Earth and Planetary Science Letters 575 (2021) 117196

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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A Neoproterozoic low-δ^{18}O magmatic ring around South China: Implications for configuration and breakup of Rodinia supercontinent

Hao Zou[a,b], Qiu-Li Li[b], Leon Bagas[a,c], Xuan-Ce Wang[d], An-Qing Chen[a], Xian-Hua Li[b,*]

[a] *State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu, Sichuan 610059, China*
[b] *State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*
[c] *Xi'an Center of China Geological Survey, 438 Youyi Road, Xi'an 710054, China*
[d] *School of Earth Sciences, Yunnan University, Kunming, 650500, China*

ARTICLE INFO

Article history:
Received 14 April 2021
Received in revised form 26 August 2021
Accepted 3 September 2021
Available online 22 September 2021
Editor: L. Coogan

Dataset link:
https://doi.org/10.17632/th7b2c9j2v.1

Keywords:
low-δ^{18}O magmatic ring
Rodinia supercontinent
South China
Yangtze Block

ABSTRACT

We report Neoproterozoic (ca. 785-780 Ma) granites from the western margin of the Yangtze Block that are characterised by magmatic zircons with δ^{18}O values as low as 2.98‰. The lack of low-δ^{18}O magmatic zircons in the ca. 820-805 Ma rhyolite samples from the Neoproterozoic Suxiong Formation indicates that there is no recycling of pre-existing hydrothermally altered crust in the study area prior to the emplacement of the ca. 785-780 Ma granites. Thus the ca. 785-780 Ma granites with low-δ^{18}O values from the western margin of the Yangtze Block can be linked to assimilation of syn-magmatically altered rocks (rather than the assimilation of a pre-existing hydrothermally altered crust). The granites have a source constrained by their depleted Hf isotopes and low-δ^{18}O values resulting from high temperature hydrothermal alteration. The δ^{18}O values of the zircons from core to rim exhibit a decrease indicative of the remelting of material during the interaction between magma and water at high temperatures. In combination with the widespread low-δ^{18}O signatures that occur in the northern and southern margins of the Yangtze Block and Cathaysia Block, the locations of low-δ^{18}O magmatic zircons exhibit a Neoproterozoic low-δ^{18}O magmatic ring around South China. This continent-scale Neoproterozoic extensional and magmatic event cannot be attributed to subduction processes in South China resulting in the emplacement of a magmatic ring of felsic igneous rocks with low-δ^{18}O values. We therefore propose a model involving a Neoproterozoic super-mantle plume with a diameter of approximately 1500 km controlling the development of the rift systems around South China.

1. Introduction

Pristine zircon grains from igneous rocks derived from the mantle commonly have δ^{18}O isotope values of around 5.3 ± 0.6‰ (2σ), which is the mantle value (Valley et al., 2005; Huang et al., 2019 and references therein). Magmatic rocks with zircon δ^{18}O values lower than the mantle value are rare, requiring high temperature interaction between heated meteoric or sea water, and source rocks with high porosities and high water to rock ratios, followed by the remelting of these rocks (Drew et al., 2013; Bindeman and Simakin, 2014). Possible ways for this to happen include: (1) a caldera collapse creating conditions for shallow hydrothermal alteration in a rift zone and the subsequent remelting of buried intra-caldera pyroclastics (Bindeman et al., 2008; Watts et al., 2011; Bindeman and Simakin, 2014), (2) Basin and Range style extension facilitating hydrothermal alteration and subsequent partial melting of source rocks (Drew et al., 2013), and (3) partial melting of subducted mafic oceanic crust (Bindeman et al., 2005).

Most low-δ^{18}O felsic rocks are reported in hotspot and rift settings (Zheng et al., 2007; Troch et al., 2020). Hydrothermal alteration in these extensional settings can change the primary whole-rock values of oxygen isotope composition of ancient igneous rocks, but it is nearly impossible to directly estimate the levels of oxygen isotope composition in ancient igneous rocks (Taylor and Sheppard, 1986). Zircon grains are stable at high temperatures and have low oxygen diffusion rates (Cherniak and Watson, 2003). This makes them resistant to hydrothermal alteration and the best target for studying the primary oxygen isotope composition of ancient magmas that zircon crystallized from (Zhang and Zheng, 2011).

Published δ^{18}O values collected from over 10,000 zircons show that there was a significant low-δ^{18}O magmatic event during the mid-Neoproterozoic around the world, of which about 53% are from South China (Spencer et al., 2017 and references therein).

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[*] Corresponding author.
E-mail address: lixh@gig.ac.cn (X.-H. Li).

https://doi.org/10.1016/j.epsl.2021.117196
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This period coincides with the timing for the breakup of the Rodinia Supercontinent. While South China is recognised as a significant component of Rodinia, its relative position has not been irrefutably established, and the major driving force triggering the breakup of the Rodinia supercontinent during the Neoproterozoic is also an unresolved issue (e.g. Cawood et al., 2016; Li et al., 2008; and references therein).

Although detailed geochronological studies of Neoproterozoic magmatic rocks along the western margin of the Yangtze Block have been carried out, the low-δ^{18}O isotopic record for Neoproterozoic granites in the region is rare, with only three low-δ^{18}O zircon having been identified for Neoproterozoic granites in the western margin of the Yangtze Block for which the method used involved the analyses of single zircon grains (Zheng et al., 2007). This contribution reports the discovery of widespread granitic rocks with low-δ^{18}O values in the western margin of the Yangtze Block and considers their implications for global Neoproterozoic tectonics by combining temporal and spatial distributions of low-δ^{18}O Neoproterozoic magmatic rocks worldwide. The aim here is to provide new evidence for reconstructing the tectonic evolution of South China and better constrain the Neoproterozoic configuration of Rodinia.

2. Geological background and sampling

South China is subdivided into the Yangtze and Cathaysia blocks, which are separated by the Neoproterozoic Sibao (or Jiangnan) Orogen (Li et al., 2002a). The Yangtze Block is bounded by the Tibetan Plateau to the west and the Triassic Qinling–Dabie Orogen to the north. The Yangtze Block includes Archaean to Neoproterozoic rocks unconformably overlain by Phanerozoic units. The western part of the region includes Early Neoproterozoic (ca. 1070-750 Ma) volcanic and sedimentary units intruded by felsic and lesser mafic to ultramafic plutons (Fig. 1; Li et al., 2002b).

Volcanic rocks in the ca. 821-803 Ma Suxiong Formation are located in the north-trending Kangdian Rift along the western margin of the Yangtze Block in the Xiaoxiangling, Daxiangling, Ganluo (Suxiong), and Xichang regions (Li et al., 2002b). The bimodal volcanic rocks range in thickness from a few hundred to around five thousand metres covering an area of ~2630 km^2. Most of the rocks are rhyolitic and dacitic lava and tuff intercalated with minor amounts of volcaniclastic sedimentary rocks and basalt (Fig. S1, Li et al., 2002b). The Suxiong Formation unconformably overlies Mesoproterozoic phyllite in the rift, is intruded by the composite Shimian Batholith, and is conformably overlain by Neoproterozoic clastic sedimentary rocks (Zhao et al., 2018). The Shimian Batholith includes medium- to coarse-grained porphyritic monzogranite and syenogranite exposed in an area covering over 2500 km^2 (Lin et al., 2007). The Guaziping Pluton is located in Panzhihua City, the south part of the western margin of the Yangtze Block (Fig. 1b).

Samples were collected from rhyolite in the Suxiong Formation, grey porphyritic monzogranite from the Shimian Batholith and grey granodiorite from the Guaziping Pluton for detailed studies (Fig. 1c, d). The rhyolite contains ~5 mm long phenocrysts of K-feldspar and embayed quartz (~20 vol.%) in a fine-grained matrix (~80 vol.%) composed of quartz, feldspar and devitrified glass (Fig. S2a-d). The grey porphyritic monzogranite consists of up to 20 mm long red porphyritic K-feldspar (15-20 vol.%) and up to 5 mm wide quartz phenocrysts (~5 vol.%) in a medium-grained matrix containing K-feldspar (20-30 vol.%), quartz (~20 vol.%), plagioclase (~20 vol.%), and biotite (<5 vol.%) (Fig. S2e-f). The Guaziping Pluton is a massive, medium- to coarse-grained, grey granodiorite consisting of smoky quartz (25-30 vol.%), grey plagioclase (50-55 vol.%), hornblende (15-20 vol.%), and Fe-Ti oxides (3-5 vol.%) (Fig. S2g-h).

3. Analytical methods

Samples of volcanic rocks from the Suxiong Formation, and granitic rocks from the Shimian Batholith and Guaziping Pluton for *in-situ* zircon U-Pb dating, *in-situ* Hf and O isotopic studies, and whole-rocks analyses. Zircons extraction from the samples involved crushing, heavy liquid and subsequent magnetic separation at the Langfang Xinhang Geological Services Co. Ltd., China. Representative zircons were then hand-picked under a binocular microscope and mounted on adhesive tape, mounted in epoxy resin, polished and photographed in reflected and transmitted light. The structures in the zircons were then studied using cathode luminescence (CL) imaging. Zircons considered to be without imperfection were selected for *in-situ* U-Pb age and O isotope measurements using a CAMECA IMS 1280HR SIMS at the Institute of Geology and Geophysics, Chinese Academy Sciences in Beijing. The Lu-Hf isotopes in the zircons were analysed using a Neptune Plus MC-ICP-MS equipped with a Geolas-2005 Excimer ArF laser ablation system in the State Key Laboratory of Geological Processes and Mineral Resources, at China University of Geosciences, Wuhan. The major and trace element analyses of the samples were analysed at ALS Chemex Guangzhou Co Ltd in China (ALS Chemex) using X-ray fluorescence spectrometry (XRF) with an analytical error of ±2%, and Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) with an analytical error of ±5% or less. The detailed analytical procedures are outlined in Supplement Text S1 (Sláma et al., 2008, Li et al., 2010, 2013, Hu et al., 2012 and Fisher et al., 2014).

4. Results

4.1. U-Pb age and Hf-O isotopes

Two hundred and thirteen zircon grains were collected from eight fresh and representative samples. Zircon grains without obvious fractures and inclusions were chosen for dating (Fig. 2). These have high Th/U ratios of >0.3 and oscillatory zoning characteristic of magmatic zircons (Rubatto, 2002). The dated zircon spots were also *in-situ* analysed for their Hf and O isotopes (Tables S1-5).

The zircons from the rhyolite samples DYF-1 and DYF-2 yield Concordia ages of 819 ± 5 Ma (MSWD = 1.04, n = 20) and 813 ± 5 Ma (MSWD = 0.17, n = 17; Fig. 2a, b). The zircons from rhyolite sample YCG-1 define a discordia with an upper intercept date of 810 ± 3 Ma (MSWD = 1.3, n = 11; Fig. 2c), and the zircons from rhyolite sample YCG-3 yield a Concordant age of 818 ± 6 Ma (MSWD = 0.21, n = 12; Fig. 2d). These dates between ca. 820 and 810 Ma are interpreted as the crystallisation age of the Suxiong Formation. The *in-situ* Hf-O isotope analyses of zircons from samples DYF-1 and DYF-2 yield $\varepsilon_{\mathrm{Hf}}(t)$ values between +0.9 and +3.3, T_{DM2} model ages between 1632 and 1501 Ma (Table S3), and δ^{18}O values between 8.20 and 9.14‰. The zircons from the samples YCG-1 and YCG-3 yield $\varepsilon_{\mathrm{Hf}}(t)$ values of +4.2 to +8.4 with corresponding T_{DM2} model age from 1411 to 1186 Ma, and δ^{18}O values between 5.3 and 6.31‰ (Fig. 3). All of the zircons from the rhyolite samples having δ^{18}O values higher than 5.3‰.

Porphyritic monzogranite samples from the Shimian Batholith yield weighted mean SIMS U-Pb dates of 786 ± 8 Ma (sample YCG-10; n = 10, MSWD = 0.97) and 787 ± 9 Ma (sample YCG-11; n = 9, MSWD = 0.83). These dates are interpreted as the emplacement age for porphyritic monzogranite (Fig. 2e, f). The *in-situ* Hf-O isotope analyses of the zircons from granite samples YCG-10 and YCG-11 yield $\varepsilon_{\mathrm{Hf}}(t)$ values of +1.3 to +8.8 and corresponding T_{DM2} model ages between 1591 and 1122 Ma, and the least-discordant zircon grains with U–Pb concordance ≥95% have δ^{18}O values between +2.98 and +5.20‰ (Fig. 3). Although Pb loss may be due to the "high-U matrix effect", radiation damage, metamictic, and subsequent alteration (Gao et al., 2014), all the zircons have δ^{18}O

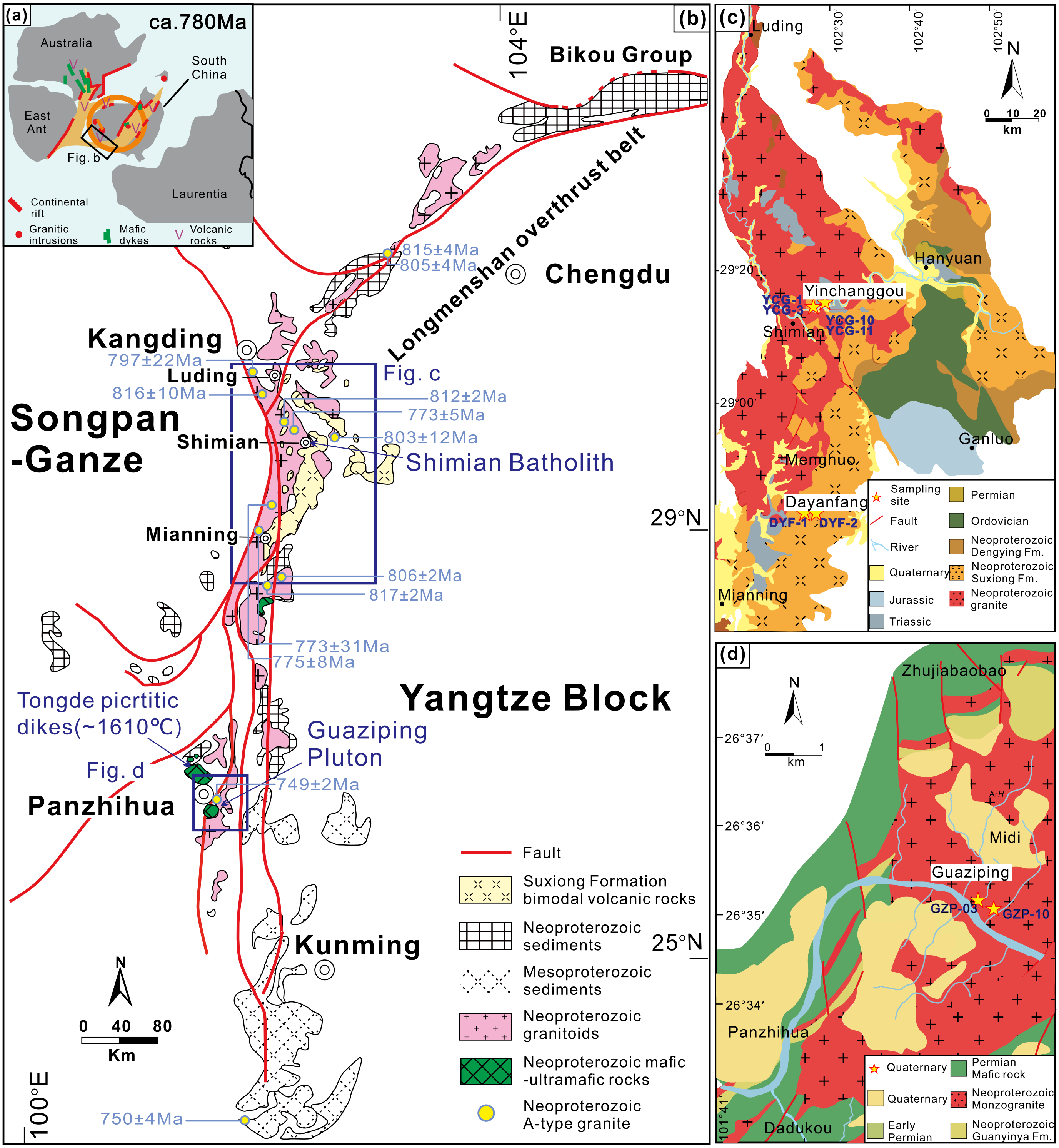

Fig. 1. The geology of the western Yangtze Block showing: (a) interpreted ca. 780 Ma Rodinia mantle plume beneath South China (compiled after Li et al., 2008); (b) simplified geological map showing the distribution of Neoproterozoic magmatic rocks along the western margin of the Yangtze Block (compiled after Li et al., 2002b; Zhao et al., 2018), The data and references of A-type granites listed in the Table S10; (c) Simplified geological map showing the distribution of volcanic rocks in the Suxiong Formation and Shimian Batholith (compiled after SBGMR, 1991); and (d) Simplified geological map showing the distribution of the Guaziping Pluton (compiled after SBGMR, 1991). (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

values lower than the mantle zircon value. Obviously, the $\delta^{18}O$ values of Shimian Batholith are lower than the rhyolite samples from the Suxiong Formation.

Except the analyses of zircons with younger dates, the two granodiorite samples GZP-3, GZP-10 from the Guaziping Pluton yield the approximate Concordia ages of 781 ± 4 Ma (MSWD = 0.8, n = 15) and 783 ± 4 Ma (MSWD = 0.3, n = 15). This ca. 782 Ma date is interpreted as the emplacement age of the Guaziping Pluton (Fig. 2g, h). The $\varepsilon_{Hf}(t)$ values of the zircon grains are between +4.3 and +8.1, the associated T_{DM2} model age is 1325 Ma–1172 Ma, and the $\delta^{18}O$ values are between 4.31 and 5.42‰, with 97.5% of these zircons having $\delta^{18}O$ values lower than 5.3‰ (Fig. 3).

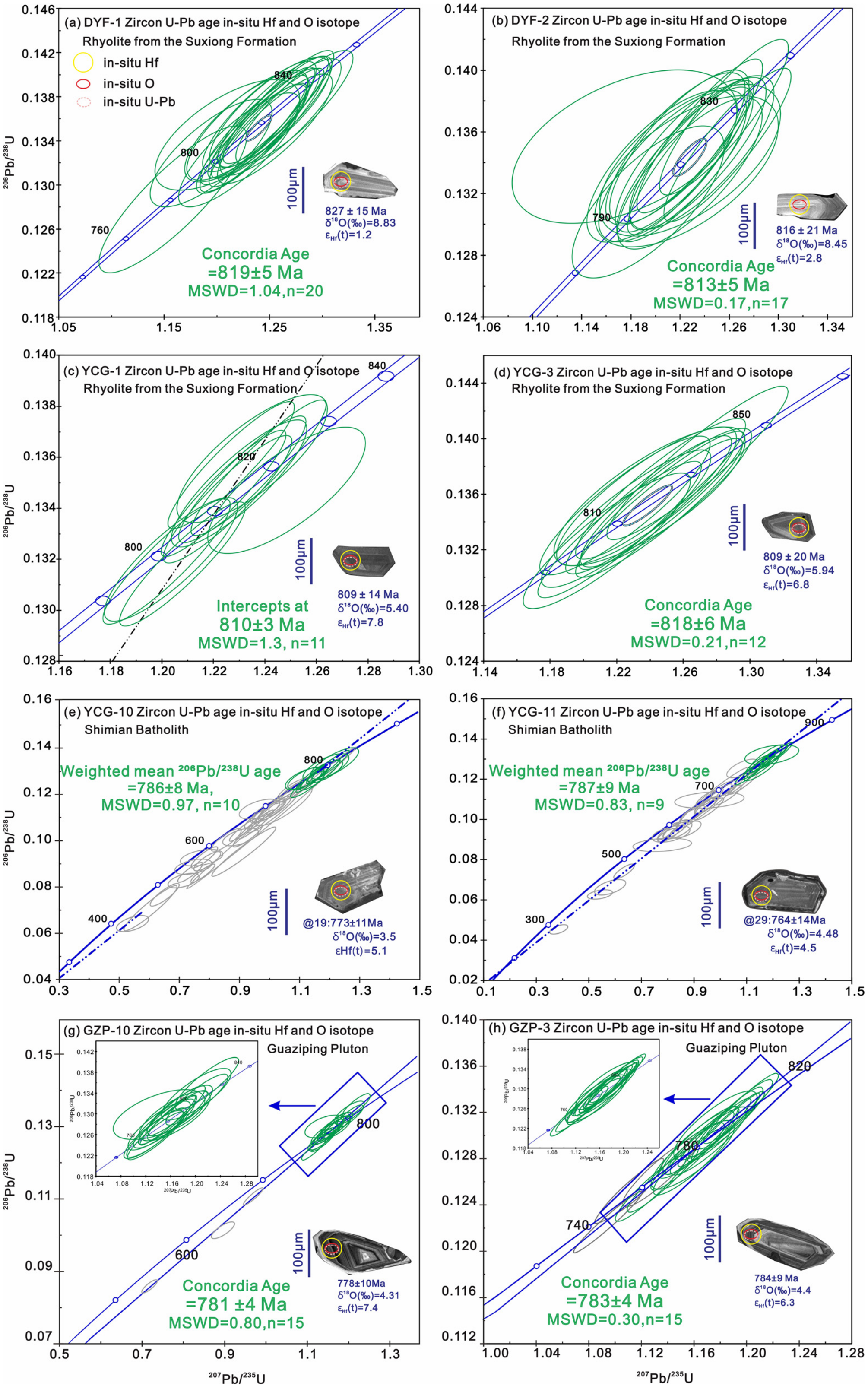

Fig. 2. U–Pb Concordia diagrams for: (a-d) magmatic zircons from rhyolite in the Suxiong Formation; (e-f) magmatic zircons from the Shimian Batholith samples with low-$\delta^{18}O$ values; and (g-h) magmatic zircons from the Guaziping Pluton with low-$\delta^{18}O$ values analysed in this study. The error ellipsoids are at the 2σ level, and grey hollow ellipses are excluded from age calculation owing to their Pb loss.

4.2. Geochemistry

Twenty-eight fresh and representative samples were collected for the whole rock analyses (Tables S6 and S7). The rhyolite samples (DYF-1 to DYF-7 and DYF-9) are abundant in SiO_2, enriched in LREEs and large ion lithophile elements (LILEs) Rb, Ba and Pb, with negative Eu-anomalies with Eu/Eu* $(2^*w(Eu)_N/[w(Sm)_N + w(Gd)_N])$ values of 0.46–0.72, and are depleted in Sr and Nb

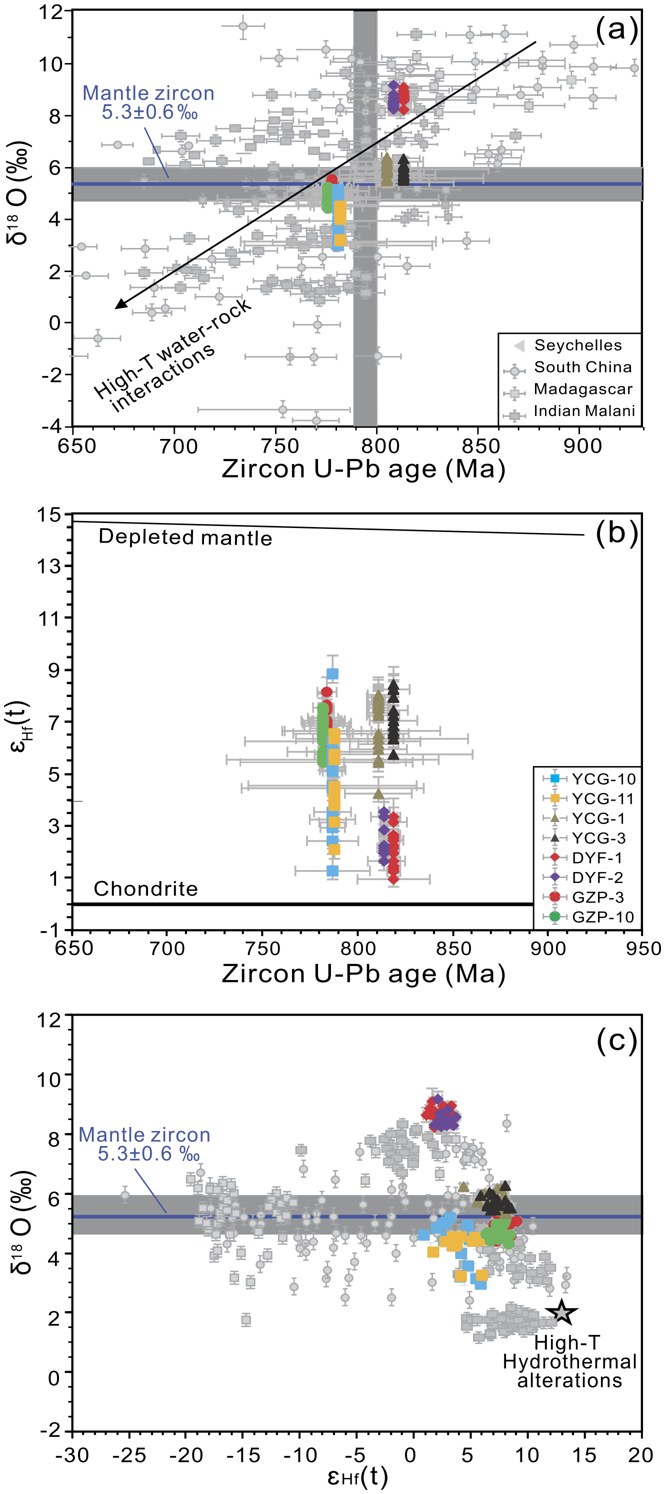

Fig. 3. Diagrams for Neoproterozoic granites from the Yangtze Block showing: (a) δ^{18}O versus U–Pb dates; (b) $\varepsilon_{\mathrm{Hf}}$(t) versus U–Pb dates; and (c) δ^{18}O versus $\varepsilon_{\mathrm{Hf}}$(t). Data for (a) and (c) are from Wang et al. (2017) and Huang et al. (2019 and references therein).

(Fig. S4a-b). The total REE (ΣREE) of rhyolite samples (YCG-1, YCG-3, YCG-5 to YCG-8) vary from 138 to 216 ppm, have a strong negative Eu-anomalies with Eu/Eu* values of 0.23–0.3, and exhibit higher the LILEs Rb, Pb and the high field strength elements (HFSE) Th and U, and depleted in Ba, Sr and Eu (Fig. S4c-d). Samples of the porphyritic monzogranite (YCG-9 to YCG-14) have high LREEs, strong negative Eu-anomalies (Eu/Eu* = 0.1–0.13), have elevated LILEs Rb, Pb and HFSEs Th and U, and depleted in Ba and Sr (Fig. S4e-f, Tables S6 and S7). The total REE (ΣREE) of the granodiorite sample (GZP-3 to GZP10) vary from 137 to 286 ppm. These are enriched in LREEs and the large ion lithophile elements (LILEs) Rb and Ba, and depleted in Nb and Ta (Fig. S4g-h).

5. Discussion

5.1. Origin of low-δ^{18}O magmas

Zircons crystallising from a low-δ^{18}O magma can serve as a tracer for the processes involved in the formation and emplacement of such a magma (Bindeman and Simakin, 2014). Hotspots and rifts with high magmatic activity and heat fluxes are ideal settings to produce low-δ^{18}O magmas (Troch et al., 2020 and references therein). Metasomatism by fluid and/or partial melting of subducted mafic oceanic crust can also generate magmas with low-δ^{18}O values (Wei et al., 2002; Bindeman et al., 2005). Troch et al. (2020) suggest that low-δ^{18}O magmas can be linked to either assimilation of pre-existing hydrothermally altered crust or, more commonly, to assimilation of syn-magmatically altered rocks.

The available Hf and O isotope data for zircons from Neoproterozoic igneous rocks in the Yangtze Block can be used to investigate their source compositions. The four ca. 820-810 Ma rhyolite samples from two areas have $\varepsilon_{\mathrm{Hf}}$(t) values range from +0.9 to +3.3 with δ^{18}O values between 8.20-9.14‰, and $\varepsilon_{\mathrm{Hf}}$(t) values range from +4.2 to +8.4 with δ^{18}O values 5.30- 6.31‰. These values are indicative of derivation from Mesoproterozoic crustal sources (Li et al., 2005). No magmatic zircons with $\delta^{18}\mathrm{O} < 5.3$‰ have been identified in the rhyolite samples from the Suxiong Formation, indicating that little, if any, pre-existing hydrothermally altered crust is present in the study area.

Zircons from the ca. 785 Ma Shimian Batholith with a U–Pb concordance of ≥95% have low-δ^{18}O values of 2.98 to 5.20‰ and the $\varepsilon_{\mathrm{Hf}}$(t) values for the zircons with low-δ^{18}O values are positive (+1.3 to +8.8). The zircons with low-δ^{18}O values from the ca. 782 Ma Guaziping Pluton have $\varepsilon_{\mathrm{Hf}}$(t) values between +4.3 and +8.1 (Fig. 3a, b), which indicates derivation by partial melting of a juvenile crustal source (Colón et al., 2019). The Shimian Batholith's $\varepsilon_{\mathrm{Hf}}$(t) values have a wide range of +1.3 to +8.8, which may be due to heterogeneity in the source of the parental magma.

All the zircon grains from the ca. 785 Ma Shimian Batholith have δ^{18}O values lower than the mantle value of 5.3‰, but no grains with low-δ^{18}O values have been found in the ca. 820 and 810 Ma rhyolite samples from the Suxiong Formation (Fig. 3a). Thus, it is possible that the parental magma of low-δ^{18}O granites attained lower δ^{18}O values during hydrothermal alteration of a magma at shallow levels and subsequent remelting in a rift zone (cf. Bindeman et al., 2005; Troch et al., 2020 and references therein).

Neoproterozoic juvenile crust characterised by depleted Hf isotopes and low δ^{18}O values associated with an extensional (rifting) tectonic setting form favourable conditions for remelting of rocks altered by high-temperature water-rock interaction to generate low-oxygen isotopic values (Fig. 3c, Huang et al., 2019 and Wang et al., 2013). Therefore, we propose that an extensional setting can explain the positive $\varepsilon_{\mathrm{Hf}}$(t) and low-$\delta^{18}$O values recorded by the zircons in the study area (Fig. 3c). Furthermore, the Hf-O isotopic systematics presented in Fig. 3c show that magmatic rocks from the southern and northern parts of the Yangtze Block, Madagascar and northwestern India all exhibit depleted Hf isotopes and low δ^{18}O values (cf. Huang et al., 2019), which is consistent with rifting during remelting of high-temperature fluid-rock interactions generating low-δ^{18}O isotopic values (Watts et al., 2011; Zhou et al., 2020).

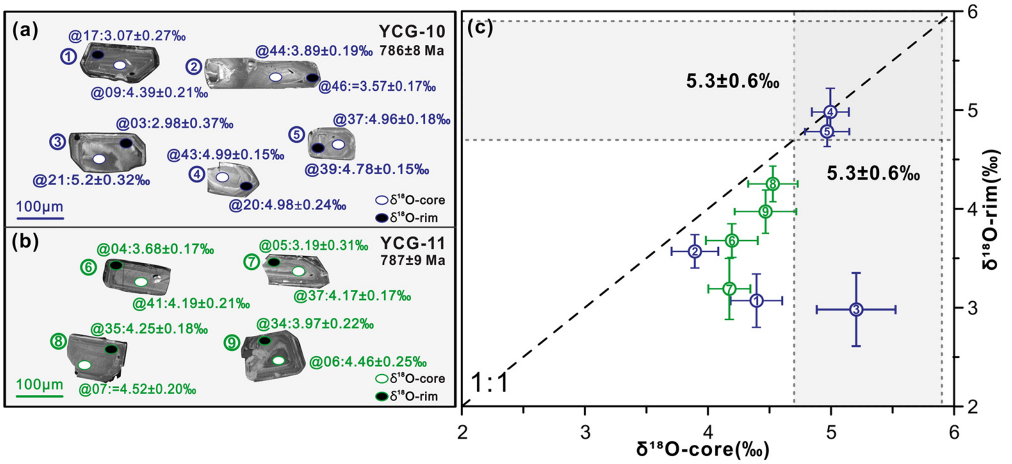

Fig. 4. *In-situ* zircon O isotopes variability of the representative zircons from Neoproterozoic Shimian Batholith in the Yangtze Block showing: (a-b) CL images of representative zircons labeled with δ^{18}O values to show the intra-grain O-isotope heterogeneity; and (c) Plot of δ^{18}O-core versus δ^{18}O-rim for magmatic zircon crystals. Error bars on zircon δ^{18}O values indicate 2σ standard errors.

Nine zircon grains were chosen to examine δ^{18}O variations from their core to rim, of which seven zircons show decrease of δ^{18}O values from the core to the rim (Fig. 4) with similar ages (Table S3). For example, the core of the zircon from sample YCG-10 (spot YCG-10@09) yields a δ^{18}O value of 4.39 ± 0.21‰, and the rim of the same zircon (spot YCG-10@17) yields a δ^{18}O value of 3.07 ± 0.27‰ (Fig. 4a). The zircons from sample YCG-11 also exhibit decreased variable values (Fig. 4b), the core of the zircon from spot YCG-11@41 yields a δ^{18}O value of 4.19 ± 0.21‰, the rim of the same zircon from spot YCG-11@4 yields a δ^{18}O value of 3.68 ± 0.17‰. In addition, the CL images in Fig. 4 show that zircon grains do not have inherited cores and their geochemistry shows that their cores and rims have similar Th/U values. This is an important observation, because it can be explained by a dynamic magma process known as "crustal cannibalization" (Bindeman and Simakin, 2014; Bindeman et al., 2008). This is consistent with remelting and assimilating the carapace around a shallow magma chamber (coeval but earlier solidified units) that is hydrothermally altered rocks by water (Zhou et al., 2020).

5.2. Mantle plume or subduction?

The Neoproterozoic paleogeographic position and tectonic events of South China are topics of interest. One school of thought presents South China, NW India and Madagascar as remnants of a giant Andean-type arc along the western margin of Rodinia with peripheral subduction leading to the break-up of Rodinia (Zhou et al., 2006; Wang et al., 2017; Cawood et al., 2016). An alternative model involves a mantle super-plume centred in South China triggering the onset of a Neoproterozoic rift and magmatism at ca. 825 Ma accompanied by the development of widespread radial dyke swarms in Laurentia, South China, Australia, and southern Africa (Li et al., 1999, 2002a, 2008).

This is the first time that well documented Neoproterozoic granites with low-δ^{18}O values by the *in-situ* analyses of O isotopes in zircons from the western margin of the Yangtze Block are presented. The northern margin of the region also includes ca. 790-635 Ma granitic and pyroclastic rocks with low-δ^{18}O values of −4 to 4‰ (Liu and Zhang, 2013; Yang et al., 2016). The low-δ^{18}O values in zircons along with the southern margin of the Yangtze Block range from 1.95 to 4.5‰ (Wang et al., 2011). Only three low-δ^{18}O zircons have been identified for Neoproterozoic granites in the western margin of the Yangtze Block, which range from 4.2 to 4.35‰, with the method used involving the analyses of single zircon grains (Zheng et al., 2007). Incidentally, the Guaziping Pluton with low-δ^{18}O values is present at least 1000 km away from the low-δ^{18}O magma region in the northern margin of the Yangtze Block (Fig. 1b). In addition, ca. 750-720 Ma granites with low-δ^{18}O values of 2.07 to 4.57‰ are also known ∼1500 km eastward from the study area in the northeastern Cathaysia Block (Huang et al., 2019). These occurrences define an ellipsoidal or circular zone totalling thousands of kilometres around the South China where similar-aged granites contain magmatic zircons with low-δ^{18}O values.

The circular zone defining the Neoproterozoic magmatism with low-δ^{18}O values around South China can be accounted for by an extensional tectonic setting where high-temperature magma was emplaced at a shallow depth. The estimated temperature of zircon crystallisation (T_{Zr}; i.e. 12900/[2.95+0.85M+ln(496000/Zr melt)]) determined from our analyses indicated a high temperature magmatic event with a maximum temperature of 1033 °C (Fig. 5a and Table S8; Liu et al., 2013; Watson and Harrison, 1983). Using the equations for the average crustal thickness or Moho depth (D_M; where $D_M = 0.67\text{Sr/Y} + 28.21$, and $D_M = 27.78 \ln[0.34\ (\text{La/Yb})_N]$), the estimated crustal thickness decreased from ∼70 to 30 km between 850 and 700 Ma (Fig. 5b and Table S9; Hu et al., 2017; Profeta et al., 2015). These data are consistent with crustal thinning during the emplacement of the granites around the edge of South China in an extensional tectonic setting, which was either due to a rifting or the action of a mantle plume, or both. In addition, ca. 825 Ma komatiitic basalts with a mantle potential temperature (T_p) of ∼1660 °C and ca. 800 Ma picrite dikes with a T_p of ∼1610 °C have been discovered in South China, these high temperature magmatism events are interpreted to relate to mantle plume activities (Wang et al., 2007; Zhu et al., 2010).

The A-type geochemical affinities of the porphyritic monzogranite samples from the Shimian Batholith and rhyolite from the Suxiong Formation (Fig. S5), and widespread A-type granities in western Yangtze Block (Fig. 1b and Table S10), suggest an extensional tectonic setting. This is supported by geophysical investigation. Numerous normal faults and eight Neoproterozoic EW-, NEE-, and NW-trending extensional structures are confirmed in the Yangtze Block by integrating 430 sets of 2D seismic data covering over 50,000 km^2, and 3D seismic data covering ∼5000 km^2 in area and large-scale aeromagnetic data (Gu and Wang, 2014).

There is a consensus that the unified South China continent was formed by amalgamation between the Yangtze and Cathaysia blocks during early Neoproterozoic (0.90-0.82 Ga) (e.g., Li et al., 2009; Wang et al., 2008), being located either in the interior of Rodinia (as a "missing link" between Laurentia and Australia-East Antarctica, Li et al., 2008 and references therein), or on

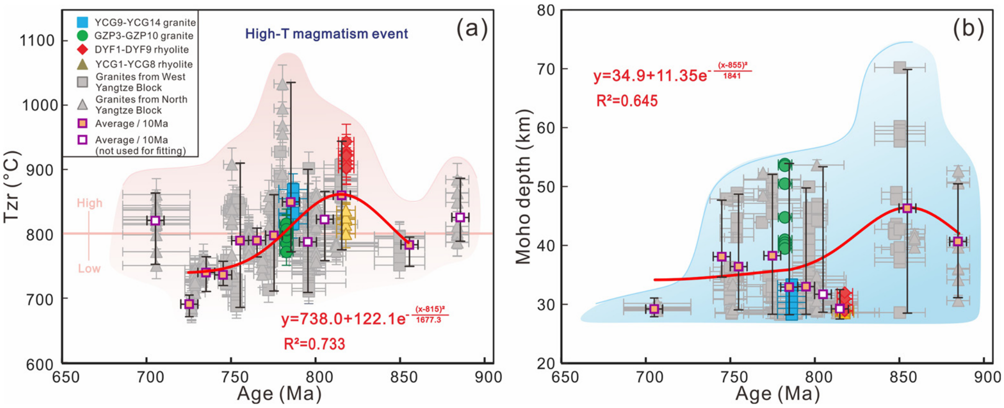

Fig. 5. Diagrams for Neoproterozoic granites from the Yangtze Block showing: (a) Variation of zircon saturation temperature over time; The estimated temperature of zircon crystallisation is calculated by using the correlation equations from Watson and Harrison (1983) (TZr; i.e. 12900/[2.95+0.85M+ln(496000/Zrmelt)]); (b) Changes of calculated crustal thickness from Sr/Y and $(La/Yb)_N$ over time. Crustal thickness with uncertainty is calculated by using the correlation equations from Hu et al. (2017), (D_M; where $D_M = 0.67Sr/Y$ / $+28.21$, and $D_M = 27.78 \ln[0.34\ (La/Yb)_N]$). Regression line (the red solid lines) and empirical relationship with R^2 are shown on each diagram. The data shown in parts (a) and (b) is listed in Supplementary Table S8 and Table S9.

the NW periphery of Rodinia (Zhou et al., 2006). Although one school of competing models interpreted that the middle Neoproterozoic low-δ^{18}O magmatic rocks along the northern margin of the Yangtze block are correlated with those of low-δ^{18}O rocks in NW India and Madagascar, and they are considered as products formed by subduction retreating along the NW margin of Rodinia (Wang et al., 2017; Zhou et al., 2006). This model is difficult to explain the occurrence of same-aged low-δ^{18}O rocks around the western and southern margin of Yangtze block and in the NW Cathaysia block, as these rocks are located within the continental interior, rather than on the active continental margins. Alternatively, the middle Neoproterozoic low-δ^{18}O magmatic ring coincides well with the development of the middle continental rift system in South China continent, including the Nanhua Rift on the southern Yangtze and northern Cathaysia blocks, the Kangdian Rift on the western Yangtze block, and an unnamed rift around the northern Yangtze block (Wang and Li, 2003).

Volcanic arcs, however, only have small components of units, samples, or even zircons that can be classified as low-δ^{18}O types (e.g. the Western Nevada volcanic field in the USA, Aleutian volcanic arc in Alaska, Kamchatka volcanic arc in Russia, and Calabozos volcano in Chile) (Troch et al., 2020). The generation of large-scale magmas with low-δ^{18}O values is thought to be controlled by the remelting and assimilation of heated rocks that have been altered by high-temperature fluids in hotspot and rift zones such as the Yellowstone Caldera on the USA (Wang et al., 2011; Drew et al., 2013). Subduction-related environments, however, are thought to be less likely to generate continental-scale, voluminous low-δ^{18}O magmas (Yang et al., 2016).

The locations of widespread low-δ^{18}O magmatic zircons are broadly coincident with the northern, western and southern margins of the Yangtze Block, and the Nanhua Rift in northern Cathaysia Block, which are indicative of large-scale crustal remelting (Fig. 6, Wang and Li, 2003). LREE-depleted mafic dyke swarms in the Yangtze Block were generated by melting of an asthenospheric mantle super-plume (Lin et al., 2007). Finally, the formation of curvilinear low-δ^{18}O magmatic feature around South China, with a diameter of around 1500 km, is more readily explained the Neoproterozoic rift-related tectonic setting through the action of a mantle super-plume centred in South China (Figs. 1a and 6; Li et al., 2008).

6. Conclusions

Neoproterozoic granites along the western margin of the Yangtze Block with low-δ^{18}O values are interpreted to be generated via the assimilation of syn-magmatically altered rocks rather than assimilation of pre-existing hydrothermally altered crust. No magmatic zircons with low-δ^{18}O values have been found in the rhyolite samples from the ca. 820-805 Ma Suxiong Formation, which is interpreted as indicating that there was no pre-existing hydrothermally altered crust in the study area.

The granites in the region have a source constrained by depleted Hf isotopes and low-δ^{18}O values resulting from high temperature hydrothermal alteration. The δ^{18}O value decreases from the zircons' core to rim, which are indicative of the progressive remelting of rocks that have reacted with water at high temperatures. Furthermore, the thinning of the continental crust between ca. 850 and 700 Ma, was accompanied by a high temperature magmatic event that easily led to the generation of large-scale low-δ^{18}O magmas.

We propose a model to explain the presence of these widespread low-δ^{18}O felsic igneous rocks, that circumscribing South China, and which record multiple magmatic cycles and remelting of various sources in the upper crust. We suggest that this was in a Neoproterozoic rift-related tectonic setting controlled by a super-mantle plume, explaining the circular zone around South China characterised by low-δ^{18}O magmatism.

CRediT authorship contribution statement

Hao Zou: Conceptualization, Investigation, Resources, Writing – Original Draft, Funding acquisition; **Qiu-Li Li**: Methodology; **Leon Bagas**: Writing – Review & Editing, Validation; **Xuan-Ce Wang**: Conceptualization, Writing – Review & Editing, Validation; **An-Qing Chen**: Investigation, Resources; **Xian-Hua Li**: Conceptualization, Supervision, Writing – Review & Editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request, the data repository can be found on the Mendeley Data https://doi.org/10.17632/th7b2c9j2v.1.

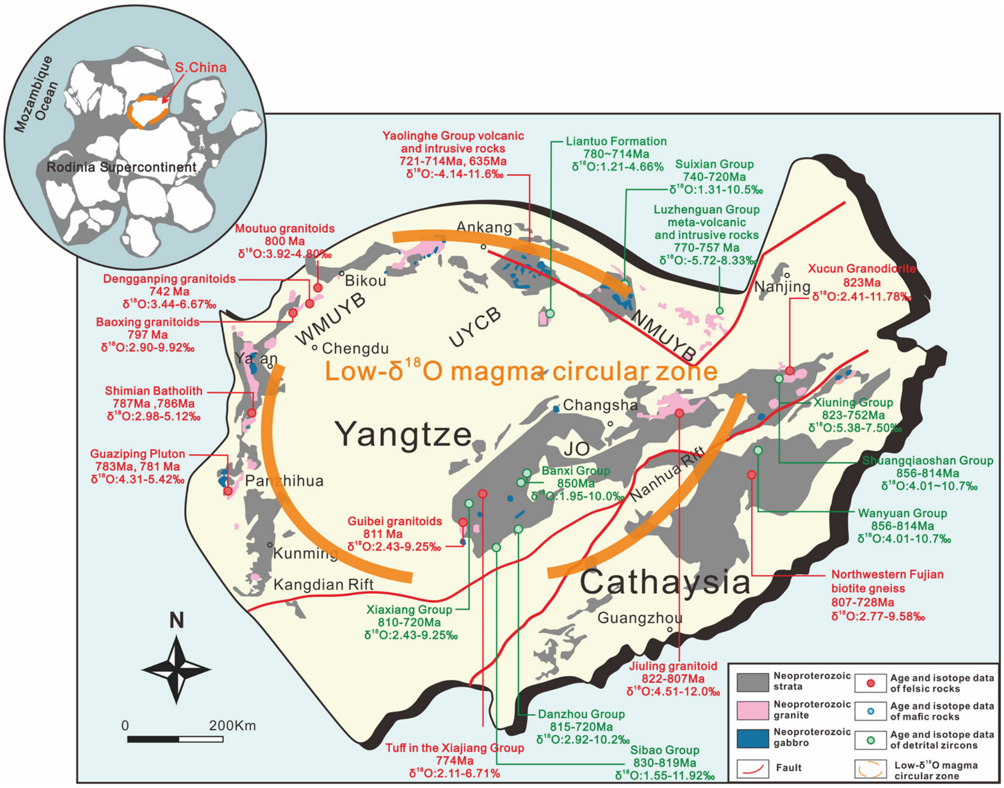

Fig. 6. Simplified map showing the distribution of the low-δ^{18}O rocks of South China (compiled from Zhou et al., 2020; Qi and Zhao, 2020; Zou et al., 2020; Huang et al., 2019 and references therein).

Acknowledgements

We thank the Editor-in-chief Laurence Coogan and the two anonymous reviewers for their helpful comments. We are grateful to Franco Pirajno for polishing the language, Hang Liu, Yang Li and Xiuwei Jiang for their assistance during field work, Han Zhao and Tingting Gong for their general assistance, Zhao-Chu Hu for his assistance with the LA-MC-ICP-MS analyses, and Jiao Li, Hong-Xia Ma, Xiao-Xiao Ling, Yu Liu and Guo-Qiang Tang for their help with the SIMS analyses. This study was financially supported by the Strategic Priority Research Program (B) of the Chinese Academy of Sciences (grant number: XDB18030300), China Postdoctoral Science Foundation (grant number: 2019M650833), State Key Laboratory of Lithospheric Evolution (grant number: SKL-K201902).

Appendix. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2021.117196.

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