. The metadata for analytical methods and results of reference materials are presented in Table S1 and Data Set S1. in the supporting information. A more detailed discussion of the methodology can be found in the supporting information (Patchett et al., 1981., Chu et al., 2002., Elhlou et al., 2006., Wu et al., 2006., Sláma et al., 2008; Li et al., 2010, 2013).

3.1. Zircon U-Pb Ages

A summary of in situ zircon U-Pb-Hf-O isotopic compositions are presented in Data Set S2. All zircon grains show clear oscillatory zoning without obvious fractures and inclusions. Neoproterozoic zircon grains are mostly concordant with a degree of concordance largely between 97.0 and 102.9%, and a total of four discordant ages were excluded in the following calculation and discussion (Data Set S3). Weighted mean $^{206}Pb/^{238}U$ ages calculated from concordant analyses are 776.8 ± 4.5 Ma, 769.5 ± 6.2 Ma, 763.2 ± 6.0 Ma, and 758.5 ± 6.9 Ma (2σ, mean square weighted deviation (MSWD) = 0.88, 1.3, 0.99, and 1.2, respectively) for samples from Jodhpur (RJW14-95 and RJW14-82) and Sindreth (RJW14-12, RJW14-11), respectively (Figure 2), statistically representing a single population (Spencer et al., 2016), in agreement with previously dated rhyolite tuff and rhyolites (Dharma Rao et al., 2012; Gregory et al., 2009; Van Lente et al., 2009). Analyses with either high common Pb or U-Pb ages significantly deviating from major age group were excluded from weighted averages. For example, one zircon grain from the Jodhpur rhyolite (RJW14-82) has an older $^{206}Pb/^{238}U$ age of 918.9 ± 23.4 Ma, much larger 1σ error and a much higher common Pb component (f_{206}% = 0.82) relative to other analyses. Similarly, the Jodhpur sample (RJW14-95) had one zircon with high common Pb (f_{206}% = 1.4) and therefore its young $^{206}Pb/^{238}U$ age of 707.8 ± 11.7 Ma was not considered further. The Sindreth sample RJW14-11 also contains one younger grain (705.6 ± 10.1 Ma), which we ascribe to lead loss due to its high Th (711 ppm) and U (658 ppm) concentrations. Seven older grains (2342 to 795 Ma) from the Punagarh dacite sample (RJW14-56) are interpreted to represent xenocrysts/antecrysts, whereas the other 10 concordant analyses yield a weighted mean age of 760.5 ± 10 Ma (2σ, MSWD = 1.5), which is interpreted as the eruption age.

3.2. In Situ Hf-O Isotopic Compositions

All the analyzed zircon grains from the Jodhpur samples (RJW14-95 and RJW14-82) show $\delta^{18}O$ values (4.12 to −1.11‰) significantly lower than expected for zircon in equilibrium with the mantle ($\delta^{18}O$ = 5.3 ± 0.6‰, 2σ) (Valley et al., 1998). Zircon grains from the Sindreth samples (RJW14-12 and RJW14-11) contain mantle-like to higher $\delta^{18}O$ values (5.12 to 8.23‰). Magmatic zircon grains from the Punagarh dacite (RJW14-56) also have low-$\delta^{18}O$ values (1.67 to 0.81‰), whereas xenocrysts/antecrysts are characterized by isotopically heavier ^{18}O signatures ($\delta^{18}O$ = 5.62 to 11.23‰).

All the low-$\delta^{18}O$ zircons have highly radiogenic Hf isotopic compositions with $\varepsilon_{Hf(t = 760\ Ma)}$ values ranging from +3.6 to +13.0 whereas isotopically heavier ^{18}O zircon grains have relatively lower $\varepsilon_{Hf(t = 760\ Ma)}$ values (+3.1 to −39.3) (Data Set S4) (Figure 3a). Xenocrystic zircon grains with ages ranging from 2342 to 795 Ma have $\varepsilon_{Hf(t)}$ at +7.3 to −15 when calculated back to their time of crystallization.

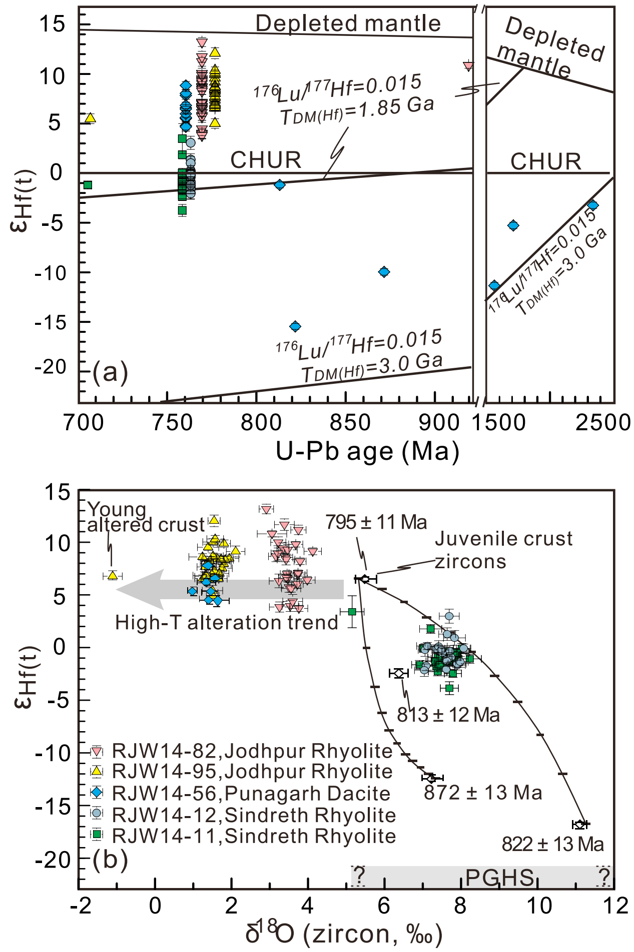

Figure 3. (a). $\varepsilon_{Hf(t)}$ versus U-Pb age of individual zircon grains from the Malani rhyolite and dacite with the evolution line of depleted mantle, CHUR (chondrite uniform reservoir) and average continental crust composition at various ages. The 1σ error bars are shown for the age and the 2σ error bars for $\varepsilon_{Hf(t)}$. (b) $\delta^{18}O$ versus $\varepsilon_{Hf(t\,=\,760Ma)}$ plot of individual zircon grains from the Malani rhyolite and dacite, showing calculated curves for mixing in the sources. The $\varepsilon_{Hf(t\,=\,760Ma)}$ value of the juvenile mafic crust is calculated using the equation: $\varepsilon_{Hf} = \varepsilon_{Nd} \times 1.36 + 2.89$ for the terrestrial array (Vervoort & Blichert-Toft, 1999), in which the average $\varepsilon_{Nd(t\,=\,760Ma)}$ value (+2.71) is adapted from the Sindreth and Punagarh basaltic rocks (Van Lente et al., 2009). The calculated $\varepsilon_{Hf(t\,=\,760Ma)}$ value (+6.6) is the same as the value (+6.6) of the 795.0 ± 11.4 Ma Xenocrystic zircon from Punagarh dacite. The average $\delta^{18}O$-$\varepsilon_{Hf(t\,=\,760Ma)}$ composition of mature continental crust that was involved in the generation of isotopically heavier ^{18}O rhyolitic magma is represented by the compositions of the 821.8 ± 13.4 Ma xenocrystic zircon. PGHS (paragneiss unit of the greater Himalayan sequence) represents prominent ~850 Ma aged crustal components reported by Spencer et al. (2012) from the greater Himalayan sequence wherein ε_{Hf} values < -20 but $\delta^{18}O$ ranges are unknown as marked by the question marks.

4. Neoproterozoic Low-$\delta^{18}O$ Magmas: Bulk Cannibalization of Juvenile Mafic Crust

Coupling the Hf isotopic ratios of zircons with their O isotope compositions can provide essential information on the source of the MIS rhyolite. Melting of protoliths that have been significantly hydrothermally altered in the presence of meteoric water prior to the onset of magmatism could produce large volumes of ^{18}O-depleted rhyolite (Boroughs et al., 2012). The presence of xenocrystic zircon in the Punagarh dacite seems to be consistent with the involvement of preexisting crustal materials during magma evolution. However, all xenocrystic (2342 Ma to 813 Ma) zircon grains in the Punagarh dacite have normal to high $\delta^{18}O$ values (Figure 3a), arguing against a preexisting low-$\delta^{18}O$ source for the MIS rhyolite. Moreover, these Paleoproterozoic to Neoproterozoic xenocrystic zircon grains have highly unradiogenic Hf isotopic compositions that are remarkably distinct from the radiogenic Hf isotopic signatures of the ^{18}O-depleted rhyolites (Figure 3b), arguing against their involvement in the generation of ^{18}O-depleted magmas because Hf isotopic composition of rocks would not be affected by meteoric water alteration. Similarly, assimilation of altered country rocks would affect both the O- and Hf-isotopic characteristics of magma, while the MIS rhyolites differ only in their $\delta^{18}O$ values from a juvenile mafic source (Figure 3b). On the other hand, significant addition of a preexisting crustal source (30–50%) is required to produce the heavier ^{18}O and unradiogenic Hf isotopic signatures of the Sindreth rhyolites (Figure 3b). Given their extremely nonradiogenic Hf isotopic composition, basement rocks from the Aravalli-Delhi were not involved in the generation and evolution of the MIS (Figure 3a). In contrast, the incorporated crustal component could be represented by an 822 ± 13 Ma zircon with $\delta^{18}O_{zircon}$ of 11.23‰ and $\varepsilon_{Hf(t)}$ of −16.8, or the prominent ~850 Ma aged crustal components reported by Spencer et al. (2012) from the Greater Himalayan Sequence wherein ε_{Hf} values are less than −20 (Figure 3b). Collectively, this contrast between low-$\varepsilon_{Hf(t)}$, but normal-$\delta^{18}O$ rhyolites, and low-$\delta^{18}O$ but high-$\varepsilon_{Hf(t)}$ rhyolites reveals that most but not all MIS rhyolites were formed by the melting of basement rocks, which is a common feature of extension-related volcanism, such as the Cenozoic silicic magmas in the Snake River Plain (Colón et al., 2015; Wotzlaw et al., 2015).

Alternatively, the source for the MIS low-$\delta^{18}O$ rhyolites may be the cogenetic basalts that became hydrothermally altered and were subsequently melted to produce low-$\delta^{18}O$ rhyolites. None of the xenocrystic zircon grains have low-$\delta^{18}O$ values, indicating that the heat source for the hydrothermal alteration also produced the MIS low-$\delta^{18}O$ rhyolites. This requires high-temperature remelting of crustal materials in a shallow (upper crustal) magma chamber, where hydrothermal alteration of an isotopically heavy $\delta^{18}O$ precursor by a low-$\delta^{18}O$ meteoric water occurred prior to or nearly simultaneously with eruption (Bindeman & Valley, 2000; Smithies et al., 2015). Given the highly radiogenic zircon Hf isotopic compositions of the low-$\delta^{18}O$ rhyolites (Figure 3), the primary upper crustal source involved in the bulk cannibalization was depleted in nature. The Punagarh dacite could be a possible source for low-$\delta^{18}O$ rhyolites in view of its cogenetic isotopic compositions (Figure 3b). However, strongly ^{18}O-depleted Punagarh dacites ($\delta^{18}O_{zircon}$ = 0.81–1.67‰) suggest that the depleted source rock had already been hydrothermally altered, because producing low-$\delta^{18}O$ magma through direct interaction between meteoric water and magma is unlikely (Boroughs et al., 2012). Given that the dacite

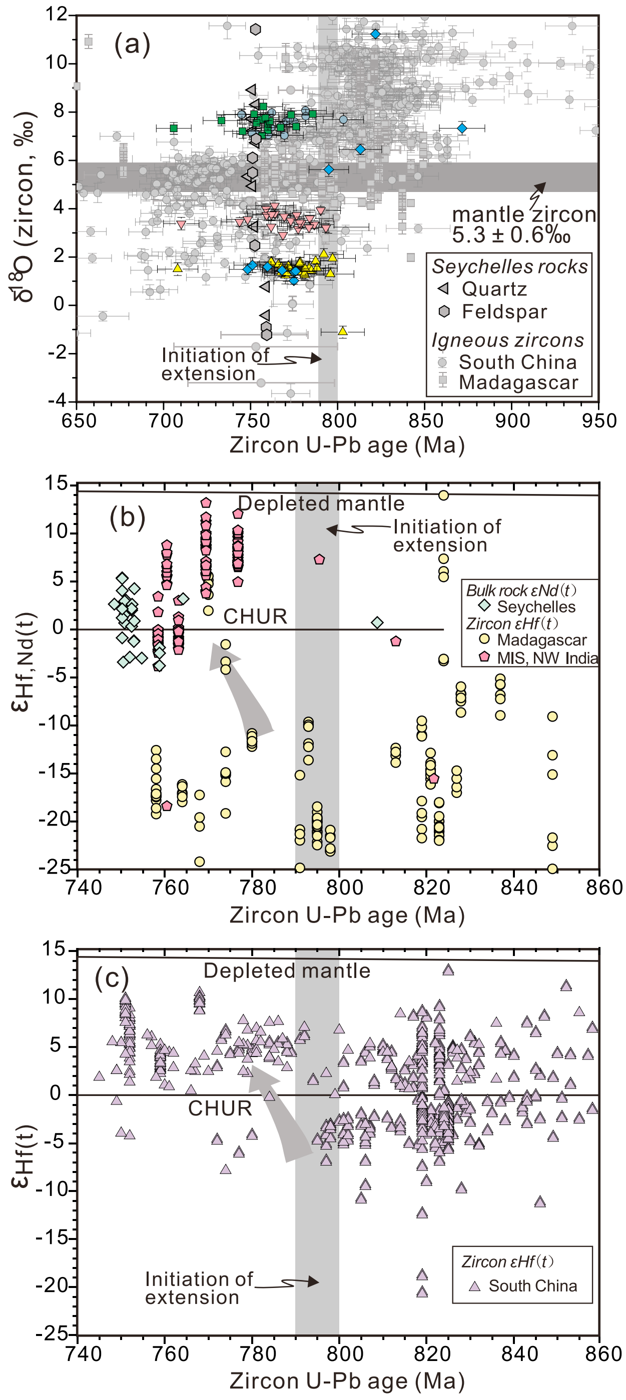

Figure 4. (a) The $\delta^{18}O$ values versus U-Pb ages of individual zircon grains from the Malani rhyolite and dacite with the O composition of Neoproterozoic igneous zircon in Madagascar and south China (data adapted from Zheng et al., 2005, 2006, 2007, 2008; Chen et al., 2011; Fu et al., 2013; Liu & Zhang, 2013; Wang et al., 2013; Zhao et al., 2013; Archibald et al., 2016). The symbols are the same in Figure 3. (b) Hf isotopic compositions for zircon from Madagascar and the MIS and bulk rock Nd isotopic compositions for the Seychelles igneous rocks (data adapted from Ashwal et al., 2002, and Archibald et al., 2016). (c) Hf isotopic compositions for zircon from the Yangtze block of south China. Note that only igneous zircon with O isotopic data are compiled here for their Hf isotopic compositions (data adapted from Chen et al., 2011; Wang et al., 2013; Zhao et al., 2013; and Zheng et al., 2005, 2006, 2007, 2008).

shares similar trace elemental patterns, including Nb-Ta depletion, to the mafic rocks (Sharma, 2005, and our unpublished data), the depleted source for the dacite and also for the low-$\delta^{18}O$ MIS rhyolite was probably the early basaltic phase that slightly predated the rhyolite within the MIS. These basaltic materials were altered in the presence of meteoric water, and then were remelted to produce low-$\delta^{18}O$ dacitic to rhyolitic melts. Therefore, we consider the genetically linked mantle-derived basaltic source contributed to the thermal (heat to extensively melt crustal assemblages) and material (low-$\delta^{18}O$ magma) budget of the Malani system. Physical evidence for early MIS phase with mantle-like Hf-O isotopic composition prior to hydrothermal alteration by low-$\delta^{18}O$ meteoric water is supported by the xenocrystic zircon from the Punagarh dacites with mantle like Hf-O isotopic signatures ($\delta^{18}O_{zircon}$ = 5.62‰ and $\varepsilon_{Hf(t)}$ = +6.6) dated at 795.0 ± 11.4 Ma (Figure 3). Nonetheless, such zircon in this potential mafic precursor was rarely preserved in the subsequent zircon-rich low-$\delta^{18}O$ rhyolite, because zircon is generally undersaturated in basaltic magmas and the subsequent remelting occurred at relatively higher temperatures (e.g., Smithies et al., 2015). Comagmatic mafic rocks, however, do exist at ~60–100 m below the surface, also documented in the borehole data in the Jodhpur area (Pareek, 1981).

5. NW India, Madagascar, and South China: Coeval Thermal and Tectonic Regimes

A broad correlation of regional thermal and tectonic regimes in NW India, Madagascar, and south China is critical in linking these terranes in the Rodinia supercontinent. The commencement of volcanic activity at 780 Ma through eruption of strongly ^{18}O and isotopically depleted rhyolitic lavas, following on from earlier magmas with mantle-like or enriched Hf-O compositions (Figure 4), represents a striking change in the thermal and tectonic regime in NW India between ~800 and 780 Ma. A similar transition also occurs in Madagascar and south China (Archibald et al., 2016; Chen et al., 2011; Fu et al., 2013; Liu & Zhang, 2013; Zhang & Zheng, 2013; Zhao et al., 2011). Emplacement of the majority of ^{18}O-depleted magmas in south China commenced at 800–780 Ma (Zhang & Zheng, 2013), following an earlier pulse of higher-$\delta^{18}O$ magma (Figure 4) (Wang et al., 2013; Zhao et al., 2013). All the low-$\delta^{18}O$ magmas are found to occur along the western and northern margins of the south China Block (Zhang & Zheng, 2013), representing a continental margin setting similar to that of the MIS in NW India. Although a recent study on detrital zircon from Cryogenian strata in the south China Block shows that some of the 870–800 Ma zircon grains have low-$\delta^{18}O$ values, the main transition to more depleted ^{18}O signatures occurred at 800–780 Ma (Wang et al., 2011; Yang et al., 2016). Moreover, given the high $\delta^{18}O$ values of 870–800 zircon from locally distributed igneous rocks (Figure 4) (Wang et al., 2013; Zhao et al., 2013), the ultimate source of these 870–800 Ma detrital zircon grains with low-$\delta^{18}O$ values in younger strata is suspect. A similar negative excursion of zircon $\delta^{18}O$ values was also observed from the Tonian (850–750 Ma) igneous rocks in central Madagascar (Archibald et al., 2016)(Figure 4). A gradual increase in $\delta^{18}O$ values occurs from ~840 Ma, reaching a maximum at ~820–810 Ma and returning to submantle values from 800 to 775 Ma (Archibald et al., 2016) (Figure 4).

In addition, ~760–750 Ma igneous rocks from the Seychelles also possess low-δ^{18}O signatures, necessitating the involvement of a low-δ^{18}O component in the generation of Seychelles granites (Harris & Ashwal, 2002).

The rare coincidence of sustained high temperatures at upper crustal levels with hydrothermally altered crust limits the distribution of voluminous depleted δ^{18}O felsic volcanic system (Boroughs et al., 2012; Smithies et al., 2015). Bulk cannibalization of juvenile mafic crust to produce low-δ^{18}O rhyolites requires remelting of shallow hydrothermally altered volcanic rocks that had been tectonically (rift zones) and/or volcanically (calderas) buried (Bindeman et al., 2007; Drew et al., 2013; Watts et al., 2011). MIS rhyolite magmatism followed the hydrothermal alteration, forming low-δ^{18}O magma in upper crustal chamber where deep circulation of meteoric fluids interacted with the juvenile mafic crust at high temperature in a likely extensional setting, in response to the top-down process driven by outboard subduction initiated at ~780 Ma. This is consistent with the notion that subduction places the overriding supercontinental in extension, which is regarded as the geodynamic control on supercontinent breakup (Cawood et al., 2016). Moreover, the negative excursion of zircon δ^{18}O values is accompanied by the increase in zircon $\varepsilon_{Hf(t)}$ in igneous rocks from Madagascar, NW India, and south China and whole rocks $\varepsilon_{Nd(t)}$ values of the Seychelles igneous rocks (Figures 4b and 4c) (Archibald et al., 2016; Ashwal et al., 2002), marking the magmatic switch from crustal reworking to juvenile addition. This mirrors the shift from compression to an extension mode induced by arc retreat, as recorded by the shift toward increasingly positive zircon $\varepsilon_{Hf(t)}$ values in the Paleozoic Terra Australis and the present-day circum-Pacific accretionary orogen (Collins et al., 2011; Kemp et al., 2009). Similar subduction-induced extension is recorded by the initiation of the Nanhua extensional basin at ~810–800 Ma, which succeeded the termination of the convergent plate interaction between the Yangtze and Cathaysia blocks in south China (Cawood et al., 2013; Zhao et al., 2011). The Nanhua sequences correlate well with coeval extension-related basins in NW India, such as the Punagarh and Sindreth sequences in the MIS and the Jaunsar-Simla and Blaini sequences in the Lesser Himalaya (Hofmann et al., 2011; Jiang et al., 2003; Wang et al., 2012). Therefore, the temporally and geodynamically linked spatial association extending from Madagascar and the Seychelles, through NW India to south China blocks, appear consistent with an extensional suprasubduction zone along western margin of Rodinia or an independent paleoposition off the supercontinent margin.

Acknowledgments
All data are available in Data Set S1 to S4. This study was supported by the National Natural Science Foundation of China (NSFC41572170), "Thousand Youth Talents Plan" grant to Wei Wang, Guangzhou municipal government (201607020029), and MOST Special Fund from the State Key Laboratory of Geological Processes and Mineral Resources (MSFGPMR11 and 01-1). P.A.C. acknowledges support from Australian Research Council grant FL160100168. We thank Qiuli Li and Liang Li for help in in situ zircon U-Pb-O-Hf analyses. Vivek Kumar Meena is thanked for his generous help during field work. Thanks go to Chris Spencer, Dylan Colón, and Editor Professor Jeroen Ritsema for their constructive comments that help to improve the presentation and interpretation greatly.

References

Archibald, D. B., Collins, A. S., Foden, J. D., Payne, J. L., Holden, P., Razakamanana, T., … Pitfield, P. E. J. (2016). Genesis of the Tonian Imorona–Itsindro magmatic suite in central Madagascar: Insights from U–Pb, oxygen and hafnium isotopes in zircon. *Precambrian Research*, *281*, 312–337. https://doi.org/10.1016/j.precamres.2016.05.014

Ashwal, L., Demaiffe, D., & Torsvik, T. (2002). Petrogenesis of Neoproterozoic granitoids and related rocks from the Seychelles: The case for an Andean-type arc origin. *Journal of Petrology*, *43*(1), 45–83. https://doi.org/10.1093/petrology/43.1.45

Ashwal, L., Solanki, A., Pandit, M., Corfu, F., Hendriks, B., Burke, K., & Torsvik, T. (2013). Geochronology and geochemistry of Neoproterozoic Mt. Abu granitoids, NW India: Regional correlation and implications for Rodinia paleogeography. *Precambrian Research*, *236*, 265–281. https://doi.org/10.1016/j.precamres.2013.07.018

Bindeman, I., Gurenko, A., Carley, T., Miller, C., Martin, E., & Sigmarsson, O. (2012). Silicic magma petrogenesis in Iceland by remelting of hydrothermally altered crust based on oxygen isotope diversity and disequilibria between zircon and magma with implications for MORB. *Terra Nova*, *24*(3), 227–232. https://doi.org/10.1111/j.1365-3121.2012.01058.x

Bindeman, I. N., & Valley, J. W. (2000). Formation of low-δ^{18}O rhyolites after caldera collapse at Yellowstone, Wyoming, USA. *Geology*, *28*(8), 719–722. https://doi.org/10.1130/0091-7613(2000)28%3C719:FOLRAC%3E2.0.CO;2

Bindeman, I. N., Watts, K. E., Schmitt, A. K., Morgan, L. A., & Shanks, P. W. C. (2007). Voluminous low δ^{18}O magmas in the late Miocene Heise volcanic field, Idaho: Implications for the fate of Yellowstone hotspot calderas. *Geology*, *35*(11), 1019–1022. https://doi.org/10.1130/G24141A.1

Boroughs, S., Wolff, J. A., Ellis, B. S., Bonnichsen, B., & Larson, P. B. (2012). Evaluation of models for the origin of Miocene low-δ^{18}O rhyolites of the Yellowstone/Columbia River large Igneous Province. *Earth and Planetary Science Letters*, *313–314*, 45–55.

Cawood, P. A., Strachan, R. A., Pisarevsky, S. A., Gladkochub, D. P., & Murphy, J. B. (2016). Linking collisional and accretionary orogens during Rodinia assembly and breakup: Implications for models of supercontinent cycles. *Earth and Planetary Science Letters*, *449*, 118–126. https://doi.org/10.1016/j.epsl.2016.05.049

Cawood, P. A., Wang, Y. J., Xu, Y. J., & Zhao, G. C. (2013). Locating south China in Rodinia and Gondwana: A fragment of greater India lithosphere? *Geology*, *41*(8), 903–906. https://doi.org/10.1130/G34395.1

Cawood, P. A., Zhao, G. C., Yao, J. L., Wang, W., Xu, Y. J., & Wang, Y. J. (2017). Reconstructing south China in Phanerozoic and Precambrian supercontinents. *Earth Science Reviews*. https://doi.org/10.1016/j.earscirev.2017.06.001

Chen, Y. X., Zheng, Y. F., Chen, R. X., Zhang, S. B., Li, Q. l., Dai, M. N., & Chen, L. (2011). Metamorphic growth and recrystallization of zircons in extremely ^{18}O-depleted rocks during eclogite-facies metamorphism: Evidence from U–Pb ages, trace elements, and O–Hf isotopes. *Geochimica et Cosmochimica Acta*, *75*(17), 4877–4898. https://doi.org/10.1016/j.gca.2011.06.003

Chu, N., Taylor, R., Chavagnac, V., Nesbitt, R., Boella, R., Milton, J., … Burton, K. (2002). Hf isotope ratio analysis using multi-collector inductively coupled plasma mass spectrometry: An evaluation of isobaric interference corrections. *Journal of Analytical Atomic Spectrometry*, *17*(12), 1567–1574. https://doi.org/10.1039/b206707b

Collins, W. J., Belousova, E. A., Kemp, A. I. S., & Murphy, J. B. (2011). Two contrasting Phanerozoic orogenic systems revealed by hafnium isotope data. *Nature Geoscience*, *4*(5), 333–337. https://doi.org/10.1038/ngeo1127

Colón, D. P., Bindeman, I. N., Ellis, B. S., Schmitt, A. K., & Fisher, C. M. (2015). Hydrothermal alteration and melting of the crust during the Columbia River basalt–Snake River plain transition and the origin of low-δ^{18}O rhyolites of the central Snake River plain. *Lithos*, *224–225*, 310–323.

Dharma Rao, C. V., Santosh, M., & Kim, S. W. (2012). Cryogenian volcanic arc in the NW Indian shield: Zircon SHRIMP U–Pb geochronology of felsic tuffs and implications for Gondwana assembly. *Gondwana Research*, *22*(1), 36–53.

Drew, D. L., Bindeman, I. N., Watts, K. E., Schmitt, A. K., Fu, B., & McCurry, M. (2013). Crustal-scale recycling in caldera complexes and rift zones along the Yellowstone hotspot track: O and Hf isotopic evidence in diverse zircons from voluminous rhyolites of the Picabo volcanic field, Idaho. *Earth and Planetary Science Letters*, *381*, 63–77. https://doi.org/10.1016/j.epsl.2013.08.007

Elhlou, S., Belousova, E., Griffin, W. L., Pearson, N. J., & O'Reilly, S. Y. (2006). Trace element and isotopic composition of GJ-red zircon standard by laser ablation. *Geochimica et Cosmochimica Acta*, *70*(18), A158–A158. https://doi.org/10.1016/j.gca.2006.06.1383

Fu, B., Kita, N. T., Wilde, S. A., Liu, X., Cliff, J., & Greig, A. (2013). Origin of the Tongbai-Dabie-Sulu Neoproterozoic low-δ^{18}O igneous province, east-central China. *Contributions to Mineralogy and Petrology*, *165*(4), 641–662. https://doi.org/10.1007/s00410-012-0828-3

Gregory, L. C., Meert, J. G., Bingen, B., Pandit, M. K., & Torsvik, T. H. (2009). Paleomagnetism and geochronology of the Malani igneous suite, Northwest India: Implications for the configuration of Rodinia and the assembly of Gondwana. *Precambrian Research*, *170*(1-2), 13–26. https://doi.org/10.1016/j.precamres.2008.11.004

Harris, C., & Ashwal, L. D. (2002). The origin of low δ^{18}O granites and related rocks from the Seychelles. *Contributions to Mineralogy and Petrology*, *143*(3), 366–376. https://doi.org/10.1007/s00410-002-0349-6

Hofmann, M., Linnemann, U., Rai, V., Becker, S., Gärtner, A., & Sagawe, A. (2011). The India and south China cratons at the margin of Rodinia—Synchronous Neoproterozoic magmatism revealed by LA-ICP-MS zircon analyses. *Lithos*, *123*(1-4), 176–187. https://doi.org/10.1016/j.lithos.2011.01.012

Jiang, G. Q., Sohl, L., & Christie-Blick, N. (2003). Neoproterozoic stratigraphic comparison of the lesser Himalaya (India) and Yangtze block (south China): Paleogeographic implications. *Geology*, *31*(10), 917–920. https://doi.org/10.1130/G19790.1

Kemp, A., Hawkesworth, C., Collins, W., Gray, C., & Blevin, P. (2009). Isotopic evidence for rapid continental growth in an extensional accretionary orogen: The Tasmanides, eastern Australia. *Earth and Planetary Science Letters*, *284*(3-4), 455–466. https://doi.org/10.1016/j.epsl.2009.05.011

Kilaru, S., Goud, B. K., & Rao, V. K. (2013). Crustal structure of the western Indian shield: Model based on regional gravity and magnetic data. *Geoscience Frontiers*, *4*(6), 717–728. https://doi.org/10.1016/j.gsf.2013.02.006

Kochhar, N. (2001). Anorogenic magmatism, mantle plume and assembly of the Late Proterozoic Malani supercontinent, NW Indian shield, paper presented at International Symp. Assembly and breakup of Rodinia and Gondwana, and Growth of Asia: GRG/GIGE Misc. Publ.

Li, X. H., Long, W. G., Li, Q. L., Liu, Y., Zheng, Y. F., Yang, Y. H., … Tao, H. (2010). Penglai zircon Megacrysts: A potential new working reference material for microbeam determination of Hf–O isotopes and U–Pb age. *Geostandards and Geoanalytical Research*, *34*(2), 117–134. https://doi.org/10.1111/j.1751-908X.2010.00036.x

Li, X. H., Tang, G. Q., Gong, B., Yang, Y. H., Hou, K. J., Hu, Z. C., … Li, W. X. (2013). Qinghu zircon: A working reference for microbeam analysis of U-Pb age and Hf and O isotopes. *Chinese Science Bulletin*, *58*(36), 4647–4654. https://doi.org/10.1007/s11434-013-5932-x

Li, Z. X., Bogdanova, S. V., Collins, A. S., Davidson, A., De Waele, B., Ernst, R., … Jacobs, J. (2008). Assembly, configuration, and break-up history of Rodinia: A synthesis. *Precambrian Research*, *160*(1-2), 179–210. https://doi.org/10.1016/j.precamres.2007.04.021

Li, Z. X., Li, X. H., Kinny, P. D., & Wang, J. (1999). The breakup of Rodinia: Did it start with a mantle plume beneath south China? *Earth and Planetary Science Letters*, *173*(3), 171–181. https://doi.org/10.1016/S0012-821X(99)00240-X

Liu, J. B., & Zhang, L. M. (2013). Neoproterozoic low to negative δ^{18}O volcanic and intrusive rocks in the Qinling Mountains and their geological significance. *Precambrian Research*, *230*, 138–167. https://doi.org/10.1016/j.precamres.2013.02.006

Menzies, C. D., Teagle, D. A. H., Craw, D., Cox, S. C., Boyce, A. J., Barrie, C. D., & Roberts, S. (2014). Incursion of meteoric waters into the ductile regime in an active orogen. *Earth and Planetary Science Letters*, *399*(399), 1–13.

Merdith, A. S., Collins, A. S., Williams, S. E., Pisarevsky, S., Foden, J. D., Archibald, D. B., … Müller, R. D. (2017). A full-plate global reconstruction of the Neoproterozoic. *Gondwana Research*, *50*, 84–134. https://doi.org/10.1016/j.gr.2017.04.001

Pandit, M. K., Sial, A. N., Jamrani, S. S., & Ferreira, V. P. (2001). Carbon isotopic profile across the Bilara group rocks of trans-Aravalli Marwar Supergroup in western India: Implications for Neoproterozoic — Cambrian transition. *Gondwana Research*, *4*(3), 387–394. https://doi.org/10.1016/S1342-937X(05)70338-5

Pareek, H. S. (1981). Petrochemistry and Petrogenesis of the Malani Igneous Suite, India. *Geological Society of America Bulletin*, *92*(2 Part II), 206–273.

Patchett, P. J., Kouvo, O., Hedge, C. E., & Tatsumoto, M. (1981). Evolution of continental crust and mantle heterogeneity: Evidence from Hf isotopes. *Contributions to Mineralogy and Petrology*, *78*(3), 279–297.

Roy, A. B., & Jakhar, S. R. (2002). *Geology of Rajasthan: Precambrian to Recent*. Jodhpur: Scientific Publishers (India).

Sharma, K. K. (2005). Malani magmatism: An extensional lithospheric tectonic origin. *Geological Society of America Special Papers*, *388*, 463–476.

Sláma, J., Kosler, J., Condon, D., Crowley, J., Gerdes, A., Hanchar, J., … Norberg, N. (2008). Plesovice zircon—A new natural reference material for U-Pb and Hf isotopic microanalysis. *Chemical Geology*, *249*(1-2), 1–35. https://doi.org/10.1016/j.chemgeo.2007.11.005

Smithies, R. H., Kirkland, C. L., Cliff, J. B., Howard, H. M., & Quentin de Gromard, R. (2015). Syn-volcanic cannibalisation of juvenile felsic crust: Superimposed giant ^{18}O-depleted rhyolite systems in the hot and thinned crust of Mesoproterozoic central Australia. *Earth and Planetary Science Letters*, *424*, 15–25. https://doi.org/10.1016/j.epsl.2015.05.005

Spencer, C. J., Harris, R. A., & Dorais, M. J. (2012). Depositional provenance of the Himalayan metamorphic core of Garhwal region, India: Constrained by U–Pb and Hf isotopes in zircons. *Gondwana Research*, *22*(1), 26–35. https://doi.org/10.1016/j.gr.2011.10.004

Spencer, C. J., Kirkland, C. L., & Taylor, R. J. M. (2016). Strategies towards statistically robust interpretations of in situ U–Pb zircon geochronology. *Geoscience Frontiers*, *7*(4), 581–589. https://doi.org/10.1016/j.gsf.2015.11.006

Valley, J., Lackey, J., Cavosie, A., Clechenko, C., Spicuzza, M., Basei, M., … King, E. (2005). 4.4 billion years of crustal maturation: Oxygen isotope ratios of magmatic zircon. *Contributions to Mineralogy and Petrology*, *150*(6), 561–580. https://doi.org/10.1007/s00410-005-0025-8

Valley, J. W., Kinny, P. D., Schulze, D. J., & Spicuzza, M. J. (1998). Zircon megacrysts from kimberlite: Oxygen isotope variability among mantle melts. *Contributions to Mineralogy and Petrology*, *133*(1–2), 1–11.

Van Lente, B., Ashwal, L., Pandit, M., Bowring, S., & Torsvik, T. (2009). Neoproterozoic hydrothermally altered basaltic rocks from Rajasthan, northwest India: Implications for late Precambrian tectonic evolution of the Aravalli craton. *Precambrian Research*, *170*(3-4), 202–222. https://doi.org/10.1016/j.precamres.2009.01.007

Vervoort, J. D., & Blichert-Toft, J. (1999). Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. *Geochimica et Cosmochimica Acta*, *63*(3-4), 533–556. https://doi.org/10.1016/S0016-7037(98)00274-9

Wang, W., Chen, F. K., Hu, R., Chu, Y., & Yang, Y. Z. (2012). Provenance and tectonic setting of Neoproterozoic sedimentary sequences in the south China block: Evidence from detrital zircon ages and Hf–Nd isotopes. *International Journal of Earth Sciences*, *101*(7), 1723–1744. https://doi.org/10.1007/s00531-011-0746-z

Wang, X. C., Li, Z. X., Li, X. H., Li, Q. L., Tang, G. Q., Zhang, Q. R., & Liu, Y. (2011). Nonglacial origin for low- δ^{18}O Neoproterozoic magmas in the south China block: Evidence from new in-situ oxygen isotope analyses using SIMS. *Geology*, *39*(8), 735–738. https://doi.org/10.1130/G31991.1

Wang, X. L., Zhou, J. C., Wan, Y. S., Kitajima, K., Wang, D., Bonamici, C., … Sun, T. (2013). Magmatic evolution and crustal recycling for Neoproterozoic strongly peraluminous granitoids from southern China: Hf and O isotopes in zircon. *Earth and Planetary Science Letters*, *366*(0), 71–82. https://doi.org/10.1016/j.epsl.2013.02.011

Watts, K. E., Bindeman, I. N., & Schmitt, A. K. (2011). Large-volume rhyolite genesis in caldera complexes of the Snake River plain: Insights from the Kilgore tuff of the Heise volcanic field, Idaho, with comparison to Yellowstone and Bruneau–Jarbidge rhyolites. *Journal of Petrology*, *52*(5), 857–890. https://doi.org/10.1093/petrology/egr005

Wotzlaw, J. F., Bindeman, I. N., Stern, R. A., D'Abzac, F. X., & Schaltegger, U. (2015). Rapid heterogeneous assembly of multiple magma reservoirs prior to Yellowstone supereruptions. *Scientific Reports*, *5*(1), 14026. https://doi.org/10.1038/srep14026

Wu, F. Y., Yang, Y. H., Xie, L. W., Yang, J. H., & Xu, P. (2006). Hf isotopic compositions of the standard zircons and baddeleyites used in U-Pb geochronology. *Chemical Geology*, *234*(1-2), 105–126. https://doi.org/10.1016/j.chemgeo.2006.05.003

Yang, Y.-N., Wang, X.-C., Li, Q.-L., & Li, X.-H. (2016). Integrated in situ U-Pb age and Hf-O analyses of zircon from Suixian group in northern Yangtze: New insights into the Neoproterozoic low-δ18O magmas in the south China block. *Precambrian Research*, *273*, 15–164. https://doi.org/10.1016/j.precamres.2015.12.008

Zhang, S. B., & Zheng, Y. F. (2013). Time and space of Neoproterozoic low δ^{18}O magmatic rocks in south China. *Chinese Science Bulletin*, *58*, 2344–2350.

Zhao, J. H., Zhou, M. F., Yan, D. P., Zheng, J. P., & Li, J. W. (2011). Reappraisal of the ages of Neoproterozoic strata in south China: No connection with the Grenvillian orogeny. *Geology*, *39*(4), 299–302. https://doi.org/10.1130/G31701.1

Zhao, J. H., Zhou, M. F., & Zheng, J. P. (2013). Constraints from zircon U–Pb ages, O and Hf isotopic compositions on the origin of Neoproterozoic peraluminous granitoids from the Jiangnan Fold Belt, south China. *Contributions to Mineralogy and Petrology*, *166*(5), 1505–1519. https://doi.org/10.1007/s00410-013-0940-z

Zheng, Y. F., Wu, R. X., Wu, Y. B., Zhang, S. B., Yuan, H., & Wu, F. Y. (2008). Rift melting of juvenile arc-derived crust: Geochemical evidence from Neoproterozoic volcanic and granitic rocks in the Jiangnan Orogen, south China. *Precambrian Research*, *163*(3-4), 351–383. https://doi.org/10.1016/j.precamres.2008.01.004

Zheng, Y.-F., Wu, Y.-B., Zhao, Z.-F., Zhang, S.-B., Xu, P., & Wu, F.-Y. (2005). Metamorphic effect on zircon Lu-Hf and U-Pb isotope systems in ultrahigh-pressure eclogite-facies metagranite and metabasite. *Earth and Planetary Science Letters*, *240*(2), 378–400. https://doi.org/10.1016/j.epsl.2005.09.025

Zheng, Y. F., Zhang, S. B., Zhao, Z. F., Wu, Y. B., Li, X. H., Li, Z. X., & Wu, F. Y. (2007). Contrasting zircon Hf and O isotopes in the two episodes of Neoproterozoic granitoids in south China: Implications for growth and reworking of continental crust. *Lithos*, *96*(1-2), 127–150. https://doi.org/10.1016/j.lithos.2006.10.003

Zheng, Y.-F., Zhao, Z.-F., Wu, Y.-B., Zhang, S.-B., Liu, X., & Wu, F.-Y. (2006). Zircon U-Pb age, Hf and O isotope constraints on protolith origin of ultrahigh-pressure eclogite and gneiss in the Dabie orogen. *Chemical Geology*, *231*(1-2), 135–158. https://doi.org/10.1016/j.chemgeo.2006.01.005

Zhou, M. F., Yan, D. P., Wang, C. L., Qi, L., & Kennedy, A. (2006). Subduction-related origin of the 750 ma Xuelongbao adakitic complex (Sichuan Province, China): Implications for the tectonic setting of the giant Neoproterozoic magmatic event in south China. *Earth and Planetary Science Letters*, *248*(1-2), 286–300. https://doi.org/10.1016/j.epsl.2006.05.032