Acta Oceanol. Sin., 2019, Vol. 38, No. 12, P. 35–42
https://doi.org/10.1007/s13131-019-1363-0
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

Implications of the melting depth and temperature of the Atlantic mid-ocean ridge basalts

Yili Guan[1, 2, 3], Xuefa Shi[1, 2*], Quanshu Yan[1, 2], Xun Wei[1, 2], Yan Zhang[1, 2], Xiaoping Xia[3], Haoda Zhou[4]

[1] Key Laboratory of Marine Sedimentology and Environmental Geology, First Institute of Oceanography, Ministry of Natural Resources, Qingdao 266061, China

[2] Laboratory for Marine Geology, Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao 266061, China

[3] State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

[4] Zhuhai Central Station of Marine Environmental Monitoring, State Oceanic Administration, Zhuhai 519015, China

Received 8 July 2018; accepted 29 October 2018

Abstract

Mid-ocean ridge basalts (MORBs) are characterized by large variations in trace element compositions and isotopic ratios, which are difficult to be interpreted solely by using magmatic process such as partial melting of a peridotitic mantle and subsequently fractional crystallization. Geochemical diversity of MORBs have been attributed to large-scale heterogeneity within the underlying mantle, and the heterogeneity might have been caused by addition of recycled crustal component, subcontinental lithosphere, metasomatized lithosphere and outer core contribution. In this study, we investigated the MORBs along the Mid-Atlantic Ridge (MAR) by estimating the temperature and pressure of partial melting, and comprehensively comparing trace element and isotope ratios. The data for MORBs from areas close to mantle plumes show large variations. Mantle plumes can affect mid-oceanic ridges 1 400 km away, but plume effects did not cover all of the ridge segments, and those segments without plume effects did not have any abnormalities in temperature, trace element or isotope ratios. We ascribed the above phenomena to result from the shapes of the plume flow, which we categorized as “pipe-like channels” and “pancake-like channels”. The “pancake-like channels” plumes affected the ambient mantle nondirectionally, but the range of the mantle affected by the “pipe-like channels” plumes were selective. Element ratios of MORBs reveal that the mantle source of the MORBs along the MAR is highly heterogeneous. We suggest that most of source heterogeneities of the MORBs may be due to the presence of subducted slab and delaminated lower crust in the source. In addition, the plume that carried materials from the core-mantle boundary may affect some of the segments.

Key words: Mid-Atlantic Ridge, MORB, mantle heterogeneity, plume-ridge interaction

Citation: Guan Yili, Shi Xuefa, Yan Quanshu, Wei Xun, Zhang Yan, Xia Xiaoping, Zhou Haoda. 2019. Implications of the melting depth and temperature of the Atlantic mid-ocean ridge basalts. Acta Oceanologica Sinica, 38(12): 35–42, doi: 10.1007/s13131-019-1363-0

1 Introduction

Numerous geochemical studies on mantle rocks and oceanic basalts have shown that the mantle source beneath the Mid-Atlantic Ridge (MAR) is heterogeneous, which suggests the presence of both enriched and depleted components in the Earth’s mantle (White and Schilling, 1978; Bougault and Treuil, 1980; Schilling, 1985; Fontignie and Schilling, 1996; Le Roux et al., 2002; Hofmann, 2003; Agranier et al., 2005; Class and le Roex, 2011; Hoernle et al., 2011). The isotopic variability in oceanic basalts indicates that most mantle sources consist of complex assemblages of two or more components with long-term isolated chemical evolution (van Keken et al., 2002; Stracke, 2012). It has been proposed that the source of some mid-ocean ridge basalts (MORBs) possibly contains a recycled crustal component (Dixon et al., 2002; Sobolev et al., 2007), subcontinental lithosphere (Dosso et al., 1999; Escrig et al., 2005), metasomatized lithosphere (Pilet et al., 2008), and outer core contribution (Burke, 2011; Kelley et al., 2013). A few trace element ratios (cerium/lead [Ce/Pb], niobium/tantalum [Nb/Ta], and niobium/uranium [Nb/U]) in MORBs remain constant over a variable degree of partial melting of mantle sources with variable isotopic compositions. These ratios are termed “canonical”, and their constancy is interpreted to be the result of similar bulk partition coefficients of trace elements during upper mantle melting (Workman and

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Foundation item: The Basic Scientific Fund for National Public Research Institutes of China under contract No. 2015G07; the National Programme on Global Change and Air-Sea Interaction under contract Nos GASI-GEOGE-02; the National Natural Science Foundation of China under contract Nos 41506079, 41576052, 41506068, 41322036 and 41776070; the AoShan Talents Program Supported by Qingdao National Laboratory for Marine Science and Technology under contract No. 2015ASTP-ES16; the Taishan Scholarship from Shandong Province; the Research Grant of State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences under contract No. SKLIG-KF-14-03; the China Postdoctoral Science Foundation under contract No. 2016M592120.

*Corresponding author, E-mail: xfshi@fio.org.cn

Hart, 2005 and references therein). Therefore, these ratios in the melts are presumed to be identical to those in the source.

Migrating plume-ridge interaction is a common phenomenon. Such interactions results in elevated mantle temperatures beneath ridges, which lead to increased melt production, shallower bathymetry, and thicker oceanic crust, to unique geochemical signatures in ridge lavas that are reflective of compositional variations in the mantle source (Kelley et al., 2013). The plume-ridge interaction can account for physical and chemical anomalies along 15%–20% of the global mid-ocean ridge system (Ito et al., 2003). The geochemical signatures of MORBs, together with seismic tomographic data, have shown that upper-mantle temperatures are elevated at significant distances (<1 400 km) away from plume–ridge interactions, indicating a far-field, indirect influence of plume–ridge interactions on the upper-mantle structure (Whittaker et al., 2015; Yang et al., 2017). Temperature variations of MORBs may be affected by different types of mantle plumes (Dalton et al., 2014). Therefore, a simple and universal relationship does not exist between plume–ridge interaction segments and abnormal geochemical signature segments (Gale et al., 2013).

In this study, we used the data of MORBs collected by Gale et al. (2013) to calculate the temperature and pressure of MORBs and to discuss the source characteristics of MORBs beneath the MAR and the range of plume-ridge interactions. Our results shed light on the characteristics and evolution of the MAR. The sampling locations of the selected data are shown in Fig. 1.

2 Selection of the MORB data

Primary magmas that have not experienced fractional crystallization are ideal for our study, but they are rare. Therefore, we focuse on the less evolved MORBs (>8 wt% magnesium oxide [MgO]) because these basalts likely have the simplest crystallization histories. All of the MORBs data along the MAR used in this study are from the compilation of Gale et al. (2013). A total of 546 data were selected for this study.

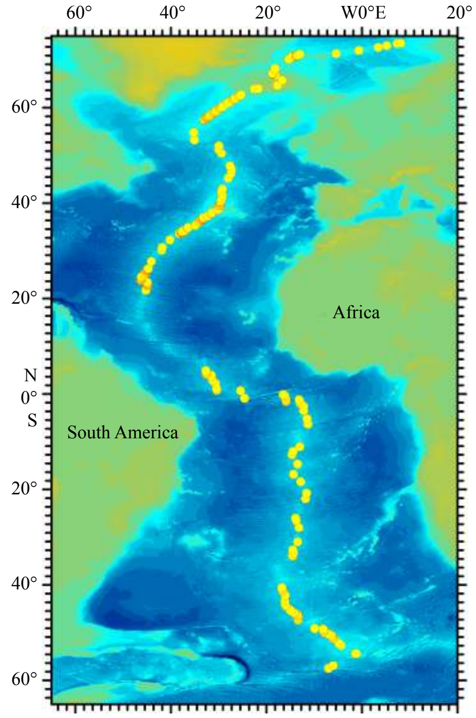

Fig. 1. Regional map showing the locations of samples. The data are reported in the paper of Gale et al. (2013).

3 Characteristics of the MORB source

3.1 *Melting depth and temperature*

Knowledge of temperature and pressure inferred from compositions of basaltic lavas is important to understand magmatic evolution. Many methods can be used to calculate the temperature and pressure of magma, including mineral composition and whole-rock chemical composition geothermobarometers, for example, two-pyroxene thermometers and barometers (Brey and Köhler, 1990), plagioclase thermometers and barometers (Putirka, 2005), clinopyroxene thermobarometry (Putirka et al., 1996, 2003), olivine thermometers (Putirka, 2005; Putirka et al., 2007), Na/Ti ratio barometer (Putirka, 1999), and silica activity barometer (Albarede, 1992). Compared with the thermobarometry of whole-rock chemical compositions, the results calculated by mineral compositions might be closer to the value of the melting condition. The average pressure and temperature of melt extracting from the mantle can be determined by estimating the average degree of partial melting. Lee et al. (2009) recently used the major elements of whole rocks to calculate the pressure and temperature of melt, and the uncertainties of the results were comparable to those reported by other geothermobarometers. Therefore, because of insufficient mineralogy, our study of the temperature and pressure of MORBs from the MAR was mainly based on the method of Lee et al. (2009). The equations are as follows:

$$T = 1\,189.6 + 13.68p(\mathrm{Mg_4Si_2O_8}) + \frac{4\,580}{p(\mathrm{Si_4O_8})} - 0.509p(\mathrm{Si_{16}O_8})\,p(\mathrm{Mg_4Si_2O_8})\,, \tag{1}$$

$$P = \frac{\ln p(\mathrm{Si_4O_8}) - 4.019 + 0.016\,5p(\mathrm{Fe_4Si_2O_8}) + 0.000\,5p(\mathrm{Ca_4Si_2O_8})^2}{-770T^{-1} + 0.005\,8T^{\frac{1}{2}} - 0.003p(\mathrm{H_{16}O_8})}, \tag{2}$$

where $p(\mathrm{Mg_4Si_2O_8})$, $p(\mathrm{Si_4O_8})$, $p(\mathrm{Fe_4Si_2O_8})$, $p(\mathrm{Ca_4Si_2O_8})$ and $p(\mathrm{H_{16}O_8})$ are the mole percentage of those species in the liquid, P is in GPa, and T is temperature in Kelvin (K). For more details, the reader is referred to the paper by Lee et al. (2009).

Our calculated results show that the pressure and temperature of melt vary greatly. The melting pressure of MORBs from MAR ranges from 0.55 GPa to 3.33 GPa, and the temperature ranges from 1 300°C to 1 563°C (Fig. 2). Figure 2 shows that pressure and temperature have a good corresponding relationship and the positions of relatively high values are on or close to the mantle plumes.

3.2 *Characteristics of the strontium-neodymium-hafnium isotopes*

The strontium-neodymium-hafnium (Sr-Nd-Hf) isotopic compositions of MORBs from MAR between 80°N and 60°S have a large range. Most peaks of the isotopic data coincide with the area affected by the mantle plume (Fig. 3). The most pronounced peak occurred at 48°–52°S between Discovery/LOMU and Shona plumes where $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ has the maximum value (0.705 878), and $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$ and $^{176}\mathrm{Hf}/^{177}\mathrm{Hf}$ have the minimum values (0.512 365 and 0.282 694, respectively). Unlike Sr-Nd isotopes, the $^{176}\mathrm{Hf}/^{177}\mathrm{Hf}$ value decreased from north to south along the MAR (Fig. 3).

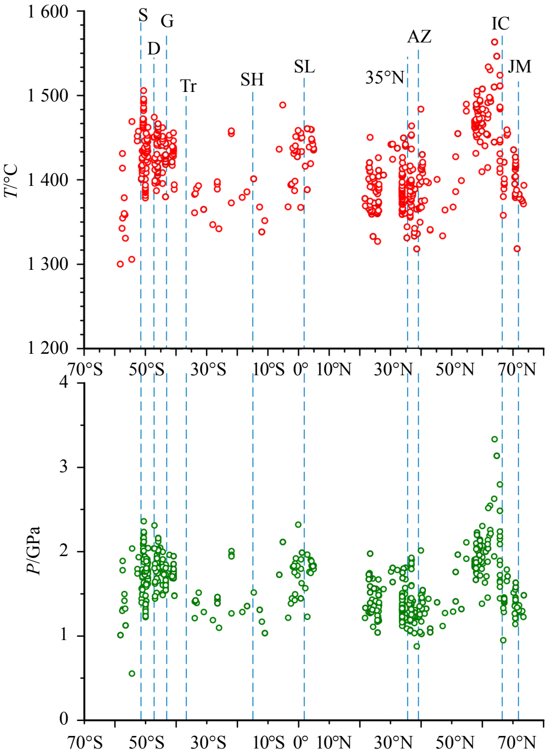

Fig. 2. Latitudinal variations in temperature (°C) and pressure (GPa) of origin of MORBs from MAR. The plumes influencing the MAR are Jan Mayen (JM), Iceland (Ic), Azores (Az), 35°N anomaly (35°N), Sierra Leone (SL), St. Helena (SH), Tristan (Tr), Gough (G), Discovery/LOMU (D) and Shona (S) (Andres et al., 2004). All of the data are from the compilation by Gale et al. (2013). The results of temperature and pressure are calculated by the method established by Lee et al. (2009).

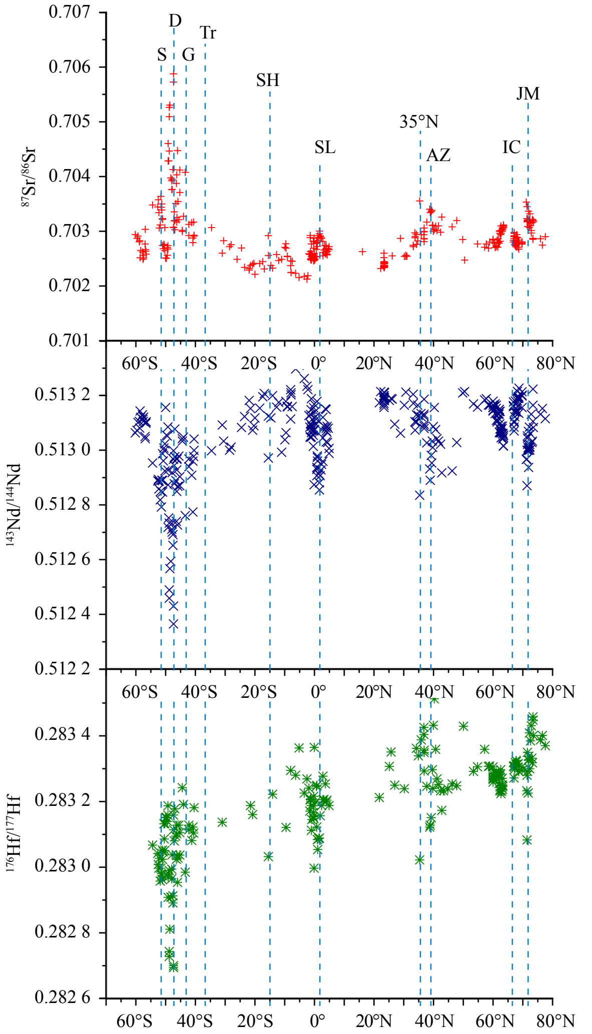

Fig. 3. Latitudinal variations in $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ isotopic ratios of MORB from MAR.

4 Implications for mantle source and magmatic evolution

4.1 *Effect of mantle plume on the MORB mantle source*

Plume-ridge interaction has long been noticed by researchers (Morgan, 1972; Schilling, 1973; Schilling et al., 1985; Ribe, 1996; Ito et al., 2003; Mittelstaedt et al., 2011; Whittaker et al., 2015), because it represents the two dominant modes (plates tectonics and plumes) of mantle transport and thermal–chemical fluxing between the Earth's deep interior and the surface. According to the relative position between mid-ocean ridges and mantle plumes, these interactions can be divided into: (1) "ridge-centered" plumes rising directly beneath a ridge (Ribe et al., 1995; Kempton et al., 2000), and (2) "off-ridge" plumes ascending at some distance from a ridge (Kincaid et al., 1996; Ribe, 1996). Asymmetric seafloor spreading may be associated with the "off-ridge" plumes (Müller et al., 1998). Since the depths at which the plumes originate (on- and off-ridges) are diverse (Courtillot et al., 2003; Montelli et al., 2006; Ito and van Keken, 2007), these plumes have different thermal conditions and compositions. Geophysical and geochemical observations have indicated that ascending mantle plumes can interact with ocean ridges located up to 1 400 km away (Ribe, 1996).

Many plumes are located on and off the MAR (Ito and van Keken, 2007) and will increase the temperature of ambient mantle (Dalton et al., 2014). Plume–ridge interactions thus cause many of the largest structural and chemical anomalies (Schilling et al., 1985; Ito et al., 2003). We, however, do not identify any temperature anomalies associated with some of the plumes including Tristan (Tr) and St. Helena (SH) (Fig. 2). The low-temperature zone identified between 7°S and 40°S along the MAR also has been observed by other researchers (2°S to 30°S along the MAR) (Dalton et al., 2014). The low melting temperatures of MORBs near these plumes might be controlled by a variety of factors.

Plumes can flow along and toward ridges in pipe-like channels or pancake-like channels (Fig. 4). The plumes on the ridge (e.g., Iceland) will affect the temperature of the MORB regardless of the channel flowing characteristics. A variety of geophysical and geochemical evidence has indicated that ascending mantle plumes can interact with ocean ridges located up to 1 400 km away (Ribe, 1996). Therefore, off-ridge plumes can still affect the compositions of MORBs on the ridge. If, however, the off-ridge plumes flow along and toward ridges in pipe-like channels, the range of influence of the plumes becomes limited. The direction of the channel is another important consideration. If the direction of channel flow is parallel to the ridge or deviates from the ridge, the plume-ridge interaction will be insignificant. In addition, if the melting source is enriched in volatile elements, it will decrease the melting temperature of the MORB source, and the expression of the plume effect will be weakened. The volatile ele-

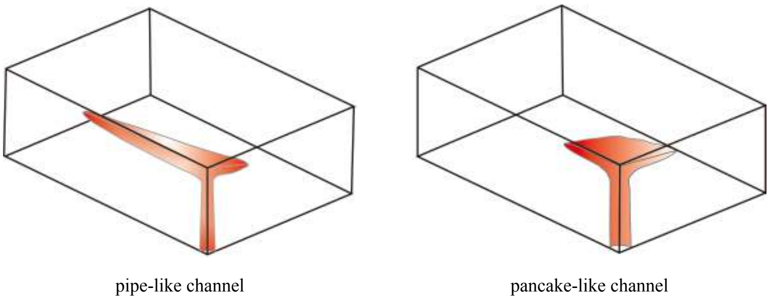

Fig. 4. Cartoon for the shapes of the plume-ridge interaction (modified from Ito et al. (2003)).

ments and corresponding incompatible elements reflect the nature of the source characteristics.

MORBs near JM have high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ with high water contents (~0.1%–0.2%) (Haase et al., 1996, 2003). The "wet" mantle lowers the solidus temperature although the JM plume increases its temperature. Thus, it is difficult to characterize the plume channel type. MORBs near the Tr and Sh plumes, however, have low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ values, which are identical to the depleted mantle. The Tr and Sh plumes have pipe-like channels that are parallel to the ridge or deviate from MAR. Therefore, the plumes do not increase the temperature of the adjacent MORB.

MORBs near Iceland have high potential temperatures (Fig. 2), and the highest temperature is ~1 550°C, which is lower than that (1 637°C) of the Iceland plume (Putirka, 2005). The oceanic crust is sensitive to small temperature fluctuations that change the thickness of newly formed crust by kilometers. Within the region influenced by this plume, the average thickness of the oceanic crust increases from 7 to 14 km (White, 1997; Parnell-Turner et al., 2014). The Reykjanes Ridge crosses the Icelandic plume and has a hot convective upwelling with a radius of at least 1 200 km (Parnell-Turner et al., 2014), which is consistent with estimates by Dalton et al. (2014). Therefore, we suggest the relationship between Iceland and its surrounding ridges to be a pancake-like channel.

Another high temperature region is located at the South Altantic Ridge between 40°S and 52°S (Fig. 2). A mantle plume group (Gough, Discovery/LOMU and Shona) is located near this area, and the root of the plume group is a low shear-wave velocity province located in the lowermost mantle beneath Africa (termed Tuzo) (Courtillot et al., 2003; Torsvik et al., 2014). The Tuzo is also called a superplume (Schubert et al., 2004; Simmons et al., 2007), and the mantle above the superplume has a high geothermal gradient. The mantle plumes (Gough, Discovery/LOMU and Shona) are located at a considerable distance from each other, but the potential temperature of MORBs between 40°S and 52°S are higher than that at the nearby ridges. This finding is consistent with the results of geophysical data (Konter and Becker, 2012). Therefore, we suggest the relationship between the mantle plume group (Gough, Discovery/LOMU and Shona) and the surrounding ridges also to be a pancake-like channel.

4.2 *Characteristics of the melting sources*

Numerous isotope and trace element studies of MORBs show that the Earth's mantle is heterogeneous (Schilling, 1985; Zindler and Hart, 1986; Hofmann, 1997; Schiano et al., 1997; Stracke and Bourdon, 2009). The isotopic variability in oceanic basalts indicates that most mantle sources consist of complex assemblages of two or more components with a long-term isolated chemical evolution on both global and local scales (Hofmann, 1997; Hart et al., 2008; Paulick et al., 2010). The ranges in isotope and canonical trace element ratios, including zircon/hafnium Zr/Hf, Ce/Pb and Nb/Ta have been used to characterize mantle sources (Hofmann et al., 1986; Salters and Stracke, 2004; Workman and Hart, 2005; Stracke and Bourdon, 2009; Arevalo and McDonough, 2010). Therefore, we use the isotope and canonical trace element ratios to constrain the mantle characteristics (the source of the MORBs) beneath the MAR.

(1) Zinc/iron and vanadium/scandium ratios

Zinc/iron (Zn/Fe) ratios of MORBs at the MAR are between 4.6 and 16.0, and vanadium/scandium (V/Sc) ratios are between 1.0 and 9.7 (Fig. 5). They are identical to primitive arc magmas, and these ratios are consistent with other researches (e.g., Lee et al., 2005, 2010; Le Roux et al., 2010). Zn/Fe and V/Sc ratios are sensitive to the barometric fO_2 and mineral association (e.g., garnet and clinopyroxene as the residue in the source increased the Zn/Fe and V/Sc ratios of melt). These ratios are also similar between MORBs and primitive arc magmas, suggesting that their sources have similar barometric fO_2 values and garnet and clinopyroxene contents (Lee et al., 2010). Previous researchers have suggested that subduction of oxidized crustal materials may not significantly alter the redox state of the mantle wedge (Le Roux et al., 2010). Therefore, Zn/Fe and V/Sc ratios of the oceanic slab will not change after subduction. It is difficult to determine whether the sources of MORBs have subducted slab materials. Some Zn/Fe and V/Sc ratios are higher than average ratios (10.60 and 6.66, respectively), which could be explained by the fact, that the garnet or clinopyroxene (or both) exist in the residue at the source regions (Lee et al., 2005; Le Roux et al., 2010). Some ratios however, are much lower than the average (e.g., 35°N; Fig. 5). This cannot be explained by the contribution of the subducted slab to the MORB source. Pyroxenites (including eclogites) from the Dabie and Sulu orogeny in China have Zn/Fe ratios of 3–11 (Le Roux et al., 2010). The intraplate lavas appear to have varied larger variation in V/Sc ratios, including values (>9), higher than those seen in MORBs (average value is 6.7) (Lee et al., 2005). Therefore, the residue after melting in the source of intraplate lavas should have low V/Sc ratios. This is the case, and continental crust is characterized by lower V/Sc ratios of 4–6 (Rudnick and Fountain, 1995). Therefore, we propose that the lower Zn/Fe and V/Sc ratios of MORBs could indicate that the continental materials were introduced into the MORB source. This view is consistent with results of studies in other area (Dosso et al., 1999).

(2) Ce/Pb ratios

The average Ce/Pb ratio of global MORBs is 22.2, which is inferred to represent the composition of the DMM (Arevalo and McDonough, 2010). The Ce/Pb ratios at 35°N, 42°–52°S, and

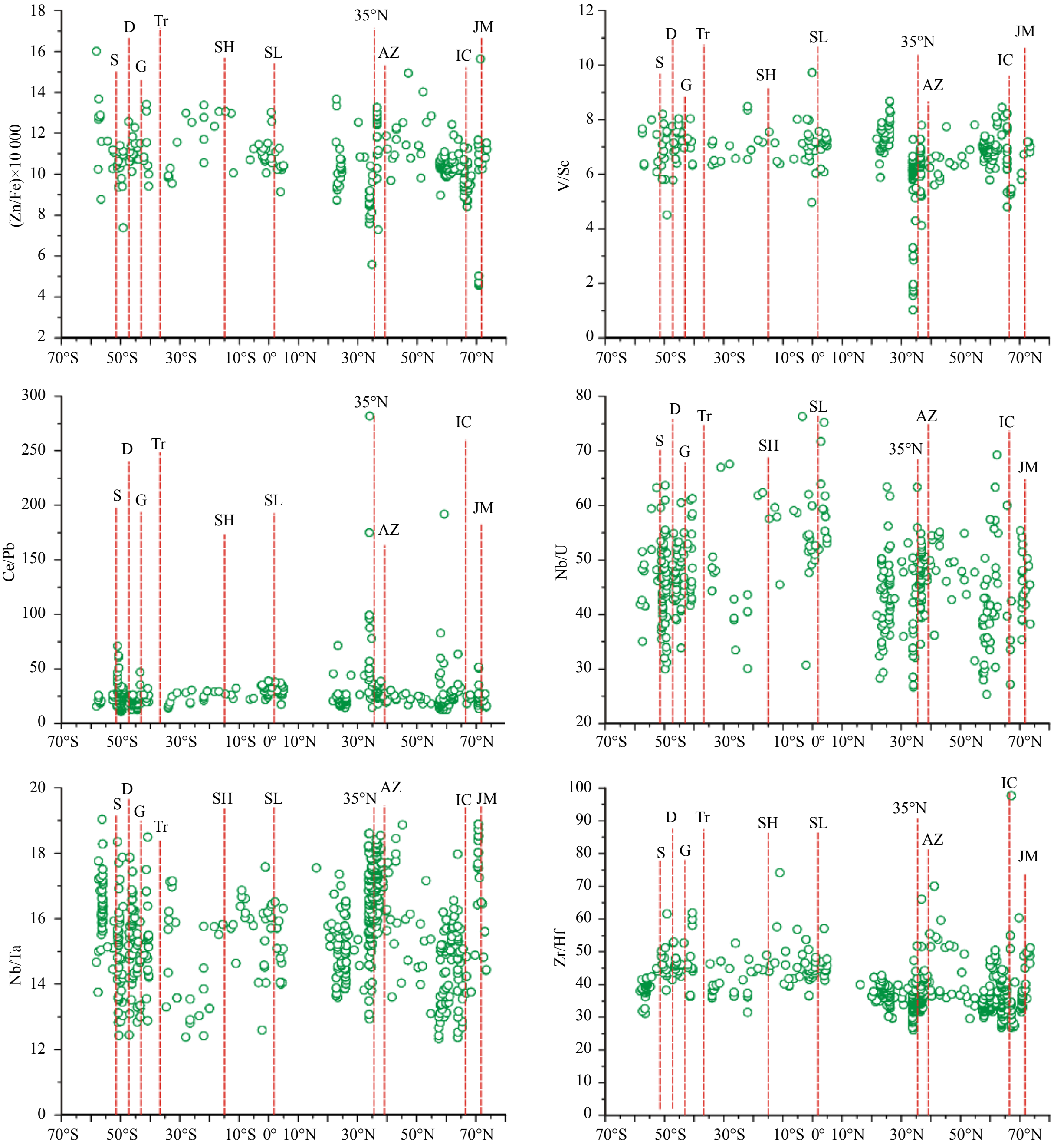

Fig. 5. Latitudinal variations in (Zn/Fe)×10 000, V/Sc, Ce/Pb, Nb/U, Nb/Ta and Zr/Hf ratios of MORBs from MAR.

58°–72°N along the MAR are abnormally high up to 300 (not shown in the plots). The Ce/Pb ratios of the average continental crust and the bulk earth are ~3 and ~10, respectively (Brenan et al., 1995). Therefore, we propose that, a reservoir with a high Ce/Pb ratio is located beneath the abnormal areas.

Pb is preferentially partitioned into the continents, which indicates that (1) Pb behaves as a highly incompatible element during continent formation; and (2) Pb is carried from the subducted oceanic crust and marine sediments to the source of continent-building magmas by fluids before melting (Miller et al., 1994). Therefore, the oceanic crust that subducted into an upper mantle at convergent margins has lower Pb content and a higher Ce/Pb ratio (Brenan et al., 1995). Partial melting of the lower continental crust and the lithospheric mantle, when they delaminated into the asthenospheric mantle, decreases the Pb content of the residue (Lustrino, 2005). Therefore, the residue of the lower continental crust and lithospheric mantle, which delaminated into the asthenospheric mantle, should also have a high Ce/Pb ratio. We consider that the mantle heterogeneity in the three areas indicates the presence of some residual continental material and subducted oceanic crust (Haase et al., 1996; Dosso et al., 1999; Le Roux et al., 2002; Escrig et al., 2005). Therefore, we suggest that a high Ce/Pb ratio of MORBs along MAR is constrained by recycled material, including subducted oceanic crust and delaminated subcontinental lithosphere.

(3) Nb/U

Log (U) versus log (Nb) of MORB pillow-rim glass collected from the Pacific, Atlantic and Indian Oceans shows that the slope is 0.954, close to 1 (Sun et al., 2008). Nb and U are almost not fractionated from each other during partial melting (Willbold and Stracke, 2006). Therefore, the Nb/U ratios of the MORBs should represent those of the mantle source region.

Unlike Ce/Pb ratios with significant variation, the Nb/U ratios of MORBs along the MAR mostly have a restricted range between 30 and 60, which is consistent with the average value (~47) of all MORBs (Gale et al., 2013). Pb-U should have fractionated in the subduction zone, and Pb is preferentially partitioned into the arc relative to U during the subduction of the oceanic crust subducted into the mantle (Kelley et al., 2005). Some 54%–98% of Pb and 25%–50% U will lose from the subducted oceanic crust (Kelley et al., 2005). The subducted residual oceanic crust will melt with the ambient mantle during they rise following the mantle convection. The melt can record signals of residual oceanic crust. Consequently, it can be expected that Ce/Pb ratios of MORBs will experience a more significant change than Nb/U ratios (Fig. 5).

(4) Zr/Hf and Nb/Ta ratios

The Zr/Hf and Nb/Ta ratios displayed large variations (Fig. 5). Previous studies have shown for natural samples that Zr/Hf ratios in mafic melts could be modified by clinopyroxene crystallization (Pfänder et al., 2007). No correlation exists, however, between Sc, nickel (Ni) and Zr/Hf (not shown); thus, crystallization of clinopyroxene and olivine could not affect the Zr/Hf ratios. Therefore, the large variation in the Zr/Hf ratios is controlled by the source heterogeneities.

Nearly all lavas with high Nb/Ta ratios are located close to the plume positions (Fig. 5). This ratio is higher than the estimated Nb/Ta ratios in the continental crust (~12–13) and the bulk-silicate earth (~14) (Pfänder et al., 2007). Like the Zr/Hf ratios, the high Nb/Ta ratios are controlled by the source heterogeneities. Subducted slab with garnet-amphibolite residues has an elevated Nb/Ta ratio after slab melt extraction, and the eclogite (the main component of the lower crust) has a high Nb/Ta ratio (Schmidt et al., 2009). Therefore, the contributions of subducted slab and the delaminated lower crust to MORBs will elevate the Nb/Ta ratios. Materials in the earth's core, as the hidden reservoir of Nb, could be entrained by the mantle plumes that stemmed from the core-mantle boundary (Wade and Wood, 2001). Alternatively, the plume could supply more Nb and elevate the Nb/Ta ratio. Abyssal peridotites, that are melting residues for MORB, also show strong correlation between Zr/Hf (~2.5–335) and Nb/Ta (~1–170) (Huang et al., 2011). This finding confirms the fact that source heterogeneity is the major cause of significant variations in the Nb/Ta and Zr/Hf ratios.

5 Summary

This study shows that the source regions of the MAR basalts are quite different. The anomalies of temperature and pressure are mainly determined by the influence of mantle plume. The changes in trace element and isotopic compositions, however, are mainly determined by the geochemical diversity in its source region. The source characteristics of MORBs determined in this study are quantitative. Specific to a ridge or to a few ridge segments, detailed issues should be considered (Kempton et al., 2000; Zhang et al., 2016). In addition, quantitative analyses of the source characteristics also need to use more analysis methods. For example, combining osmium (Os) isotope with Sr-Nd-Pb-Hf isotopes and trace elements could be used to quantitatively estimate the source characteristics of MORBs (Escrig et al., 2004). Nevertheless, some problems have not been resolved. For instance, no mantle plume activities exist around some areas with high temperatures (e.g., 5°S and 21°S on the MAR, see Fig. 2). It is unclear, whether there are hidden mantle plumes beneath these areas, and if not, what causes the decrease in Hf isotopes of MORBs from north to south along the MAR. Therefore, future work is needed to solve these problems.

Acknowledgements

We thank Liyan Tian and the other two anonymous reviewers for their constructive comments that have greatly improved the manuscript.

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