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Formation mechanism of the global Dupal isotope anomaly

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The Dupal anomaly has been a frequently discussed feature since it was first proposed three decades ago. We here limit the distribution of the Dupal anomaly based on more than 10 000 Sr–Nd–Pb isotopic composition analyses and classify the anomaly into three types, located in three different oceans and with different mechanisms of formation. The Dupal anomaly in the East Asian Continental Margin subduction zone is related to enriched mantle II, which may originate from the recycling of the subducting plate or continental mantle. The high μ and enriched mantle I are the reason for the Dupal anomaly in the Pacific Ocean, which is related to the superplume. However, the source of the Dupal anomaly in the Indian Ocean and the Southern Atlantic Ocean is a mixture of enriched mantle I and enriched mantle II, and they come from the African superplume and the recycling of subcontinental mantle or continental crust of Gondwana. In consideration of all the above factors, we suggest that the superplume from the core–mantle boundary, the recycling subducting plate and continental mantle are the main characteristics of the global Dupal anomaly.

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KEY WORDS Dupal anomaly; mantle reservoir; superplume; hotspots

1. INTRODUCTION

Dupré and Allègre (1983) first recognized a Pb and Sr isotope anomaly when studying the Central Indian Ridge in the 1980s. They suggested that the mid-ocean ridge basalt (MORB) in the Central Indian Ridge is quite distinctive by its high radiogenic Pb and Sr isotopic compositions. Hart (1984) subsequently named it the 'Dupal anomaly' and indicated that it represented an abnormal mantle under the oceans of the southern hemisphere. Hart (1984) also defined the boundary of the Dupal anomaly quantitatively, based on the variation in Pb and Sr isotope compositions.

Much intensive research work has been done to explain the formation mechanism of the Dupal isotope anomaly, but arguments still exist. Dupré and Allègre (1983) considered that the recycling of the oceanic crust and sediments was the reason for the high $^{208}Pb/^{204}Pb$ composition of the oceanic island basalt (OIB) and MORB from the Indian Ocean, and the 670 km discontinuity may be the origin of the Dupal anomaly (Roex *et al*., 1989; Weis *et al*., 1989). McKenzie and O'Nions (1983) suggested that the Dupal anomaly originates from the oldest lithosphere under the continent that is not depleted. Tatsumoto (1991) proposed that the high Th/U ratio under the lithospheric mantle may be the reason for the high $^{208}Pb/^{204}Pb$ ratio, and Weis *et al*. (1989) regarded its origin as shallow mantle. Castillo (1988) argued that the Dupal anomaly arises from the boundary between the core and the mantle. Meanwhile, the geochemically enriched mantle I (EMI) and high μ (HIMU, $\mu = {}^{238}U/{}^{204}Pb$) in the southern hemisphere are the reason for its specific distribution, which had lasted for a billion years. Therefore, all arguments have focused on where and when the Dupal anomaly originates from.

As part of the ongoing process of ocean investigation, multiple obvious anomalies in the northern hemisphere have been reported, especially in the East Asian Continental Margin. Studies of the South China Sea (SCS), the Japan Sea and the Philippine Sea suggest that OIB and MORB samples mostly show the characteristics of a Dupal anomaly (Mukasa *et al*., 1987; Tatsumoto and Nakamura, 1991; Yan *et al*., 2015). However, we cannot find the related Sr–Nd–Pb isotopic studies about the basalts from the Okinawa Trough. Researches on the Tethys and structural zones also established that the Dupal anomaly actually existed for a very long time, since at least the Proterozoic (Xu *et al*., 1996). But most of them regard its existence as evidence

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for the presence of a former mantle plume, on the basis of the understanding of the modern-day Dupal anomaly.

In this paper, we try to explain the origin of the Dupal anomaly and the reason for its distribution. We limit its distribution based on an assessment of more than 10 000 isotopic data analyses that we collected and also some data from a palaeo-ocean that has been used to explain the origin of the Dupal anomaly from the perspective of deep time.

2. DISTRIBUTION OF THE DUPAL ANOMALY

Using the definition of Dupal anomaly from Hart (1984), the anomaly is usually regarded as a kind of isotopic anomaly in the southern hemisphere that represents roughly continuous belts between the equator and 60°S. However, more and more studies have suggested that the Dupal anomaly is not necessarily restricted to the southern hemisphere (Mukasa *et al*., 1987; Tatsumoto and Nakamura, 1991; Yan *et al*., 2015). Thus, the origin of the Dupal anomaly continues to be controversial.

In order to define the current distribution of the Dupal anomaly, we plot more than 10 000 data of basalts (Fig. 1a) on the map of $\Delta 8/4$ (Fig. 1b), $\Delta 7/4$ (Fig. 1c) and ΔSr (Fig. 1d), and we delimit its boundary with $\Delta 8/4 \geq 60$, $\Delta Sr \geq 50$ (Hart, 1988) and $\Delta 7/4 \geq 11$ (Hart, 1984). In Figure 1, the regions coloured with warm tones (yellow–red–purple) are related to the Dupal anomaly.

We can define several distributions of the Dupal anomaly in Figure 1. The Indian Ocean Region, which is the original source of the Dupal anomaly, is the most typical region. Meanwhile, the Southern Atlantic Ocean Region, adjacent to the Indian Ocean Region, also includes the distribution of the Dupal anomaly. In addition, there is a small region near the Pacific mid-ocean ridge related to the Dupal anomaly.

2.1. The East Asian Continental Margin

The East Asian Continental Margin has always remained controversial and arguments with the most typical subduction zone that is the most important tectonic boundary in this region. Thus, discussion about the East Asian Continental Margin must be separated into two parts. However, the area outside (east) of the island arc belongs to the Pacific Ocean.

The inner (west) side of the island arc includes the Japan Sea, Bohai Sea, East China Sea, SCS and Philippine Sea, and we can define the Dupal anomaly in all three maps in Figure 1b–d. There are abundant studies about the basalts in the SCS, and also controversies exist there. However, there are not as many studies on basalts in the other regions.

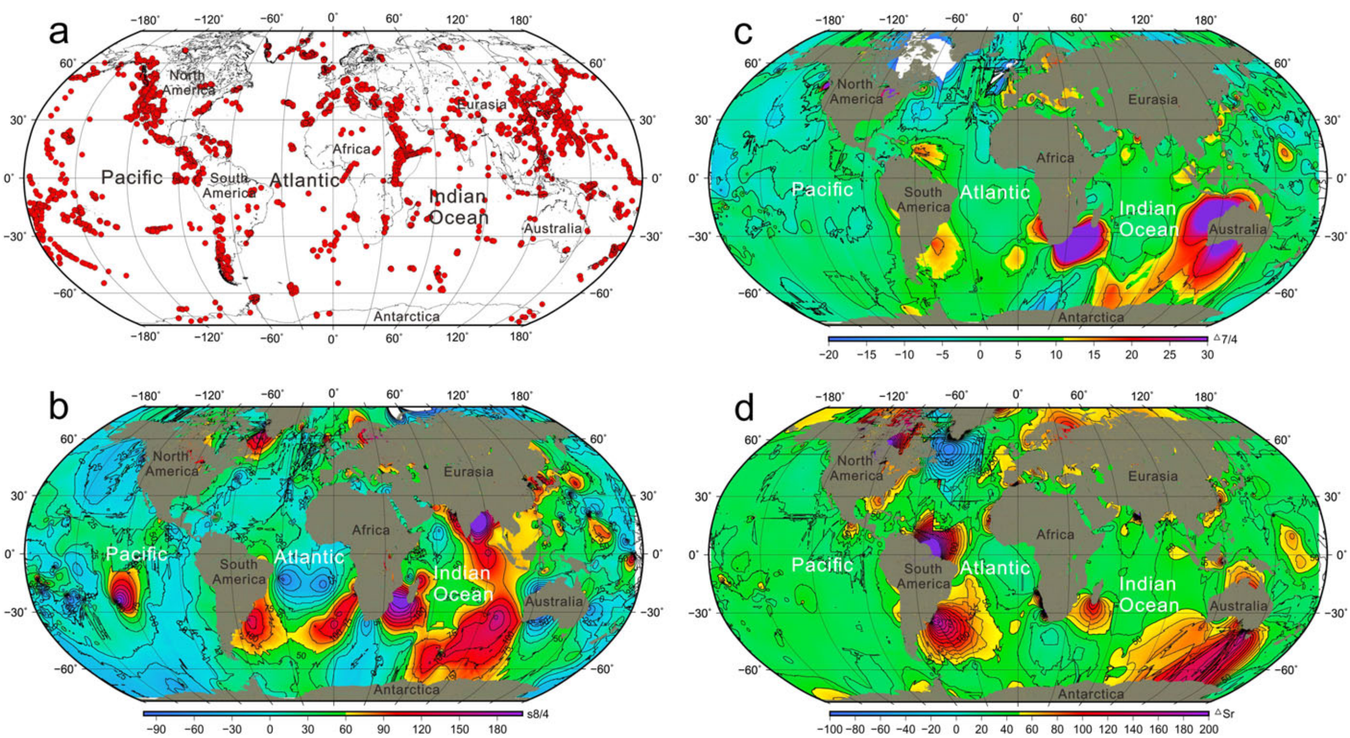

Figure 1. The distribution of the Dupal anomaly in today's oceans. {$\Delta 7/4 = [(^{207}Pb/^{204}Pb)$ DS-$(^{207}Pb/^{204}Pb)$ NHRL] * 100; $\Delta 8/4 = [(^{208}Pb/^{204}Pb)$ DS-$(^{208}Pb/^{204}Pb)$ NHRL] * 100; $\Delta Sr = [(^{87}Sr/^{86}Sr)$ DS −0.7] * 104; data source: EarthChem and Georoc}. This figure is available in colour online at wileyonlinelibrary.com/journal/gj

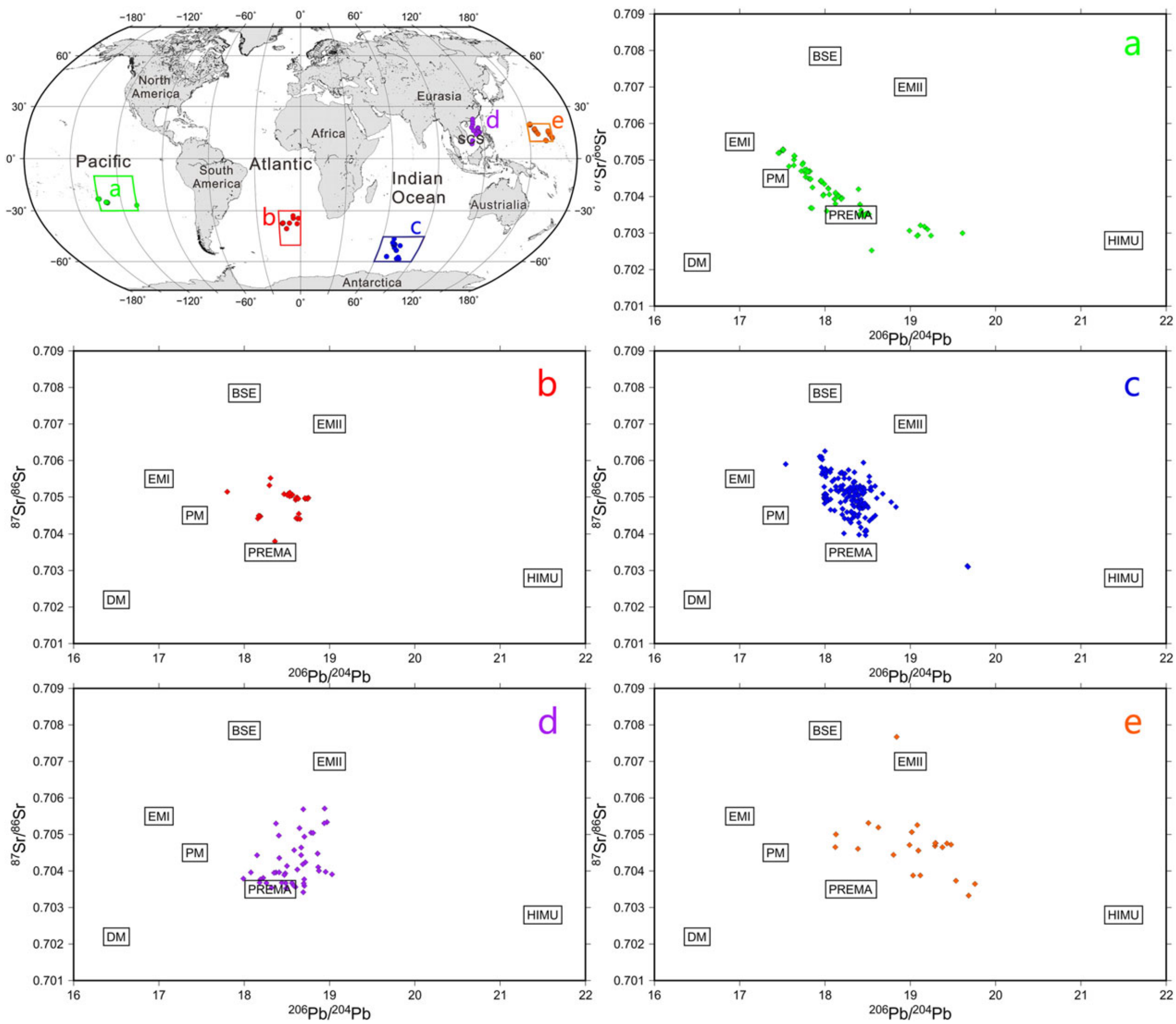

Figure 2. Plots of $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ of the basalts from several typical regions with Dupal anomaly. (a) Pacific Ocean, (b) South Atlantic Ocean, (c) southern Indian Ocean, (d) East Asian Continental Margin and (e) Okinawa. BSE, bulk silicate earth; DM, depleted mantle; PM, primitive mantle; PREMA, prevalent mantle; EMI, enriched mantle I; EMII, enriched mantle II; HIMU, high μ. This figure is available in colour online at wileyonlinelibrary.com/journal/gj

Thus, we propose to use the SCS as an example to discuss its origin.

The geochemical characteristic features of the basalts from SCS are similar to those of OIB (Wang *et al*., 2009; Xu *et al*., 2012; Yan *et al*., 2008; Yang *et al*., 2011; Fig. 2). But Zou (1993) suggests that the seamount in SCS is more likely to be continental basalt, which is quite different to the MORB suggested by the evidence obtained from rare earth elements and isotopes. The basalts in SCS show up the Dupal anomaly by the evidence of Sr–Nd–Pb isotopes, and they originate from a mixture of depleted mantle (DM) and enriched mantle II (EMII) (Xu *et al*., 2012; Yan *et al*., 2008, 2015; Zou, 1993), while Yang *et al*. (2011) indicate that it is a mixture of DM and EMI. Meanwhile, most of these researches agree that the Dupal anomaly in SCS is related to a mantle plume (Xu *et al*., 2012; Yan *et al*., 2008) and the continental crust may have had a great influence (Yang *et al*., 2011). Also, we can indicate that the basalts from SCS are quite closely related to the EMII in Figure 2d.

2.2. Indian Ocean region

The MORBs from the Indian Ocean featured as higher $^{87}Sr/^{86}Sr$, and lower $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ are the typical Dupal anomaly (Hart, 1984). The Sr, Nd and Pb isotope tracers indicate that the Dupal anomaly may be related to recycled continental lithosphere, old sub-continental lithosphere or sediments associated with subducting oceanic crust (Rehkamper and Hofmann, 1997). Meanwhile, studies of Hf, Os and Li isotopes suggest that the Dupal anomaly

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originated from recycled continental crust (Escrig *et al*., 2004; Hanan *et al*., 2004; Nishio *et al*., 2007).

The distribution of the Dupal anomaly in the Indian Ocean is mainly concentrated in the southern section that used to be part of the Gondwana supercontinent (Fig. 1). Also, we can suggest that the origin of the Indian Ocean MORB may be related to prevalent mantle (PREMA) and enriched mantle (Fig. 2c).

2.3. *Southern Atlantic region*

The Dupal anomaly in the Southern Atlantic Region is quite limited in extent but representative. It occurs in a small region of the Southern Atlantic (Fig. 1). Regelous *et al*. (2009) suggested that the seamount lavas here are more depleted in highly incompatible elements than the axial (ridge) lavas and record the highest Sr, Nd and Eu concentrations, indicating that the Dupal anomaly is related to EMI. Regelous *et al*. (2009) also speculated that this extreme Dupal anomaly origin originated from the lower continental crust and continental lithospheric mantle, rather than from the deeper mantle by plumes. However, Class and le Roex (2011) believe that the Southern Atlantic Dupal anomaly is linked to African sources instead of a shallow origin. The Sr versus Pb diagram (Fig. 2b) also has some similarities to the Indian Ocean (Fig. 2c).

2.4. *Pacific region*

The Dupal anomaly under the Pacific superplume is quite unique in chemistry. High $\Delta 8/4$ and low $\Delta 7/4$ and ΔSr indicate that the Dupal anomaly here is definitely not typical. The origin of these MORBs is related to HIMU and EMI, which may be the source of the Dupal anomaly here (Fig. 2a).

We can also define the Dupal anomaly outside the island arc in the East Asian Continental Margin from Figure 1. Numerous seamounts and seamount chains are the most prominent feature of this region. Few researches have been undertaken on the geophysics and geochemistry here. The basalts in this region seem quite different in geochemistry to the basalt inside the island arc, and their origin might be related to EMI and HIMU (Li, 2013; Tan, 2010), and they may originate from the lower mantle (Chu *et al*., 2005). Also, we can define the basalts in this area as possibly coming from the mantle, and hence related to EMI and HIMU in Figure 2e, and thus quite different to the SCS in their origin.

Therefore, we can define three types of Dupal anomalies in today's oceans with different origins. The Dupal anomaly in the East Asian Continental Margin and Pacific Ocean, divided by the subduction zone, is quite different, while the Dupal anomaly in the Indian Ocean and the Southern Atlantic Ocean seems likely to be a mixture of EMI and EMII, which is quite different to the others.

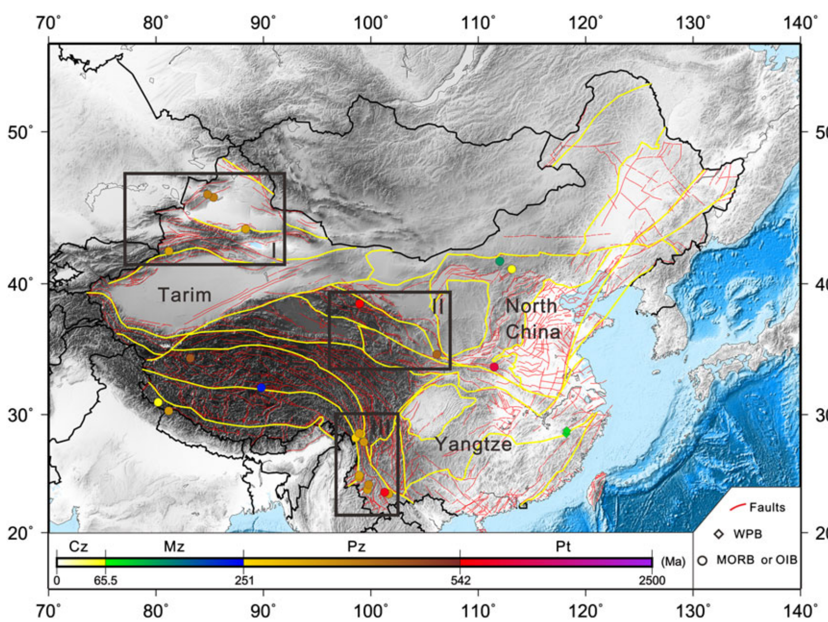

Figure 3. The distribution of the Dupal anomaly in the Chinese Mainland (The colour of the samples represents their ages according to the colour bar beside the map. Data source: Hou *et al*., 2005; Huang *et al*., 2004; Lai *et al*., 2010; Lee *et al*., 2010; Lei *et al*., 2008; Li, 2008; Li *et al*., 2007; Liu *et al*., 2013a, b; Peng *et al*., 2013; Wang *et al*., 2006; Wei *et al*., 2003; Wu *et al*., 2014; Zhang *et al*., 1995, 2005, 2015; Zhou *et al*., 1995a, 2001; Zhu *et al*., 2006). WPB, within-plate basalt; MORB, mid-oceanic ridge basalt; OIB, oceanic island basalt; CZ, Cenozoic; Mz, Mesozoic; Pz, Palaeozoic; Pt, Proterozoic. Tectonic domains I: Palaeo-Asian Oceanic Tectonic Domain; II: Proto-Tethys Tectonic Domain; and III: Sanjiang Suture Zone. This figure is available in colour online at wileyonlinelibrary.com/journal/gj

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3. THE DUPAL ANOMALY IN THE PALAEO-OCEAN

The definition of Dupal anomaly comes from studies about the ocean nowadays, while it also existed in the Palaeo-oceans. Thus, studies about its age and distribution may be helpful to explain its origin. The Chinese Mainland may be the best region to study the Dupal anomaly in the Palaeo-ocean, because almost all stages of the suture zone exist there.

The Dupal anomaly exists almost in every suture in the Chinese Mainland (Fig. 3). The most ancient oceanic crust with Dupal anomaly in this region is the Songshugou ophiolite (Lee *et al*., 2010). Many studies on the Songshugou ophiolite indicate that it is an oceanic fragment of Proterozoic age, instead of an Early Palaeozoic suture of the Proto-Tethys (Dong *et al*., 2008; Zhang *et al*., 2015). Evidence from Sr–Nd–Pb indicates that the Songshugou ophiolite shows high Δ7/4 while the Δ8/4 is not quite as high (Xu *et al*., 1996), which may represent a kind of atypical Dupal anomaly. The reconstructions of Rodinia (*ca*. 1000 Ma) show that the suture zone exists beside the northern margin of the Yangtze Craton (Li *et al*., 2008). Also, petrological studies indicate that the Songshugou ophiolite may represent a limited ocean basin (Zhou *et al*., 1995b) or back-arc basin (Zhang *et al*., 2015), which may be similar to the East Asian Continental Margin nowadays.

The protolith of the subduction complex from the Palaeo-Asian Oceanic Tectonic Domain (Figs 3, domain I, and 4, domain I) combines the OIB, MORB, abyssal sediments and overlying rocks, and the mantle source may be a mixture of EMI and EMII (Huang *et al*., 2004). Studies of the MORB from Yushigou (Figs 3, domain II, and 4, domain II) suggest that its mantle source is mainly related to DM

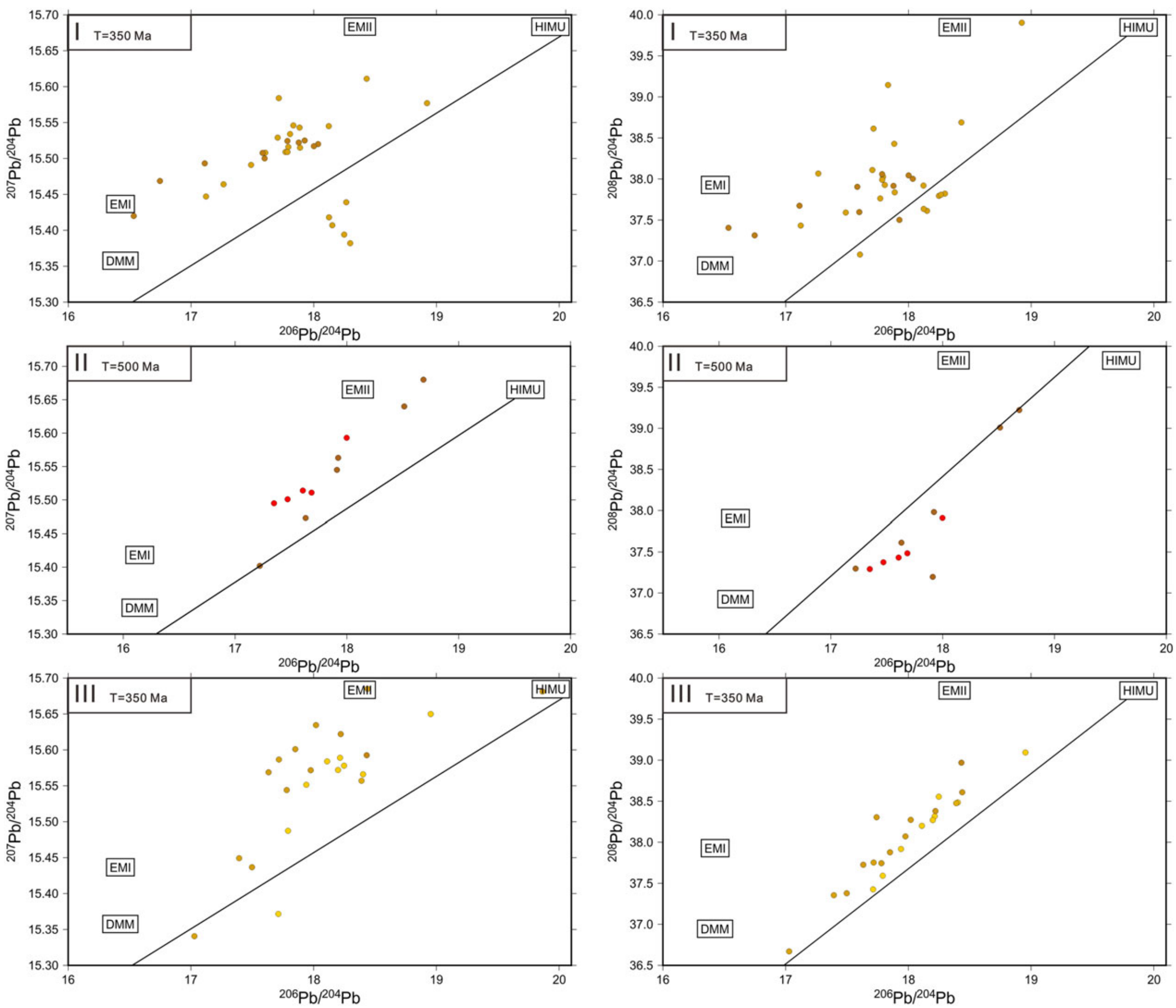

Figure 4. Plots of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ of the suture zones in China. I: Palaeo-Asian Oceanic Tectonic Domain; II: Proto-Tethys Tectonic Domain; and III: Sanjiang Suture Zone. See Figure 2 for explanation of abbreviations. This figure is available in colour online at wileyonlinelibrary.com/journal/gj

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and EMII (Hou *et al*., 2005) and the Qingshui–Hongtubao (Fig. 3, domain II) bimodal basalts, which may be related to a back-arc basin (Li, 2008), originate from the mantle source of EMII (Fig. 4, domain II). Also, the Dupal anomaly of the ophiolite in the Sanjiang suture zone (Fig. 3, domain III) is related to the mantle source of EMII (Lai *et al*., 2010; Wei *et al*., 2003; Zhou *et al*., 1995a). However, the entire Dupal anomaly in the Palaeo-ocean seems to be EMII related, which is quite confusing.

4. DISCUSSION

In order to explain the formation of the Dupal anomaly, the mantle reservoirs are the essential factors. The most popular classification scheme comprises DM, EMI, EMII, HIMU, focal zone and PREMA (Condie, 2011), and the EMI, EMII and HIMU are the main factors of the Dupal anomaly. The DM is mainly related to the N-MORB. The EMI enriches the Pb isotope with higher Rb/Sr ratio and lower Sm/Nd ratio, while the EMII with higher $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios may be related to the recycling of terrigenous sediment, continental crust, erosive MORB or OIB. The HIMU with high $^{238}U/^{204}Pb$ may come from the core–mantle boundary. There is no distinct difference in the PREMA and focal zone components. Meanwhile, the DM, EMI, EMII and HIMU are not quite prevalent because they only appear in limited areas (Zhu, 2007). The EMI and HIMU may be derived by filtration and residue (Hart, 1988) instead of an independent mantle source (Chauvel *et al*., 1992). And the high U isotope composition of HIMU comes from the core (Hart, 1988) or the recycling of ancient crust. Meanwhile, the superplume and hotspots may be the upwelling channel of the HIMU, and the crystallization differentiation in the process may lead EMI out of HIMU.

The Global Dupal anomaly can be classified into three categories by the different mantle reservoirs (Fig. 2). The Dupal anomaly in the Pacific (Fig. 2a and e) is related to HIMU and EMI, and EMII is the reason for the Dupal anomaly inside the island arc in the East Asian Continental Margin (Fig. 2d). Meanwhile, the mantle origin of the Dupal anomaly in the Indian Ocean and the Southern Atlantic (Fig.2b and c) seems to be a mixture of EMI and EMII.

The presence of a mantle plume in the SCS remains contentious, but the mantle origin involving a mixture of DM and EMII does have some agreement (Xu *et al*., 2012; Yan *et al*., 2008). Moreover, studies of the EMII indicate that its isotopic characteristics ($^{87}Sr/^{86}Sr > 0.71$, $^{143}Nd/^{144}Nd < 0.5120$ and $^{206}Pb/^{204}Pb = 18.5$–19.2) are quite similar to the upper crust or terrigenous sediments (Zindler and Hart, 1986). Furthermore, the location of the East Asian Continental Margin, where the most typical trench–arc–basin system is located, leads to the most violent recycling of oceanic crust and sediments.

Studies on the Dupal anomaly in the Indian Ocean and Southern Atlantic Ocean indicate that it may be related to a hotspot (Wen, 2006). The special location that is under the African superplume may explain the EMI mantle reservoir. Reconstruction of the Gondwana supercontinent shows that the African superplume may have remained fixed for a very long time and the Gondwana supercontinent is simply located on it (Torsvik and Cocks, 2013). Thus, the residual subcontinental mantle or continental crust arising from the breakup of Gondwana may be the reason for EMII.

Two massive low seismic velocity areas correspond to the Dupal anomalies in the Pacific Ocean and Indian Ocean (Castillo, 1988). The boundary of the two superplumes that may be the location of the hotspots seems to have remained stable since the last 200 Ma (Hassan *et al*., 2015), and it coincides with the boundary of the Dupal anomaly (Fig. 1). These hotspots can be the channel for EMI and HIMU from the superplumes to form the Dupal anomaly in the Pacific Ocean and Indian Ocean, respectively. The Dupal anomaly comes into being with the addition of the EMII from the recycling of subcontinental mantle and continental crust. In the back-arc basin, the EMII may be the only factor for the Dupal anomaly here.

The origin of the entire Dupal anomaly in the ancient ocean (Fig. 5) seems to be related to EMII, which may be because of the subduction and the contamination of the continental component. These basalts may have different sources of Dupal anomaly, while the mixture of the continental crust in the process causes EMII like.

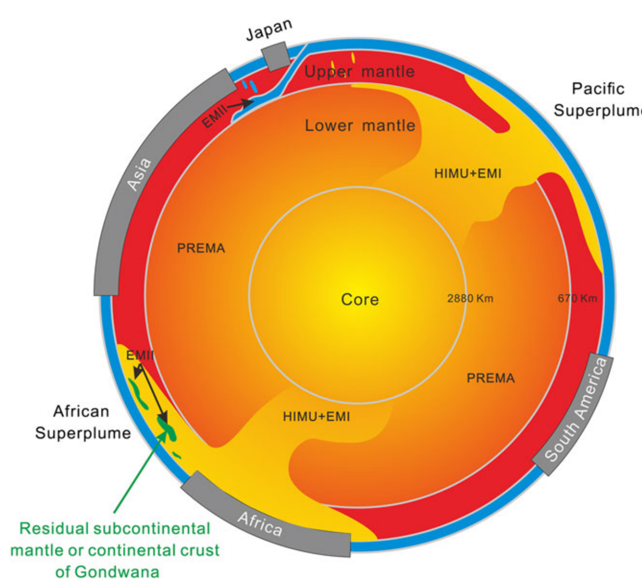

Figure 5. The formation of the EMI, EMII, HIMU which are related to the Dupal anomaly.

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5. CONCLUSIONS

The Dupal anomaly, which is mainly distributed in the subduction zones or hotspots with different genesis, can be classified into three types based on their different origins. The EMII reservoir results from the mixing of recycling crust, sediments and the continental mantle and is the source of the Dupal anomaly in the subduction zone. Meanwhile, the EMI is the other factor of the Dupal anomaly in the hotspots, and it is derived from the HIMU reservoir coming from the core–mantle boundary.

The Dupal anomaly in the Indian Ocean and Southern Atlantic Ocean is the mixing of EMI and EMII, and the recycling of subcontinental mantle or continental crust of Gondwana and the African superplume are the origins of EMII and EMI. Recycling of oceanic crust and sediments is the main reason for the EMII reservoir and the Dupal anomaly inside the East Asian Continental Margin. And the superplume under the Pacific is the origin of the EMI and HIMU.

Therefore, the presence of a superplume and the recycling of crust, sediments or continental mantle are the two main factors for the Dupal anomaly. They are the origin of the HIMU, EMI and EMII.

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REFERENCES

Castillo, P.R. 1988. The Dupal anomaly as a trace of the upwelling lower mantle. *Nature* **336**, 667–670.

Chauvel, C., **Albercht, W.**, **Hofmann, V. 1992**. HIMU-EM: the French Polynesian connection. *Earth and Planetary Science Letters* **110**, 99–119.

Chu, F.-Y., **Chen, J.-L.**, **Ma, W.-L.**, **Gao, S.-T.**, **Wu, G.-H. 2005**. Petrologic characteristics and ages of basalt in middle Pacific mountains. *Marine Geology & Quaternary Geology* **25**, 55–59.

Class, C., **Le Roex, A. 2011**. South Atlantic Dupal anomaly—dynamic and compositional evidence against a recent shallow origin. *Earth and Planetary Science Letters* **305**, 92–102.

Condie, K.C. 2011. *Earth As an Evolving Planetary System* second edn. **1–574**. Academic Press: The Netherlands.

Dong, Y.-P., **Zhou, M.-F.**, **Zhang, G.-W.**, **Zhou, D.-W.**, **Liu, L.**, **Zhang, Q. 2008**. The Grenvillian Songshugou ophiolite in the Qinling Mountains, Central China: implications for the tectonic evolution of the Qinling orogenic belt. *Journal of Asian Earth Sciences* **32**, 325–335.

Dupré, B., **Allègre, C.J. 1983**. Pb-Sr isotope variation in Indian Ocean basalts and mixing phenomena. *Nature* **303**, 142–146.

Escrig, S., **Capmas, F.**, **Dupré, B.**, **A, C.J. 2004**. Osmium isotopic constraints on the nature of the Dupal anomaly from Indian mid-ocean-ridge basalts. *Nature* **432**, 59–63.

Hanan, B.B., **Blichert-Toft, J.**, **Pyle, D.G.**, **Christie, D.M. 2004**. Contrasting origins of the upper mantle MORB source as revealed by Hf and Pb isotopes from the Australian-Antarctic discordance. *Nature* **432**, 91–94.

Hart, S.R. 1984. A large-scale isotope anomaly in the Southern Hemisphere mantle. *Nature* **309**, 753–757.

Hart, S.R. 1988. Heterogenous mantle domains: signature, genesis and mixing chronology. *Earth and Planetary Science Letters* **90**, 273–296.

Hassan, R., **Flament, N.**, **Gurnis, M.**, **Bower, D.J.**, **Müller, D. 2015**. Provenance of plumes in global convection models. *Geochemistry, Geophysics, Geosystems* **16**, 1465–1489.

Hou, Q.-Y., **Zhao, Z.-D.**, **Zhang, H.-F.**, **Chen, Y.-L. 2005**. Isotopic composition features and geological significance of the Indian MORB of the ophiolite from Yushigou, Northern Qilian. *Science in China Series D: Earth Sciences* **38**, 710–719. (in Chinese with English abstract)

Huang, D.-Z., **Gao, J.**, **Dai, T.-G.**, **Zou, H.-Y.**, **Xiong, X.-M.**, R, K. **2004**. The ancient west Tianshan subduction zone of deep fluid sources—evidence from Pb and Sr isotope of the high voltage pulse body and host rock from high pressure metamorphic belt. *Science in China Series D: Earth Sciences* **34**, 835–844. (in Chinese with English abstract)

Lai, S.-C., **Qin, J.-F.**, **Li, X.-J.**, **Zang, W.-J. 2010**. Geochemistry and Sr-Nd-Pb istopic features of the Ganlongtang-Nongba ophiolite from the Changning-Menglian suture zone. *Acta Petrologica Sinica* **26**, 3195–3205. (in Chinese with English abstract)

Lee, B., **Zhu, L.-M.**, **Gong, H.-J.**, **Guo, B.**, **Yang, T.**, **Wang, F.**, **Wang, W.**, **Xu, A. 2010**. Genetic relationship between peridotites and chromite deposit from Songshugou area of North Qinling. *Acta Petrologica Sinica* **26**, 1487–1502. (in Chinese with English abstract)

Lei, M., **Zhao, Z.-D.**, **Hou, Y.-Q.**, **Zhang, H.-F.**, **Xu, J.-F.**, **Chen, Y.-L.**, **Zhang, B.-R.**, **Liu, X.-J. 2008**. Geochemical and Sr-Nd-Pb isotopic characteristics of the Dalabute ophiolite, Xinjiang: comparison between the Paleo-Asian ocean and the Tethyan mantle domains. *Acta Petrologica Sinica* **24**, 661–672. (in Chinese with English abstract)

Li, C. 2013. Geochemical characteristics of basalt and research on co-rich crust formation in the Mid-Pacific CH Seamount. *Jilin University*, 1–42. (in Chinese with English abstract)

Li, W.-Y. 2008. Geochronology and geochemistry of the ophiolites and island-arc-type igneous rocks in the Western Qinling orogen and the Eastern Kunlun orogen: implication from the evolution of the Tethyan Ocean. *University of Science and Technology of China*, 1–154. (in Chinese with English abstract)

Li, Y., **Wu, T.-R.**, **Luo, H.-L.**, **Zhao, L. 2007**. Early Cretaceous lithospheric thinning of northern margin of the North China Craton : evidence from Pb isotope of Shoshonite. *Acta Scientiarum Naturalium Universitatis Pekinensis* **43**, 176–182.

Li, Z.X., **Bogdanova, S.V.**, **Collins, A.S.**, **Davidson, A.**, **De Waele, B.**, **Ernst, R.E.**, **Fitzsimons, I.C.W.**, **Fuck, R.A.**, **Gladkochub, D.P.**, **Jacobs, J.**, **Karlstrom, K.E.**, **Lu, S.**, **Natapov, L.M.**, **Pease, V.**, **Pisarevsky, S.A.**, **Thrane, K.**, **Vernikovsky, V. 2008**. Assembly, configuration, and break-up history of Rodinia: a synthesis. *Precambrian Research* **160**, 179–210.

Liu, F., **Yang, J.-S.**, **Chen, N.-S.**, **Li, Z.-L.**, **Lian, D.-Y.**, **Zhou, W.-D.**, **Zhang, L. 2013**. Geochemistry and Sr-Nd-Pb isotopic composition of mafic rocks in the western part of Yarlung Zangbo suture zone Evidence for intra-oceanic supra-subduction within the Neo-Tethys. *Geology in China*, **742–755**. (in Chinese with English abstract)

Liu, F., **Yang, J.-S.**, **Chen, N.-S.**, **Liang, F.-H.**, **Niu, X.-L.**, **Li, Z.-L.**, **Lian, D.-Y. 2013**. Ascertainment and environment of the OIB-type basalts from the Dongbo ophiolite in the western part of Yarlung Zangbo Suture Zone. *Acta Petrologica Sinica* **29**, 1901–1932. (in Chinese with English abstract)

McKenzie, D., **O'Nions, R.K. 1983**. Mantle reservoirs and ocean island basalts. *Nature* **301**, 229–231.

Mukasa, S.B., **McCabe, R.**, **Gill, J.B. 1987**. Pb-isotopic compositions of volcanic rocks in the West and East Philippine island arcs: presence of the Dupal isotopic anomaly. *Earth and Planetary Science Letters* **84**, 153–164.

Nishio, Y., **Nakai, S.i.**, **Ishii, T.**, **Sano, Y. 2007**. Isotope systematics of Li, Sr, Nd, and volatiles in Indian Ocean MORBs of the Rodrigues Triple Junction: constraints on the origin of the Dupal anomaly. *Geochimica et Cosmochimica Acta* **71**, 745–759.

Peng, Z., **Geng, Q.**, **Pan, G.**, **Wang, L.**, **Zhang, Z.**, **Cong, F.**, **Guan, J. 2013**. Zircon SHRIMP geochronology and Nd-Pb isotopic characteristics of the meta-basalt in the central part of Tibetan Plateau's Qiangtang region. *Science China Earth Sciences* **57**, 428–438. (in Chinese with English abstract)

Regelous, M., **Niu, Y.**, **Abouchami, W.**, **Castillo, P.R. 2009**. Shallow origin for South Atlantic Dupal anomaly from lower continental crust: geochemical evidence from the mid-Atlantic Ridge at 26°S. *Lithos* **112**, 57–72.

Rehkamper, M., **Hofmann, A.W. 1997**. Recycled ocean crust and sediment in Indian Ocean MORB. *Earth and Planetary Science Letters* **147**, 93–106.

Roex, L., **Dick, A.P.**, **Fisher, H.J.B. 1989**. Petrology and geochemistry of MORB from 25°E to 46°E along the southwest Indian Ridge: evidence for contrasting styles of mantle enrichment. *Journal of Petrology* **30**, 947–986.

Tan, X.-J. 2010. The studies of isotopic geochemistry of basalt from Lamont Guyot in the Western Pacific. *Ocean University of China*, 1–55. (in Chinese with English abstract)

Tatsumoto, M. 1991. Dupal anomaly in the Sea of Japan: a plate recycling model for OIB sources. *Mantle Plume Symposium in USA* 2–4.

Tatsumoto, M., **Nakamura, Y. 1991**. Dupal anomaly in the Sea of Japan: Pb, Nd, and Sr isotopic variations at the eastern Eurasian continental margin. *Geochimica et Cosmochimica Acta* **55**, 3697–3708.

Torsvik, T.H., **Cocks, L.R.M. 2013**. Gondwana from top to base in space and time. *Gondwana Research* **24**, 999–1030.

Wang, Y.-J., **Han, X.-Q.**, **Luo, Z.-H.**, **Qiu, Z.-Y.**, **Ding, W.-W.**, **Li, J.-B.**, **Gao, S.-T.**, **Chen, R.-H. 2009**. Late Miocene magmatism and evolution of Zhenbei-Huangyan Seamount in the South China Sea: evidence from petrochemistry and chronology. *Acta Oceanologica Sinica* **31**, 93–102.

Wang, Y.-X., **Gu, L.-X.**, **Zhang, Z.-Z.**, **Wu, Z.-C.**, **Zhang, K.-J.**, **Li, H.-M.**, **Yang, J.-D. 2006**. Geochronology and Nd-Sr-Pb isotopes of the bimodal volcanic rocks of the Bogda rift. *Acta Petrologica Sinica* **22**, 1215–1224. (in Chinese with English abstract)

Wei, Q.-R., **Shen, S.-Y.**, **Mo, X.-X.**, **Lu, F.-X. 2003**. Recognition and significance of Dupal isotope anomaly in the middle part of Sanjiang Area. *Geology-Geochemistry* **31**, 36–41.

Weis, D., **Bassias, Y.**, **Gautier, I.**, **Mennessier, J.-P. 1989**. Dupal anomaly in existence 115 Ma ago: evidence from isotopic study of the Kerguelen Plateau (South Indian Ocean). *Geochimica et Cosmochimica Acta* **53**, 2125–2131.

Wen, L. 2006. Mantle thermo-chemical plumes, the Dupal anomaly and a compositional anomaly at the Earth's core–mantle boundary. *Geochimica et Cosmochimica Acta* **70**, A696.

Wessel, P., **Smith, W.H.F. 1998**. New, improved version of generic mapping tools released. *Eos Transactions AGU* **79**, 579.

Wu, J.-H., **Xiang, Y.-X.**, **Zhong, Z.-F. 2014**. SHRIMP zircon U-Pb dating and Sr-Nd-Pb-O isotope characteristics of shoshinite from Guangfeng and Yushan basins in Jiangxi Province. *Acta Petrologica et Mineralogica* **33**, 645–656.

Xu, J.-F., **Zhang, B.-R.**, **Han, Y.-W. 1996**. The founding and the significance of the Proterozoic basement in North Qinling with high radioactive isotopic composition. *Chinese Science Bulletin* **41**, 1771–1774. (in Chinese with English abstract)

Xu, Y.-G., **Wei, J.-X.**, **Qiu, H.-N.**, **Zhang, H.-H.**, **Huang, X.-L. 2012**. Opening and evolution of the South China Sea constrained by studies on volcanic rocks: preliminary results and a research design. *Chinese Science Bulletin* **57**, 3150–3164. (in Chinese with English abstract)

Yan, Q.-S., **Shi, X.-F.**, **Wang, K.-S.**, **Bo, W.-R.**, **Xiao, L. 2008**. Research about the main major elements, trace elements and Sr, Nd–Pb isotope of the Cenozoic alkaline basalt from South China Sea. *Science in China Series D: Earth Sciences* **38**, 56–71. (in Chinese with English abstract)

Yan, Q., **Castillo, P.**, **Shi, X.**, **Wang, L.**, **Liao, L.**, **Ren, J. 2015**. Geochemistry and petrogenesis of volcanic rocks from Daimao Seamount (South China Sea) and their tectonic implications. *Lithos* **218–219**, 117–126.

Yang, S.-Y., **Fang, N.-J.**, **Yang, S.-X.**, **Yao, B.-C.**, **Liang, D.-H. 2011**. A further discussion on formation background and tectonic constraints of igneous rocks in central sub-basin of the South China Sea. *Earth Science-Journal of China University of Geoscience* **36**, 455–469. (in Chinese with English abstract)

Zhang, Q., **Zhou, D.-J.**, **Li, X.-Y.**, **Chen, Y.**, **Huang, Z.-X.**, **Han, S.**, **Jia, X.-Q.**, **Dong, J.-Q. 1995**. Characteristics and genesis of Shuanggou Ophiolites, Yunnan Province, China. *Acta Petrologica Sinica* **11**, 190–202. (in Chinese with English abstract)

Zhang, W.-H., **Han, F.-B.**, **Du, W.**, **Liu, Z.-Q. 2005**. Characteristics of mantle source from Jining Cenozoic basalts from southern Inner Mongolia: evidence from element and Sr-Nd-Pb isotopic geochemistry. *Acta Petrologica Sinica* **21**, 1569–1582. (in Chinese with English abstract)

Zhang, Z., **Li, S.-Z.**, **Cao, H.-H.**, **Somerville, I.D.**, **Zhao, S.-J.**, **Yu, S. 2015**. Origin of the North Qinling microcontinent and Proterozoic geotectonic evolution of the Kuanping Ocean, Central China. *Precambrian Research* **266**, 179–193.

Zhou, D.-J., **Shen, L.-P.**, **Zhang, Q.**, **Xu, R.-H.**, **Zhou, Y.-S.**, **Qiao, G.-S. 1995**. The Dupal anomaly of basalts in Paleo-Tethyan Belts, Western Yunnan. *Progress in Geophysics* **10**, 39–44.

Zhou, D.-W., **Zhang, Z.-J.**, **Dong, Y.-P.**, **Liu, L. 1995**. Geological and geochemical characteristics on Proterozoic Songshugou Ophiolite piece from Shangnan Country, Qinling. *Acta Petrologica Sinica* **11**, 154–164. (in Chinese with English abstract)

Zhou, X.-H., **Zhang, G.-H.**, **Yang, J.-H.**, **Chen, W.-J.**, **Sun, M. 2001**. Sr-Nd-Pb isotope mapping of Late Mesozoic volcanic rocks across northern margin of North China Craton and implication to geodynamic processes. *Geochimica* **30**, 10–23.

Zhu, B. 2007. Pb-Sr-Nd isotopic systematics of mantle-derived rocks in the world. *Earth Science Frontiers* **14**, 24–36. (in Chinese with English abstract)

Zhu, D.-C., **Pan, G.-T.**, **Mo, X.-X.**, **Wang, L.-Q.**, **Zhao, Z.-D.**, **Liao, Z.-L.**, **Geng, Q.-R.**, **Dong, G.-C. 2006**. Identification for the Mesozoic OIB-type basalts in Central Qinghai-Tibetan Plateau: geochronology, geochemistry and their tectonic setting. *Acta Geologica Sinica* **80**, 1312–1328. (in Chinese with English abstract)

Zindler, A., **Hart, S.R. 1986**. Chemical geodynamics. *Annual Review of Earth and Planetary Sciences* **14**, 493–571.

Zou, H.-P. 1993. On the problem about the crust's attribution of South China Sea Basin—discussion from comparative study on basalts of seamounts in South China Sea Basin and the neighboring areas. *Geotectonica et Metallogenia* **17**, 293–303.

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