Th, Nb and Zr characteristics and plume causes identification of Emeishan basalts

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Abstract: Having compared with the characteristics of world typical mantle plume basalts and analyzed Th, Nb and Zr characteristics of Emeishan basalt, this paper points out that although there were some differences about the formation environment of the three rock areas (WEST, CENTRE and EAST rock area), main rocks of them shared common geochemistry characteristics of ocean island basalts, implying that rocks came from metasomatic enriched mantle. Further studies showed that Emeishan basalt is generated from the mantle plume, but the crustal hybridism, the fractional crystallization of basaltic magma and different magma source regions lead to the fact that rock is generally rich in Th, Th/Nb ratio. In the tectonic setting discrimination diagram, their samples mostly fall into the tholeite area of intracontinental rift and epicontinental rift, as opposed to the mantle plume area the samples of typical basalt of the world would fall into. The paper also indicates that the data collection must have certain criteria, this means that the samples must have low crustal contamination, little magma fractional crystallization, namely as representative of the rock of forming original magma as possible when using Th/HF - Ta/HF double logarithmic diagram (proposed by Wang et al. (2001)) and discrimination diagrams of basalt tectonic settings (proposed by Sun (2003)) to discriminate the tectonic setting of magmatic rock formation.

Keywords: Emeishan basalt, Th, Nb and Zr characteristics, cause, magma regions, mantle plume.

1. Introduction

Discriminating tectonic settings for basalt formation by using the geochemical characteristics of trace elements became very popular in 1980s. A number of methods and theories for use in the discrimination were established for oceanic settings, which could well discriminate the tectonic settings of magma source regions in ocean, especially the basaltic magma and granitic magma the most widely distributed in the crust, but they stopped short of discriminating the magma source regions of complex tectonic settings at continent or ocean-continent transition zone.

According to the theory of plate tectonics, the magma produced in mantle above lithosphere lies at divergent plate boundary, convergent plate boundary and intra-plate. As the research attention shifted from ocean to continent, the researches on the continental dynamics in geosciences also underwent unprecedented development. The researches begin to explore approaches and methods to solve the geological problems in the depth of continent with focus on both the geochemical evolution

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characteristics of rocks in the deep activity process and the discrimination of tectonic settings for rock formation.

Pearce and Cann (1973)\textsuperscript{[1]} proposed and applied the Zr-Ti-3Y triangle plot to discriminate the within-plate basalt (WPB), low-K tholeiite (KLT), ocean floor basalt (OFB) and the island arc calc-alkali basalt (CAB). The plot was mainly applicable to the discrimination of primary magmatic rocks, as they were subject to relatively small impacts of fractional crystallization of magma in their formation process. In 1978, O’Nions selected the two elements (applied often to large-ion lithophile elements and radiogenic heat-generation elements with similar geochemical characteristics) as a pair. Their abundances form a ratio diagram of rectangular coordinate system. The diagram could reflect the composition and characteristics of rocks and determine the metamorphic facies and crustal thickness, but be only applicable to the island arcs with volcanic eruption and active continent margin. It is widely used in the study of Archean gray gneiss and granite and the tested samples were limited to alkaline volcanic rocks and island arc tholeiitic basalts. Wood et al. (1979)\textsuperscript{[2]} proposed Th-Ta-1/3Hf discriminant triangular. Arculus (1987) revised the boundary between different tectonic areas. The map can distinguish the island arc calc-alkaline basalt (CAB), a normal mid-ocean-ridge basalt (N-MORB), enriched mid-ocean-ridge basalt (E-MORB), within plate basalt-tholeiite (WPB-T) and within plate basalt-alkaline (WPB-A). The Wood triangular diagram\textsuperscript{[2]} can be used to divide different tectonic zones in the ocean environment, but it is restricted for the discrimination of tectonic settings at the continent and the ocean-continent transition zone. For the continental crust mantle (within the continental plate, for example, Paraná continental flood basalts in Brazil generated in the continental plate of ancient South America and Africa), subduction zones (such as magma from the oceanic plate subducting under the mantle source regions of the South America continental plate, the basalt and andesite series in Andes Mountains, South America), continental margins (e.g. basalt series of southeastern coast and offshore ocean-land transition zone originated from residual continental mantle, nearly east-west the Atlantic east to the Rio Grande Rise and Walvis Ridge in Atlantic), the component points of these rock series basically fall onto the Th-Hf side of island arc calc-alkaline basalt region in the triangular diagram (CAB region in Figure 1b), being difficult to make further discrimination. Some tectonic zones and magma source regions are mixed products, such as arc-continent collision zone, whose components are between island arc and continental crust (or continental mantle). In the Wood diagram, component points basically fall into the CAB zone and it is difficult to make a clearly division. Furthermore, the mantle-derived magma due to crustal contamination may be placed under different tectonic zones in the Wood diagram, which is obviously unreasonable. Ouma(1981) proposed the S-B plot to accommodate the genesis relation of Japanese island arc volcanic rocks. The plot could obviously identify the fractional crystal-lization trend line and the partial melting trend line. Component points of various rocks put into the plot could identify consanguinity of volcanic rocks, determine the mineral phase characteristics of fractional crystallization, discriminate the accumulative phase, and qualitatively determine the degree of partial melting. But the plot could neither quantitatively discuss the characteristics of magmatism (such as the degree of fractional crystallization, ratio of mineral phases in fractional crystallization etc.), nor investigate the impact on the trend line by the fractional crystallization of mineral phases except for anorthosite, clinopyroxene and hornblende. From 1982 to 1989, Dupuy, Myers, Ellam, etc., proposed a ratio cobweb graph using
standardized values of abundance of elements arranged in a certain order. Most of the elements used were lithophilic or incompatible elements. It can distinguish similar rocks, compare the characteristics of rock areas, provide geodynamic information about magma eruption, and determine the structural background. The disadvantage is that the sample selection needs to use the sample close to the studied rock composition as the standard sample. Otherwise ambiguous conclusions will be obtained. In 1990, Wang Yunliang, etc.[3], proposed to use Th/Hf-Ta/Hf double logarithmic diagram to distinguish the tectonic environment formed by basalt (Figure 1). This method can clearly reflect the source of magmatic rock in the figure, it made certain progress in identification of magma source regions in the complex tectonic settings of continent and ocean-continent transition zone and discrimination of the source regions of magmatic rocks, sedimentary rocks, magmatic rocks of mixed source regions, magmatic rocks with high degree of crustal contamination etc., There has been progress in the discrimination of, but the data collection has certain limitations, and the instrument test also has certain limitations (some instruments can analyze Th, Ta, Hf, and other instruments can analyze Th, Nb, Zr). In order to make the Th/Hf-Ta/Hf double logarithmic graphic judgment basis more sufficient and reliable, Sun Shuqin et al. (2003)[4] according to the similarity of the properties of Ta and Nb, Hf and Zr, using the world's typical tectonic environment area basalt The latest data of Th, Nb, and Zr proposes another method to distinguish the geotectonic environment formed by basalt, that is, the Th/Zr-Nb/Zr double logarithmic diagram discrimination (Figure 2). This method uses trace elements to discriminate the geotectonic environment formed by magmatic rocks. The above opened up a new way. When using this map to distinguish the tectonic environment formed by the Emeishan basalt, it has also been well verified.

![Figure 1 Tectonic settings identification scheme of basalts on the Th/Hf-Ta/Hf diagram](image1)

![Figure 2 Tectonic settings identification scheme of basalts on the Th/Zr and Nb/Zr diagram](image2)

- primary mantle; I. The margin of divergent oceanic plate. II. The margin of convergent plate (II; oceanic is land arc; II; island arc and volcanic arc of continental margin). III. The oceanic intra plate (the oceanic is land an d seamount, T-MORB, E-MORB). IV. Within continental plate (IV; continental rift; IV; continental tensional zone; IV; collision zone of two continental plates). V. Mantle plume.

Previous studies believe that the Emeishan basalt is a relatively typical product of mantle plume
activity\[^5\], but because the basaltic magma erupted from the mantle plume is exposed in different parts of the plate, it is mixed by the ocean crust and continental crust in different proportions. The composition of the formed magmatic rocks is very different, so it is difficult to distinguish the tectonic environment of its formation. When using trace elements and rare earth elements to map the tectonic environment of its formation, not all points fall in the mantle plume. However, most of the regions fall within the continental plate (Figure 8), and are mainly in the continental rift valley and continental rift basal area. The author concluded through research and analysis that most of the data points in the Emeishan basalt tectonic environment discriminant map did not fall into the mantle plume range because of the high content of Th and the large Th/Nb ratio. This is not only related to crustal contamination, separation and crystallization, but also to the degree of influence of asthenospheric substances, that is, the difference in Th content.

2. Discrimination of Th, Nb, Zr in Typical Mantle-Derived Basalt of the World

Mantle plumes are columns of hot cylindric rock that ascend from deep of volcano with high gravity because of disintegration of radioactive elements and release of heat and upwell from the volcano. Plumes are marked by volcanism, high heat flow and broad crustal swells (Wilson J.T., 1973; Morgan, W.J., 1971).

Mantle plume does not represent a specific type of plate tectonics, and the rock formed by it belongs to alkali basalt series. The magma source is located in the asthenosphere, or from the upper mantle of lithosphere, but it is obviously affected by the asthenosphere material. As the asthenosphere is under the plate, mantle plumes can travel through plates of different natures and different parts of a plate. Hence the basalt series from the source region, in addition to appearing in the form of mantle plumes within oceanic plate (e.g. basalts in Juna Fernandez chain, Chile), are generated at the divergent margins of oceanic plates (such as basalts of Mayen island at Mayen oceanic ridge, Arctic ocean), continental rift (such as basalts at the edge of Antarctica, East African Kenya Rift), island arc and near cross linking points of three plates (such as basalts in Leizhou peninsula, Guangdong and the northern part of Hainan Island, near the intersection of the Eurasian plate, the Indian continental plate and the Philippine plate).

Now the mostly researched mantle plumes are distributed in the ocean environment, because oceans cover most of the Earth’s surface. The mantle plume in the ocean environment appear in the forms of oceanic islands, chain seamounts, ocean platforms or sea platforms. In general, the ocean islands are small in scale, which represents the product of the head of the mantle plume or the product of the initial eruption of mantle plume magma. The oceanic platform is larger in scale. Compared with the scale of continental overflow basalt, it represents the product of the main mantle plume eruption. A seamount chain comprises a series of oceanic islands that are sequenced in chronological order towards a fixed direction; that is to say, the oceanic islands in the same line are not formed simultaneously. The ageing direction of these oceanic islands is generally considered to represent the direction of plate movement. The series of regularly distributed oceanic island are known as hotspot tracks. The largest or the most recent large-scale erupted oceanic islands are directly called the plumes \[^6\].
Table 1. Contents of Th, Nb, Zr (10^-6) in mantle plume basalts and their ratios.

| Places                                             | Th    | Nb   | Zr    | Th/Nb   | Nb/Zr   | Th/Zr   | Data sources                                      |
|----------------------------------------------------|-------|------|-------|---------|---------|---------|--------------------------------------------------|
| Basalts in the northern arm of the Eastern African Kenya | 1.12-7.37 | 23-101 | 98-237 | 0.05-0.0817 | 0.2203-0.4262 | 0.0117-0.034 | Class C., et al., 1994[7]                            |
| Basalts of Erebus plume in Ross Island, Antarctica | 6.6-25.4 | 11-261 | 347-1085 | 0.0524-0.0984 | 0.237-0.3659 | 0.019-0.0268 |                                                 |
| Continental intra plate                           |       |      |       |         |         |         |                                                  |
| Cenozoic plume basalts of western Germany          | 3.4-18.8 | 55-128 | 147-325 | 0.0486-0.1741 | 0.2407-0.5845 | 0.0133-0.0723 | Wedepohl L H., et al., 1994[8]                       |
| Basalts of Mayen island at Mayen oceanic ridge     | 2.7-13 | 43-154 | 108-567 | 0.0628-0.0884 | 0.257-0.3981 | 0.0212-0.0283 | Tronnos R G, et al., 1999[9]                         |
| Continental intra plate                           | 6.0-12 | 69-145 | 189-401 | 0.0615-0.0909 | 0.3087-0.4127 | 0.0235-0.0348 | M. Wilson, et al., 1995[10]                          |
| Basalts of kimberlites from Arkhangelsk region, Russia | 0.9-18.1 | 23-210 | 70-289 | 0.018-0.1194 | 0.327-1.7647 | 0.0074-0.117 | A.D. Beard, et al., 2000[11]                         |
| Alkaline volcanic rocks in the Nunatak region, northeast Greenland | 4.3-14.6 | 55-142 | 286-843 | 0.0675-0.1141 | 0.1234-0.2394 | 0.01-0.0271 | S Bernstein, 2000[12]                               |
| Alkaline olivine basalt of the plume of continental intraplate rift zone in Guangdong Leizhou Peninsula-northern Hainan, China | 1.02-6.1 | 8.5-72.6 | 79-279 | 0.0691-0.1459 | 0.1076-0.2606 | 0.0118-0.0253 | K.-S.Ho, et al., 2000[13]                           |
| Basalts in Chile Juan-Fernandez islands             | 2.74-5.84 | 43.8-79.2 | 223-380 | 0.0606-0.079 | 0.1758-0.2135 | 0.0109-0.0162 | C.W.Devey, et al., 2000[14]                         |

Table 1 and Figures 3 collectively reflect different characteristics and regions of composition of typical
mantle-derived basalts series in different regions of the world. The characteristic is Th/ Nb<0.11, Nb/Zr>0.15. It is reported the basalts carrying the above characteristic include the following: the mantle-derived Hawaiian Haleakala volcano basalts[15], Oahu island basalts[16], alkaline volcanic rock series of Koolau[17], the basalts in Polynesian Islands, South Pacific[18], alkali basalts- olivine tholeiitic basalts in the northern part of Hainan island, China[19], basalts of Canary islands, North Atlantic ocean[20], basalts in northwest of Taiwan[21] as well as mantle-derived kimberlites, olivine cancalites and picrites of Kola Peninsula, Russia etc[22].

![Figure 3 Mantle plume basalts](image)

The above characteristics indicate that the Th, Nb, and Zr characteristics of the mantle plume-derived basalt are basically the same regardless of the tectonic environment in which they are produced. And the most significant difference from basalts of other genesis is that the ratio of highly enriched Nb, Nb/Zr is generally greater than 0.15 (Figure 3). This obviously contrasts with the high degree of Nb loss in the N-MORB and the magma source regions of island arc basalts.

### 3. Th, Nb, Zr Characteristics of Emeishan Basalt Source Regions

Emeishan Basalt is concentrated in the southwestern margin of the Yangtze platform, restricted by the fault zone and appearing in the shape of nearly north-south long axis of diamond. The southwest (Red River fault zone) and northwest (Xiaojinhe - Longmenshan fault zone) are connected with Nujiang-Lancangjiang-Jinshajiang tectonic belt by large faults. According to the regular spatial and temporal changes of magma eruptive facies and rock series, Emeishan Basalt in the region can be divided into three large regions: the east region (Guizhou Plateau), including large areas of basalt regions distributed in Yunnan, Guizhou and Sichuan in the east of Xiaojianfang fault zone, the middle region (Panxi rock region, or called volcanic rock distribution region of double peaks in Panxi Rift), and between them the west region (Yanyuan-Lijiang rock region)[23], including the widespread uplift basalt regions between Qingher-Chenghai fault and Xiaojinhe fault zone (Figure 4). There are significant differences in terms of eruption environment and rock assemblage of basalts in different
regions. The west region has typical marine basalts, the middle region has marine and continental basalts, and the east region has continental flood basalts.[24]

Emeishan Basalt is longer than 1,000 km in the north and south direction and the east-west width is also more than 900 km. According to the rough calculation of basalt thickness variation graph, its total volume exceeds 30×10^4 km^3. From west to east, its thickness and geochemical characteristics of rocks exhibit a regular change[25]. For example, in Shang chang, Binchuan, Yunnan Province (the west region), the basalt layer thickness is more than 5,000m, while the thickness of basalts in Guizhou in the east region is only tens to hundreds of meters (Lin J.Y., 1985)[23], so it is thick in south and west and thin in north and east (Figure 5). This is because the Guizhou Plateau rock region (the east region) and Panxi rock region (the middle region) are formed in the Yangtze Platform with thick crust; in particular Panxi rock region (the middle region) is located in the ancient Kangdian Axis, where the tectonic setting is complex. Yan yuan-Lijiang rock region (the west region) is formed at the western margin of the Yangtze Plate with thin crust.

![Figure 4 Distribution of Emeishan basalts in Southwestern China](image)

**Figure 4** Distribution of Emeishan basalts in Southwestern China
Fault zones (Che et al., 2002; Wu., 2008): ①Long Menshan fault; ②Jin He-Qing He fault; ③Jin Sha River fault; ④Pan Zhihua fault; ⑤Lu Zhi River fault; ⑥An Linghe fault; ⑦Pu Dinghe fault; ⑧Xiao Jiang fault.
Geotectonic units of China: I. Yangtze platform; II. Qinghai -tibet folds area; III. Kunlun- qingling fold system; IV. North china platform; V. Qilianshan fold belt; VI. Chaidam block; VII. Fold area in the north of China.

![Figure 5 The isopach map of Permian basalts in southwestern China](image)

**Figure 5** The isopach map of Permian basalts in southwestern China
(Change from Zhang et al. 1988)
1. Thickness isoline; 2. Fault.

Emeishan Basalt has multiple times, multi-center fissures and intermittent eruptions and effusions along deep faults with multiple eruption cycles[25]. The magmatic activity time is as long as 251~260Ma, with the main eruption period being in the late Maokou period in the middle Permian–early Xuanwei period in the late Permian, namely 257~259Ma[26]. The eruption time is only1~2Ma[27][28]. The
Emeishan Basalt is mostly considered as the large areas of flood basalts within a few hundreds of thousands or even millions of years of rapid eruption of enormous basalts, with a very high yield of magma. Xu Lianzhong et al. (2006)[29] also confirmed that the eruption time of Emeishan Basalt is less than 3Ma.

**Table 2.** Statistical results of Th, Nb, Zr, Sr and Nd in three basalt rock area.

| Rock area | West rock area | Middle rock area | East rock area |
|-----------|----------------|------------------|---------------|
|           | Range          | average          | range         | average          | range         | average          |
| Th        | 0.50-10.5      | 3.32             | 0.70-20.6     | 7.62             | 2.80-9.28     | 6.62             |
| Nb        | ω/10^-6        | 4.25-196         | 14.0-118      | 40.9             | 32.7-54.3     | 41.6             |
| Zr        | 17.4-454       | 165              | 72.0-1190     | 313              | 160-690       | 350              |
| (87Sr/86Sr) | 0.704-0.708 | 0.706            | 0.704-0.708   | 0.705            | 0.705-0.706   | 0.705            |
| εNd       | -6.74-4.84     | -0.46            | -4.00-4.00    | 0.63             | -2.69-2.92    | 0.57             |

The geochemical data of three rock regions of Emeishan Basalt (Table 2) are projected on to the Th-Hf/3-Ta diagram (Wood, 1980), showing that the samples of the three rock regions are concentrated in the transition zone within plate basalts and island arc tholeiitic basalts (Figure 6); in the Zr/4-Nb-Y diagram of Meschede (1986), the most of samples of the east region are distributed in within-plate alkaline basalt and tholeiitic basalts (A1, A2), and as for the samples of the west region, in addition to the distribution in within-plate alkaline basalt and tholeiitic basalt area (A2), some of samples are also distributed in the enriched ridge basalts and volcanic arc basalt areas (C, B)(Figure 7); In the diagram proposed by Huang Zhilong et al. (2004)[30] and Sun Shuqin et al. (2003)[4] for discriminating
the basalt formation environment (Figure 8), most samples of the three regions are distributed in the intracontinental rift and continental rift porphyry basalt area (IV₁) and the initial rift basalt area (IV₂), and only a few are distributed in the mantle plume basalt area (V). It shows that the formation environment of the Emeishan basalt is slightly different, and it has the geochemical characteristics of the ocean island basalt.

According to Sun-Linchung et al. (1995), Lu Jiren (1996), Hou Zenqian et al. (1999) [31], Wang Yunliang et al. (1999), Emeishan Basalt is mantle plume derived, with its Nb/Zr ratios being mostly between 0.15-1. This is similar to alkaline basalts in the continental margin rift zone, which suggests that magma source region be rich with Th, and the magma impacted by the mantle plume ascend along the continental margin rift and form the Emeishan Basalt.
The statistical results of Song Xiyan et al. (2001)[26] showed that the ratios of trace elements in the three rock regions (Zr/Nb, La/Nb, Rb/Nb, Th/La and Ba/La, etc.) are similar to those of oceanic island basalts (OIB), indicating that the Emeishan Basalt had the same geochemical characteristics of oceanic island basalts and also suggesting that the basalts originate from the enriched metasomatic mantle.

4. Exploring the Genesis of Emeishan Basalt

The formation of magmatic rocks, like tectonic movements, belongs to major geological events in the history of geological development in a region. It does not just fall into the field of petrology, but also is an issue in geology involving a number of aspects of geosciences. In the past, the genesis of magmatic rocks was studied from the mechanism of magma formation, but now focus is placed on exploring the genesis of magmatic rocks by integrating tectonic settings.

As the Emeishan Basalt in the southwest China is part of entire magmatic rocks on earth, its genesis always caught people’s attention. Discussion on the genesis has made certain progress with important theoretical significance and practical implication.

The major elements composing the Emeishan Basalt in Kangdian Rift and Dianqian depression zone have overall similarities, and the tectonic setting for eruption of basalts in Kangdian region has the trait of continental margin rift[32][33]. According to the discrimination of continental flood basalt presented by Thompson (1984), the fractional crystallization has occurred before the eruption of basaltic parental magma. The Emeishan Basalt of Yanyuan-Lijiang rock region (the west region) in the west of Kangdian Rift is obviously different from basalts of the rift zone (the middle region) in petrology and petro-chemistry. This is due to different tensile speed, the former has strong tension and locally tends to be oceanic, but both are still products at the intracontinental rift stage[32].

Although the rock types, geochemistry, magma evolutions and the forming environments are different to some extent for the three rock regions of Emeishan Basalt (east, middle and west regions), but the bulk rocks in all rock regions are basalts with same (or similar) projected positions on the geochemical diagrams, namely within the Internal rift and rift margin tholeiitic basalts. This indicates that the materials in the three rock regions would be erupted from the same magma. Currently the origins of Emeishan Basalt are summarized as follows: ① the Pacific Plate subduction causing up welling of the lower plume of the Yangtze Plate and the asthenosphere[33]. ② Paleo-Tethys Plate-subducting-eastward making ascending of plume[25]. ③ diapirism of the mantle[34]. ④ mantle plume activities[35][36][37]. There is evidence that the westward subduction of the Pacific Plate occurred in the late Yanshan -Himalayan period[38][39], rather than the Hercynian period when the Emeishan Basalt erupted on a large scale. The Paleo-Tethys Ocean in the southwest China was the Jinsijiang ocean basin, and its westward subduction occurred in the Carboniferous-early Triassic[40]. The mantle diapir can undoubtedly become the driving force of the continental rift, but the kinetic energy and thermal energy of the mantle diapirism must be provided by larger-scale mantle tectonic-thermal events. In summary, it is believed that the Emeishan Basalt is related to the mantle plume activity, and there is the following evidence:
(1) Large amounts of magma accumulate rapidly. The Emeishan Basalt covers the three provinces: Sichuan, Yunnan and Guizhou with the distribution area of about 50×10^4 km^2 and the volume of about 30×10^4 km^3. According to the main eruption period of 2 Ma, the magma eruption rate could be as high as 15×10^4 km^3/ Ma. Such a high eruption rate of magma requires that its lithosphere or even asthenosphere must have unusually high heat flow and massive crust-mantle melting, which can never be completed by the subduction and mantle diapirism of oceanic plate, but the massive eruption of continental flood basalts (CFB) in a short period (<1 Ma) is the result of mantle plume activities. He Bin et al. (2003) held the opinion that before the Emeishan basalt eruption there was a quick dome-like uplift according to the spatial distribution characteristics of limestone of Maokou Formation, provided that there is evidence of a mantle plume. Zhang Zhaochong et al. (2004) through the study of high-magnesium olivine in picrites, obtained the liquidus temperature of its formation as 1600 ℃, which was 250~320 ℃ higher than that of the global asthenosphere, indicating that the formation of Emeishan Basalt was relevant to the mantle plume.

(2) Widely exposed picrites. Picrite is regarded as a sign of mantle plume activity. The main elements of picritic rocks and their associated rocks are characterized by high Fe8 and (CaO/Al2O3) and low Na8, showing the characteristics of high pressure. The distribution curve of their rare earth elements is basically similar to the standard curve of the primary plume for trace elements, and the ratios vary slightly. Combined with their isotopic characteristics, it is found that the source region is the mantle plume. These rocks are exposed in the west and middle rock regions of the southwest Emeishan Basalt. The exposed thickness of picrite in Binchuan is up to 170 m and nearly 300 m in Lijiang, and they constitutes everalpicrite - picritic basalt-basalt cycles, according to the geochemical data of picrites in the Emeishan Basalt analyzed by Chung and Jahn (1998), Xu Y.G., et al. (2001), the proportion of MgO in picrites is between 16%~27%, Cr>400×10^6, Ni>500×10^6, and the mantle involved in the magmatism has an abnormally high potential temperature (1550 ℃). The results of high temperature and high pressure experiment show that magma of such high proportions of MgO, Cr, Ni are the products of mantle high temperature (>1400 ℃) and high partial melting (>20%), and its melting temperature is 200 ~ 300 ℃ higher than that of basaltic magma. The basaltic magma of this abnormally high temperature can only come from the lower mantle, and no intense exchange of materials and energy occurs with surrounding upper mantle.

(3) It has the geochemical characteristics of OIB (ocean island basalt). OIB is the product of plume eruption in the oceanic plate and characterized by enriched large-ion lithophile elements (LILE), rare earth elements (REE) and high field strength elements (HFSE). In (87Sr/86Sr)~ εNd diagram, Sr, Nd isotopes of the three rock regions also enter into the range of OIB (Figure 9). This not only proves that
Emeishan Basalts has OIB geochemical characteristics, but also suggests that the rocks are originated from enriched mantle.

(4) Large-scale and long-period acidic magma activities. After eruption of the Emeishan Basalt, large-scale and prolonged acidic magma intrusion and eruption occur\(^45\). In the profile of some basalts in the west and middle rock regions, the rhyolite-dacite directly cover on basalts and this indicates crustal activation and melting by large-scale underplating of basaltic magma and thermal erosion of lower mantle.

(5) Significant crustal uplift. In the early 1990s, a series of studies have shown that the rising mantle plume usually caused massive crustal uplift and formed a dome-like uplift\[^{43}\][\(^{46}\)[\(^{47}\], and further pointed out that the rising mantle with the diameter of 500km could lead to the rising of 2000m of crustal uplift. Therefore, another important feature of the mantle plume activity is the crustal uplift and the shallow geological records caused by it (differential erosion, disintegration, ancient river valley, catastrophic deposition, etc.) caused. He Bin et al. (2003)\(^{37}\) found that differential erosion existed in limestone of the western margin Maokou of the Yangtze before eruption of basalts, ranging from west to east as the deep erosion zone (inner zone), partial erosion zone (mid-zone), ancient weathering crust or a short depositional break (outer zone), and the scope of erosion zone was basically consistent with the distribution regions of Emeishan Basalt. Thus, it is believed that this differential erosion is the result of a rapid crustal uplift and dome-like uplift in the western margin of Yangtze in the late period of middle Permian, and this provides an effective stratum evidence for the mantle-derived Emeishan Basalt.

(6) Large-scale species extinction. At the turn of T/P, 90% of marine species and 70% of the land species were extinct, and the internationally recognized time limit is 251.4±0.4Ma, which is basically consistent with the diagenetic stage of Emeishan Basalt. Massive magma only erupts from mantle plume activities, forming a large amount of volcanic ashes, so that the climatic temperature rises and the ecological environment is destructed, causing massive extinctions. Thus, large-scale species extinction is another evidence for the mantle plume origin of Emeishan Basalt.

Although the Emeishan Basalt has many of the above characteristics, there are double-peak volcanic rocks in the middle rock region of Emeishan Basalt (i.e. Panxi Rift)\[^{25}\][\(^{34}\]. The alkaline rock series share similarities with the modern continental rift magmatism summarized by Wilson (1999)\[^{46}\], reflecting the control of tectonic setting of rift for the magma generation. However, it is difficult to explain the genesis of the Emeishan Basalt for the rift magmatism mode from the aspects of energy or rock scale\[^{31}\]. Mei H.J., et al. (2003)\[^{47}\] found that one thousand kilometers of alkaline rocks sandwiched between the tholeiitic basalts in the profile of Longzhoushan in the middle rock region, but the natures of these tholeiitic basalts are very similar to the basalts in the east rock region, so it is considered that the magmatism in Panxi Rift Zone (middle rock region) may be the comprehensive product of mantle plume activity and extension of rift.

It is generally believed that due to the thin oceanic lithosphere, most ocean overflow basalts come from mantle plumes and are less contaminated by lithospheric materials\[^{48}\]. For the origin of mantle plumes, currently there are two viewpoints: one holds that it is originated in the boundary of upper and lower mantles\[^{49}\][\(^{50}\], and another view thinks that it originates from the core-mantle boundary (Campbell I H, Griffiths R W, 1990). Zhang Zhaocong et al. (2003)\[^{51}\] conducted the theoretical
simulation of picrites of the Emeishan Basalt, found addition of outer nuclear substances in the source
region of Emeishan picrites, and thought that the Emeishan mantle plume may originate from the
core-mantle boundary. This also explains the origin of Emeishan basalt as the joint result of mantle
plume and rift.

Through the above discussion, it is known that Emeishan Basalt is the causes of mantle plume.
The most of data points projected onto the tectonic setting diagram of Emeishan Basalt do not fall
within the scope of the plume. This is due to high Th content and large Th/Nb ratio. This is not only
related to crustal contamination, separation and crystallization, but also to the degree of influence of
asthenospheric substances, that is, the difference in Th content.

(1) Crustal contamination. According to geochemical research on basalts in Binchuan, Xu Y. G.,
et al. (2001) estimated the shaft of Emeishan mantle plume was in the western Binchuan (west rock
region), but did not point out the exact location. Since the source region of volcanic rocks in the west
rock region is mainly the mantle plume (presumably the west rock region may be the location of the
shaft of the Emeishan mantle plume), there is little or no contamination of lithospheric mantle or crust,
the melting depth>75km, and the partial melting is 25%. In the east and middle rock regions, there is
contamination of lithospheric mantle or crust to different degrees. This indicates that the west rock
region has a large tensile strength (may be the result of the rising of mantle plume), the lithosphere is
thin and the magma rises faster without being contaminated, and the Th/Zr ratio is low (Figure 8D).
Through comparison of limestone strata in Maokou Formation, He Bin et al. (2003) thought that
although Lijiang region was substantially uplifted, but not the highest uplift, the western part of
Binchuan (west rock region) had the highest crustal uplift, and the shaft of mantle plume was located
around today’s Lijiang county seat, Yunnan Province. This disagrees with the result obtained by this
paper from picrites, and further study may be needed.

(2) Fractional crystallization. The parental magma of Emeishan Basalt is the unsaturated basaltic
magma on the critical surface, mainly olivine basaltic magma. Its fractional crystallization path is
peridotite-olivine gabbro-gabbro-syenite. The magma is held on the critical surface during fractional
crystallization, and finally evolves towards the trachyte.

(3) Differences of source regions. When the asthenosphere matter more, Th/Nb ratio is low (such
as the West Rock area), and when the substance mainly come from the lithosphere uppermantle, Th/Nb
ratios is more high (East Rock area).

Conclusions

Based on evidences and discussion presented above, the following points can be made:

(1) Through Th, Nb, Zr discrimination of typical mantle-derived basalts of the world, it is found
that the most significant difference with other causes of basalt is highly enriched in Nb, Nb/Zr ratio is
generally greater than 0.15.

(2) The Emeishan Basaltin southwest China is mantle plume derived and its Nb/Zr ratio is mostly
between 0.15-1. The reason of Th/Nb ratio change larger related with Th content of magma source, but
also with the asthenosphere impact substances, fractional crystallization and crustal contamination.
When there are many substances from asthenosphere, the Th/Nb ratio is generally low, and when the
substances mainly from the upper mantle of lithosphere or obviously affected by crustal contamination,
the Th/Nb ratio is high. The rock formed by the residual magma after strongly separation and
crystallization, has higher Th/Nb ratio. The forming environments of the west, middle and east rock regions of Emeishan Basalt are slightly different, but the main rock has geochemical characteristics of ocean island basalts, similar to the alkali basalts in continental margin rift, suggesting magma source be rich with Th.

(3) The Emeishan Basalt not only has the general characteristics of other typical mantle-derived plumes of the World (e.g. basalts in the northern part of Kenya), but more typical characteristics of the basalt in southwest China. It is formed in the tectonic setting of continental collision and extension, located in intersection and overlapping portion of the eastern coast of the Pacific tectonic domain and the western Paleo-Tethys tectonic domain, and clearly shows the complete plume “head” and “tail” contour. There exists unusually significant thermal erosion of mantle plume in Emeishan Basalt lithosphere.

(4) Disputes still exist for the genesis of Emeishan Basalt. When the tectonic setting of forming magma is identified either by Th/Hf-Ta/Hf or Th/Zr-Nb/Zr double logarithmic plot, there are limitations on the sample selection and further studies are still needed.

(5) In-depth study of the Emeishan basalt can not only provide typical examples of mantle plume magmatism in China, but also can deeply understand the process of deep continental lithosphere, and deepen the process and mechanism of material-energy exchange and transmission in the deep continental lithosphere.

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