



Article Geochronological and Geochemical Constraints on the Petrogenesis of Lamprophyre from the Giant Weishan REE Deposit in China

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- ² Shandong Provincial Lunan Geology and Exploration Institute (Shandong Provincial Bureau of Geology and Mineral Resources No.2 Geological Brigade), Jining 272100, China; shangzhen@lny2.wecom.work
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Abstract: The Weishan REE deposit is located in the southwest of the Luxi Terrane of the North China Craton (NCC), where a large number of lamprophyre dikes are spatially exposed with the deposit. Here, we report petrology, geochemistry and zircon U-Pb geochronology data for the lamprophyre of the Weishan REE deposit in order to develop constraints for the determination of the petrogenesis, magma source and evolution of the lamprophyre and the tectonic environment. LA-LCP-MS zircon U-Pb dating shows that the crystallization age of the lamprophyre is 125 ± 0.86 Ma. The geochemical data suggest that these lamprophyres have high levels of Al2O3, K2O, MgO and alkalis, moderate level of Na₂O and low levels of SiO₂, Fe₂O₃ and TiO₂, and that they are enriched with LREEs (La, Ce) and LILEs (Rb, Ba) and depleted with regard to HREEs and HFSEs (Nb, Ta, Ti). They displayed negative ϵ Hf(t) values of -14.98 to -9.03, T_{DM1} ages of 1.1–1.4 Ga and T_{DM2} ages of 1.7–2.1 Ga, which suggest that the magma source originates from an enriched mantle. Low Rb/Sr and high Dy/Yb ratios suggest that the enriched mantle source was partially melted at the amphibole-bearing lherzolite garnet-facies. The high Ba/Th and Sr/Th ratios indicate that the enriched source was derived from subduction dehydration fluids of the oceanic crust. We propose that the mafic dike intrusions are consistent with an Early Cretaceous alkaline magma emplacement in an extensional setting, in which the magma was not contaminated by crustal material during its emplacement.

Keywords: lamprophyre; zircon U-Pb-Hf isotope; whole-rock geochemistry; Weishan area; mantle enrichment

1. Introduction

Lamprophyre is a melanocratic hypabyssal igneous rock characterized by porphyritic textures and containing mafic phenocrysts [1] that forms dikes in various tectonic environments. Lamprophyre can be divided into ultramafic lamprophyre, alkaline lamprophyre and calc-alkaline lamprophyre [1]. However, multiple petrogenetic models have been proposed for the formation of lamprophyre, including mafic magma differentiation [2], magma miscibility [3] and partial melting of an enriched mantle [4–6]. Thus, investigation of lamprophyre has significance for exploring magma sources, mantle signatures and tectonic evolution [7–9].

Rare earth elements (REEs) are indispensable raw materials for modern science and technology and play significant roles in international resource strategy [10–12]. The Weishan REE deposit is located in Weishan Village, Weishan County, Zaozhuang City, Shandong Province. The deposit is a typical LREE deposit and is genetically related to the host alkaline complex. There are abundant lamprophyre dikes exposed in the mining area and its periphery. Extensive previous studies have been carried out on deposit geology,



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). metallogenic age, geochemistry, ore-forming fluid, ore-forming environment and the genesis of ore deposit [13–20]. The deposit mainly takes the form of NW-trending REE veins. Previous studies reported muscovite Rb-Sr and zircon U-Pb ages of ca. 120 Ma from the REE vein [17], which is consistent with the crystallization age of 123–130 Ma for the alkaline complex [21]. The alkaline rocks are genetically related to the REE deposit, and the magma source originates from the enriched mantle [21]. Lamprophyre primarily consists of mantlederived rock through which the nature of the mantle source can be traced. However, the lamprophyre is widely distributed in the Weishan area, and thus the petrogenesis and the timing of the magma emplacement remain ambiguous.

In this study, we present results concerning the petrography, whole-rock geochemistry, zircon U-Pb geochronology and Lu-Hf isotope of the lamprophyre from the Weishan area in order to develop constraints for the determination of the petrogenesis and the magma source of the lamprophyre and the tectonic environment.

2. Geological Setting

The Luxi Terrane is located in the eastern part of the NCC (Figure 1A) and intersects to the north with the Qihe-Guanggrao fault, to the south with the Feng-Pei fault, to the west with the Liaocheng-Lankao fault and to the east with the Yi-Shu fault [21] (Figure 1B). The exposed formations include Late Archean amphibolites and TTG gneisses, Paleoproterozoic granitoids, Cambrian to Permian carbonates and clastic rocks, Triassic to Cretaceous clastic rocks, volcanic rocks, lamprophyre and dioritic porphyrite dikes, carbonatites and alkaline rocks and Cenozoic clastic rocks [22]. The area underwent a long period of tectonic activity, which formed abundant fold and fault structures. The folds include closed synclinal and anticlinal folds [23]. The fault is comprised of the NW Nishan and Dujiaoganlin faults and the NWW Zaozhuang, Caowangmu and Changlong faults [24]. There were frequent magmatic activities in the Luxi Terrane during the early Precambrian to Mesozoic. Among them, the Mesozoic Yanshanian magmatic activity was relatively strong and formed serpentinite, hornblende, gabbro, diabase, diorite, granodiorite and granite [25]. Abundant mineral resources are exposed in the Luxi Terrane, mainly REE, gold, iron and coal deposits [15,26–29].



Figure 1. (**A**) Geological sketch map of the North China Craton [30]. (**B**) Geological sketch map of the Luxi Terrane [16].

The Weishan REE deposit is located in the southwestern Yicheng uplift of the western Luxi Terrane (Figure 1). The major strata include Neoarchean granodiorite and Quaternary sedimentary cover. The structure is dominated by NW and NE faults. The majority of the magmatic rock is comprised of Mesozoic quartz syenite, aegirine quartz syenite and alkali granite, which constitute the Weishan alkali complex. The alkaline magma intrudes into the Neoarchean granodiorites and takes the form of irregular branches. The proven resources in Weishan REE deposit amount to 44 t, with an average grade of 4.6% [31]. Most of the REE veins are distributed as NW trending, which is determined by the NW fault structure (Figure 2).



Figure 2. Geological sketch map of the Weishan REE deposit [16].

There are abundant lamprophyre dikes exposed in the Weishan REE deposit and its periphery. The lamprophyre takes the form of dikes intruded into the Neoarchean granodiorite, biotite plagioclase gneiss and Mesozoic alkaline complex. These lamprophyre dikes are mainly exposed as NE and NW trending and show size variations of 20 to 200 m in length and 2.0 to 5.0 m in width (Figure 2). The rock is mostly characterized by porphyritic or non-porphyritic lamprophyre textures and massive structures. The main lithological types of lamprophyre are kersantite, spessartite and alkaline lamprophyre.

3. Petrography

3.1. Kersantite

The kersantite (20CS15) is collected from REE vein No. 12 (-160 m) (34°42′13″ N, 117°15′24″ W) and is characterized by a greenish color, porphyritic lamprophyre texture and massive structure (Figure 3A,B). The rock consists of 15% phenocrysts, which are dominated by biotite (1~3 mm). The matrix is composed of fine- to medium-grained plagioclase (60–65%), biotite (25–30%), hornblende (<5%) and minor calcite (Figure 4A,B). Accessory minerals include zircon, apatite and sphene. The biotite is brown in color, euhedral to subhedral and tabular, with a size of 120–1000 µm. The plagioclase is subhedral and columnar, with a size of 20–150 µm, and it exhibits lamellar and polysynthetic twinning. Some plagioclase grains show saussurite alteration.



Figure 3. Field and hand-specimen photographs of the lamprophyres. (A) Kersantite vein; (B) kersantite; (C) damkjernite; (D) spessartite.



Figure 4. Photomicrographs of the lamprophyres. (**A**) kersantite; (**B**) biotite phenocryst in kersantite; (**C**) damkjernite; (**D**) spessartite. Mineral abbreviations: Amp—amphibole; Bt—biotite; Cal—calcite; Pl—plagioclase; Phl—phlogopite; Ser—sericite.

3.2. Damkjernite

The damkjernites (21CS01, 21CS01A) are collected from drill hole ZK5 ($34^{\circ}42'17''$ N, $117^{\circ}15'04''$ W) and are characterized by a brownish color, porphyritic lamprophyre texture and massive structure (Figure 3C). The rock is composed of 15% phenocrysts, which are dominated by biotite, phlogopite and calcite, with a grain size of 0.5–5 mm. The matrix of the damkjernite is dominated by plagioclase (25–30%), phlogopite (20–25%), biotite (25–30%), calcite (15–18%), diopside (<5%), olivine (<5%) and minor amphibole (Figure 4C). Accessory minerals include zircon, sphene and apatite. The biotite is a brown to green color and subhedral, with a grain size of 0.5–2 mm. The phlogopite is a yellow color and euhedral tabular, with a grain size of 0.3–2 mm. The plagioclase is subhedral columnar, with a size of 50–500 µm. Some plagioclase grains exhibit obvious lamellar twinning, polysynthetic twinning and partial saussurite alteration. The calcite is colorless, flashed with diamond cleavage.

3.3. Spessartite

The spessartite (21CS03) is collected from drill hole ZK5 ($34^{\circ}42'17''$ N, $117^{\circ}15'04''$ W) and is characterized by a greenish color and a massive, non-porphyritic lamprophyre structure (Figure 3D). The rock is composed of amphibole (40–45%), plagioclase (20–25%), biotite (8–10%), orthoclase (6–9%), chlorite (<5%), quartz (<5%) and pyrite (Figure 4D). Accessory minerals include zircon, sphene and apatite. The amphibole is yellow to brownish in color,

with an anhedral or columnar morphology and a size of $500-1000 \mu m$. The plagioclase is subhedral columnar, and some grains exhibit polysynthetic twinning, chloritization and sericitization. Some of the plagioclase shows large grain sizes up to 5 mm. The biotite is brown to green in color, subhedral to anhedral. The orthoclase is subhedral and some grains show obvious parallel cleavage. The quartz is fine-grained and anhedral.

4. Analytical Methods

4.1. Whole-Rock Major and Trace Element Analyses

Geochemical data for the major and trace elements of the studied samples were obtained at the testing center of the Shandong Lunan Geological Engineering Investigation Institute, China. First, the samples were crushed and powdered to 200 mesh in an agate bowl. The ferrous oxide content was determined with the potassium dichromate volumetric method, and other major elements were analyzed with X-ray fluorescence spectrometry using a Rigaku RIX 2100 spectrometer (Rigaku Corporation, Tokyo, Japan)with uncertainties of less than 5%. Trace and rare earth elements were analyzed using a PEE 6000 ICP-MS instrument with uncertainties of less than 5%.

4.2. Zircon LA-ICP-MS U-Pb Dating

Zircon separation was completed at the Langfang Geological Survey, Hebei Province, China. The samples were crushed to 40–60 mesh, and the zircon grains were separated through coarse and fine crushing, panning, magnetic separation and other methods. Transmission, reflection and cathodoluminescence (CL) imaging were completed at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The relatively complete and transparent zircon crystals were carefully handpicked under a binocular microscope and mounted in the epoxy, polished to nearly half-section to expose the internal structure and cleaned in an ultrasonic cleaner containing a 5% HNO₃ solution. Zircon grains were carefully examined under microscopes and electron microscopes to identify internal structures and textures.

LA-ICP-MS Zircon U-Pb isotope analysis was completed at the Isotopic Laboratory, Tianjin Center, China Geological Survey. The laser analysis was performed using a Neptune double-focusing multiple-collector ICP-MS (Thermo Fisher Scientific, Waltham, MA, USA) attached to a NEW WAVE 193 nm-FX ArF Excimer laser ablation system (Express Scripts Inc., Saint Louis, MI, USA). All zircon analysis was completed with a beam diameter of 35 μ m, 8 Hz repetition rate and an energy density of 11 J/cm². Zircon 91,500 is used as an internal standard for U-Pb chronology analysis. In order to ensure the accuracy of the test, the zircon 91,500 standard sample was tested twice, before and after every eight samples were tested. An SRM 610 glass standard sample was used as an external standard to calculate the U, Th and Pb concentrations of zircon. Data were calculated using ICPMS DataCal 8.4 at the China University of Geosciences, Wuhan, China [32], and zircon age concordant plots were obtained using the Isoplot 4.0 program [33]. Common Pb corrections were undertaken using the method described by Anderson [34].

4.3. Zircon Lu-Hf Isotope

The zircon Lu-Hf isotope analysis was completed in the Isotopic Laboratory at Tianjin Center, China Geological Survey, using a Neptune MC-ICP-MS (Thermo Fisher Scientific, Waltham, MA, USA) equipped with a NEW WAVE 193 nm-FX ArF Excimer laser ablation system (Express Scripts Inc., Saint Louis, MI, USA). The laser ablation beam diameter was 42 μ m, the energy density was 14 J/cm² and the repetition rate was 10 Hz. A GJ-1 standard sample was used as an external standard for in situ zircon Hf isotopic analyses.

5. Results

5.1. Major and Trace Element Geochemistry

The major elements of spessartite (20CS15) and kersantite (21CS03) are similar (Figure 5), showing high concentrations of SiO₂ (52.74–55.44 wt.%), K_2O (1.80–6.33 wt.%), Al_2O_3

(12.31–18.80 wt.%) and Na₂O (3.53–7.45 wt.%); moderate concentrations of MgO (1.79–4.55 wt.%) and CaO (2.05–5.20 wt.%); and low concentrations of TiO₂ (0.52–0.59 wt.%) and P₂O₅ (0.23–0.68 wt.%). The kersantite and spessartite show high alkali concentrations of 9.25 and 9.86 wt.%, respectively. Their K/Al and K/(K + Na) ratios are 0.17–0.40 and 0.14–0.54, respectively. In the TAS diagram, the samples fall into the basaltic phonolite and trachyandesite fields and belong to the alkaline series. In the (K₂O + Na₂O) vs. SiO₂ classification diagram (Figure 6A), the samples fall into the calc-alkaline lamprophyre fields, while in the K/Al vs. K/(K + Na) diagram (Figure 6B), the samples fall into the altyl lamprophyre and potassic lamprophyre fields, respectively.







Figure 6. Geochemical classification plots of the lamprophyres. (**A**) (K₂O + Na₂O) vs. SiO₂ classification diagram [1]. (**B**) K/Al vs. K/(K + Na) diagram [36]. Data are given in Table 1. CAL—calalkaline lamprophyre; AL—alkaline lamprophyre; UML—ultrabasic lamprophyre; LL—potassiummagnesium lamprophyre. L1—altyl lamprophyre; L2—weakly potassic lamprophyre; L3—potassic lamprophyre; L4—ultralithic lamprophyre; L5—peraluminite lamprophyre; L6—potassiummagnesium lamprophyre.

The major element of damkjernite (21CS01 and 21CS01A) show high concentrations of MgO (12.16–13.07 wt.%), K_2O (6.56–7.39 wt.%), Al_2O_3 (6.59–7.21 wt.%), Na_2O (0.25–0.79 wt.%) and CaO (14.76–16.17 wt.%) and low concentrations of SiO₂ (27.08–29.93 wt.%), TiO₂ (0.72–0.80 wt.%) and P_2O_5 (2.13–2.46 wt.%) (Figure 5). The damkjernites are classified as low-titanium lamprophyre (TiO₂ < 1.5%) and show high alkali concentrations of 7.35–7.64 wt.%. Their K/Al and K/(K + Na) ratios are 1.19–1.22 and 0.85–0.95, respectively. In the TAS diagram, the samples fall into the foidite field and belong to the alkaline series. In the (K₂O + Na₂O) vs. SiO₂ classification diagram (Figure 6A), the samples are close to the ultrabasic lamprophyre fields, while in the K/Al vs. K/(K + Na) diagram (Figure 6B), the samples fall into the peraluminite lamprophyre and potassium-magnesium lamprophyre fields.

The chondrite-normalized REE patterns of the lamprophyres show right-inclined characters (Figure 7A and Table 1). The high $(La/Lu)_N$ (85–286) and $(La/Yb)_N$ (66–220)

ratios indicated strong fractionation between light rare earth elements (LREEs) and heavy rare earth elements (HREEs). High $(La/Sm)_N$ (7.13–16.26), $(Gd/Yb)_N$ (4.64–11.30) and LREEs/HREEs (12–32) ratios indicated high fractionation from LREEs to HREEs. There were high concentrations of total REEs ranging from 1012 to 2793 ppm. LREE content ranged from 976 to 2793 ppm and the HREE content ranged from 32 to 135 ppm. In the primitive mantle-normalized trace element patterns (Figure 7B), all samples showed relative enrichment of large ion lithophile element (LILEs, Rb and Ba) and LREEs (La and Ce) and strong depletion of high field strength element (HFSEs, Nb, Ta, Ti and Zr) and HREEs, among which Nb, Ta and Ti showed significantly negative "TNT" anomalies.



Figure 7. (**A**) Chondrite-normalized REE patterns for lamprophyres. (**B**) Primitive mantle-normalized trace element patterns for lamprophyres. Data sources: chondrite [37], primitive mantle [38], N-MORB and OIB [39].

5.2. Zircon U-Pb Geochronology

Most of the zircons from the lamprophyre (20CS15) are colorless, transparent, subhedral to anhedral and had rounded or irregular morphology. The zircon grains show grain sizes of 50–300 μ m and aspect ratios of 1:1–2.5:1. In the cathodoluminescence (CL) image, the zircons show obvious patchy, banded and sector zoning (Figure 8A), indicating a magmatic origin [40].

Seventeen zircons from the lamprophyre (20CS15) were analyzed (Table 2). To obtain an accurate and reliable age, most of the analyzed spots were selected from the large grains of the magmatic oscillatory zoning domain. The measured concentrations of U and Th in these zircons are 545–1999 ppm and 14–3290 ppm, respectively. Th/U ratios ranged from 0.38 to 0.61, similar to magmatic zircon (Th/U > 0.1) [41]. The sample yield a weighted mean age of 125 \pm 0.86 Ma (2 σ , *n* = 17, MSWD = 0.60) (Figure 8B), representing the crystallization age of lamprophyre.



Figure 8. (**A**) CL image of zircon grains from lamprophyre sample 20CS15. (**B**) Zircon U-Pb concordant plot for the lamprophyre sample 20CS15.

	Sample	20CS15	21CS03	21CS01	21CS01A	11SF01	11SF02	11SF03	11SF04	11SF05	SF1-1	SF1-2	11SZ05-01	11SZ05-02	11SZ02-01	11SZ02-02	11SZ02-03
	Data Source		This	Study							Yang	et al. [42]					
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	SiO ₂	55.44	52.74	27.08	29.93	44.08	45.56	45.55	40.22	46.23	45.99	46.04	41.51	42.38	34.74	34.42	34.39
Ko 180 6.33 7.79 6.66 4.2 4.22 322 4.34 3.79 3.84 3.62 3.64 3.08 3.13 3.15 ALO 1.33 1.35 0.37 0.78 1.26 1.43 1.52 1.08 1.075 1.08 1.075 1.23 1.04 0.04 0.07 0.07 0.07 0.05 0.07 0.07 0.03 0.05 0.07 0.07 0.03 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 0.04 </td <td>MgO</td> <td>4.55</td> <td>1.79</td> <td>12.16</td> <td>13.07</td> <td>4.73</td> <td>4.18</td> <td>4.73</td> <td>4.4</td> <td>4.92</td> <td>6.11</td> <td>6.03</td> <td>1.71</td> <td>1.74</td> <td>13.92</td> <td>13.78</td> <td>13.76</td>	MgO	4.55	1.79	12.16	13.07	4.73	4.18	4.73	4.4	4.92	6.11	6.03	1.71	1.74	13.92	13.78	13.76
NepO 7.45 3.53 0.25 0.79 1.54 1.62 1.6 1.64 1.43 1.85 1.72 2.78 2.84 0.77 0.76 1.2 CoO 5.20 2.00 1.61 11.25 11.21 11.25 11.2	K ₂ O	1.80	6.33	7.39	6.56	4.2	4.2	4.22	3.82	4.34	3.79	3.98	3.62	3.64	3.08	3.13	3.13
Co.O 5.20 2.05 14.17 14.76 12.12 11.51 11.02 11.02 11.03 16.83 16.82 12.05 12	Na ₂ O	7.45	3.53	0.25	0.79	1.54	1.62	1.6	1.26	1.43	1.85	1.72	2.78	2.84	0.77	0.76	1.2
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	CaO	5.20	2.05	16.17	14.76	12.57	12.12	11.51	11.75	12.01	11.02	11.15	16.38	16.82	12.05	12.03	11.98
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Al_2O_3	12.31	18.80	7.21	6.59	10.46	10.55	10.52	9.41	10.52	10.98	10.75	11.91	12.13	7.08	7	6.99
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	TFe ₂ O ₃	8.32	8.56	7.32	6.60	5.83	6.03	5.89	5.19	5.8	5.87	5.81	5.26	5.37	10.97	11.03	11
Prob 0.68 0.23 2.46 2.13 0.78 0.87 0.83 0.87 0.89 1.67 1.69 MaO 0.08 0.07 0.04 0.07 0.08 0.07 0.08 0.07 0.09 0.04 0.07 0.08 0.07 0.09 0.04 0.07 0.08 0.07 0.09 0.04 0.07 0.09 0.07 0.09 0.07 0.09 0.08 0.07 0.09 0.07 0.09 0.07 0.09 0.07 0.09 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.03 0.04 0.04 0.04 0.05 0.05 0.07 0.04 0.04 0.05 0.03 0.03 0.03 0.04 0.04 0.04 0.03 0.05 0.06 0.05 0.06 0.04 0.04 0.04 0.03 0.05 0.07 0.04 0.04 0.03 0.05 0.07 0.0	TiO ₂	0.59	0.52	0.80	0.72	0.75	0.78	0.74	0.61	0.65	0.76	0.72	0.5	0.51	2.25	2.25	2.25
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	P_2O_5	0.68	0.23	2.46	2.13	0.78	0.87	0.78	0.69	0.75	0.83	0.83	0.87	0.89	1.67	1.69	1.67
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	MnO	0.08	0.07	0.15	0.18	0.08	0.08	0.07	0.06	0.07	0.08	0.07	0.09	0.09	0.14	0.14	0.14
	LOI	4.76	3.56	12.84	11.22	13.78	12.76	13.18	22.3	12.62	12.26	12.29	14.81	13.32	13.24	13.18	13.19
k ₂ (N _k) 9.25 9.86 7.64 7.24 7.24 7.24 7.24 7.24 7.24 7.24 7.24 7.24 7.24 7.24 7.2 7.2 7.3 7.3 Mg8 0.23 0.24 0.27 0.24 1.47 160 163.4 9.84 163.4 163.4 163.4 39.84 36.47 22.2 21.8 22.2 23 34.3 43.7 153 124 141 143 12.7 156.6 54.4 53.8 123	Total (%)	101.16	98.19	93.82	92.53	98.8	98.8	98.8	99.73	99.35	99.5	99.39	99.43	99.72	99.92	99.42	99.69
K _A O, Na ₂ O 0.24 1.79 30.04 8.27 0.37 0.39 0.38 0.33 0.49 0.43 0.77 0.78 0.25 0.24 0.38 Mgt 52.24 29.49 7687 79.33 64 60 64 65 65 70 70 42 24 74 73 73 K/(Na + N 0.11 0.44 0.45 0.47 0.48 0.44 0.44 0.46 0.45 0.56 0.53 0.53 L 24.49 25.19 47.07 0.75 0.41 0.44 0.54 0.56 0.57 77.1 0.75 0.43 Sin 0.54 9.04 1.53 9.04 1.64 4.29 4.49 4.89 4.64 6.64 6.7 0.7 77.1 1.35 9.35 Md 16.34 9.38 3.47 1.62 1.64 1.22 1.61 2.23 1.44 1.47 1.46 1.45 1.5	$K_2O + Na_2O$	9.25	9.86	7.64	7.35	5.74	5.82	5.82	5.09	5.77	5.64	5.7	6.4	6.47	3.85	3.89	4.33
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	K_2O/Na_2O	0.24	1.79	30.04	8.27	0.37	0.39	0.38	0.33	0.33	0.49	0.43	0.77	0.78	0.25	0.24	0.38
K/Λ 0.17 0.49 1.12 0.14 0.44 0.44 0.43 0.44 0.43 0.46 0.56 0.52 0.53 0.53 La 248.29 285.91 487.81 942.85 212 216 209 199 198 199 206 279 274 147 160 158 C 441.04 487.81 942.85 212 216 209 199 198 199 206 279 274 147 160 158 C 441.04 43.93 44.4 42.9 44.9 43.9 41.3 46.4 62.5 60.7 37.5 39.9 40.8 Sm 18.9 16.34 39.84 36.47 27.7 50.7 50.44 81.4 7.75 50.66 51.9 40.8 Gd 13.0 0.42 12.3 13.7 12.5 14.6 14.5 14.9 14.48 22.7 12.8 16.8 16.	Mg#	52.24	29.49	76.87	79.83	64	60	64	65	65	70	70	42	42	74	73	73
	K/Al	0.17	0.40	1.22	1.19	0.48	0.47	0.48	0.48	0.49	0.41	0.44	0.36	0.36	0.52	0.53	0.53
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	K/(Na + K)	0.14	0.54	0.95	0.85	0.64	0.63	0.63	0.67	0.67	0.57	0.60	0.46	0.46	0.73	0.73	0.63
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	La	248.29	285.91	487.81	942.85	212	216	209	199	198	199	206	279	274	147	160	158
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Ce	471.20	514.98	767.85	1255.00	401	405	393	392	388	378	406	543	535	321	325	325
Nd163.43156.05221.05334.76162164157165160162170230219145155155Eu5.073.7810.188.535.175.22.42.392.42.252.42.39Gd14810.3528.7523.3513.513.712.214.614.514.914.82.475.065.945.96Tb1.300.953.242.051.291.321.261.331.311.311.971.961.881.541.59Dy5.004.521.508.645.475.645.475.315.315.315.357.967.816.697.136.91Ho0.730.602.101.120.830.820.820.840.860.861.241.141.021.111.11Fr1.631.905.803.121.741.781.711.771.781.951.862.452.142.020.220.220.220.210.210.210.240.420.441.691.62Tm0.170.170.690.360.220.220.220.220.220.210.210.24 <t< td=""><td>Pr</td><td>51.69</td><td>49.82</td><td>79.02</td><td>111.15</td><td>43.9</td><td>44.4</td><td>42.9</td><td>44.9</td><td>43.9</td><td>41.3</td><td>46.4</td><td>62.5</td><td>60.7</td><td>37.5</td><td>39.9</td><td>40.8</td></t<>	Pr	51.69	49.82	79.02	111.15	43.9	44.4	42.9	44.9	43.9	41.3	46.4	62.5	60.7	37.5	39.9	40.8
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Nd	163.43	156.05	271.05	334.76	162	164	157	165	160	162	170	230	219	145	155	155
Eu 5.07 3.78 10.18 8.53 5.17 5.2 4.93 4.87 4.77 5.07 5.04 8.14 7.75 5.66 5.94 5.98 Gd 14.84 10.35 28.75 23.35 13.5 13.7 12.5 14.6 14.5 14.9 14.8 1.37 1.96 1.88 1.54 1.59 1.62 Dy 5.00 4.52 15.20 8.64 5.47 5.31 5.31 5.85 5.7 7.97 7.71 6.69 7.13 6.91 Ho 0.73 0.60 2.10 1.12 0.83 0.82 0.84 0.84 0.86 0.86 1.2 1.14 1.02 1.11 1.11 Fr 1.63 1.90 5.80 0.32 0.22 0.22 0.22 0.22 0.22 0.22 0.21 0.24 0.2 0.2 0.21 0.23 0.24 0.21 0.21 0.21 0.21 0.21 <	Sm	21.89	16.34	39.84	36.47	22.7	22.8	21.8	22.2	21.6	22.2	23	34.9	32.8	22.5	24	23.9
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Eu	5.07	3.78	10.18	8.53	5.17	5.2	4.93	4.87	4.77	5.07	5.04	8.14	7.75	5.66	5.94	5.98
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Gd	14.84	10.35	28.75	23.35	13.5	13.7	12.5	14.6	14.5	14.9	14.8	22.7	21.2	15.6	16.8	16.2
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Tb	1.30	0.95	3.24	2.05	1.29	1.32	1.26	1.33	1.32	1.41	1.37	1.96	1.88	1.54	1.59	1.62
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Dy	5.00	4.52	15.20	8.64	5.47	5.64	5.47	5.31	5.31	5.85	5.5	7.97	7.71	6.69	7.13	6.91
Er1.631.905.803.121.741.781.711.771.781.951.82.452.362.142.342.37Tm0.170.161.135.002.281.321.311.31.291.331.291.321.821.691.461.631.62Lu0.120.100.590.370.170.180.180.180.180.170.190.240.240.240.20.21<	Ho	0.73	0.60	2.10	1.12	0.83	0.83	0.82	0.84	0.84	0.86	0.86	1.2	1.14	1.02	1.11	1.11
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Er	1.63	1.90	5.80	3.12	1.74	1.78	1.71	1.77	1.78	1.95	1.8	2.45	2.36	2.14	2.34	2.37
Yb 1.06 1.13 5.00 2.88 1.32 1.31 1.3 1.29 1.33 1.29 1.32 1.82 1.69 1.46 1.63 1.62 Lu 0.12 0.10 0.59 0.37 0.17 0.18 0.18 0.18 0.17 0.19 0.24 0.2	Tm	0.17	0.17	0.69	0.36	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.31	0.29	0.27	0.29	0.29
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Yb	1.06	1.13	5.00	2.88	1.32	1.31	1.3	1.29	1.33	1.29	1.32	1.82	1.69	1.46	1.63	1.62
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Lu	0.12	0.10	0.59	0.37	0.17	0.18	0.18	0.18	0.18	0.17	0.19	0.24	0.24	0.2	0.21	0.21
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Zr	587.35	623.90	868.60	801.45	223	234	231	220	230	230	231	299	297	312	321	334
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Nb	27.15	73.06	10.61	12.06	8.2	8.36	8.27	7.68	7.8	8.2	7.99	10.9	11	61.5	62.6	62.4
V 81.49 66.15 121.14 105.94 85.5 85.2 85.6 78.9 80.7 90.7 83.3 99.1 99.3 183 168 185 Cr 33.30 8.62 496.46 401.29 535 530 531 510 510 532 518 104 108 624 322 629 Co 13.61 4.44 39.48 41.43 23.1 26.8 27.8 21.5 26.7 21.2 21.1 19.6 19.7 58.1 55.4 56.7 Ni 24.20 9.43 282.26 377.92 269 269 246 234 219 242 243 106 106 325 311 319 Cu 24.19 31.23 16.95 62.66 12.2 13.7 15.4 13.1 15.9 14.1 15.2 46.8 47.6 60.2 57.7 59.4 Zn 54.94 53.73 149.61 165.00 81.9 85.4 78.6 84.6 81.8 76.4 88.8 77.1 79.6 106 105 105 Ga 29.50 52.80 84.10 13.70 19 19.4 19 17.8 17.6 16.2 17.9 18.3 16.4 70.4 72.2 Sr 5967.00 1037.34 9809.50 8965.21 738 725 771 694 730 981 991 684 690 1162 1	Ti	3519.60	3116.54	4794.67	4285.24	4500	4680	4440	3660	3900	4560	4320	3000	3060	13,500	13,500	13,500
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	V	81.49	66.15	121.14	105.94	85.5	85.2	85.6	78.9	80.7	90.7	83.3	99.1	99.3	183	168	185
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Cr	35.30	8.62	496.46	401.29	535	530	531	510	510	532	518	104	108	624	322	629
Ni 24.20 9.43 282.26 377.92 269 269 246 234 219 242 243 106 106 325 311 319 Cu 24.19 31.23 16.95 62.66 12.2 13.7 15.4 13.1 15.9 14.1 15.2 46.8 47.6 60.2 57.7 59.4 Zn 54.94 53.73 149.61 1650.0 81.9 85.4 78.6 84.6 81.8 76.4 88.8 77.1 79.6 106 105 105 105 Ga 29.50 52.80 84.10 131.70 19 19.4 19 17.8 17.6 162 17.9 19.4 19.7 15.8 16.1 Rb 45.47 141.39 547.10 383.06 113 105 108 113 107 96.7 102 73.8 74.8 56.4 70.4 72.2 Sr 5967.00 1037.34 9809.50 8965.21 73.8 725 771 694 730 981 991 684 690 1162 1182 1213 Cs 2.12 0.75 9.66 6.74 6.13 5.65 5.79 6.8 6.34 4.89 5.77 1.79 1.82 63.9 67.9 77.0 Ba 2814.60 1651.00 3597.10 6457.00 2199 2008 2032 2177 2017 2188 2536 740 753	Co	13.61	4.44	39.48	41.43	23.1	26.8	27.8	21.5	26.7	21.2	21.1	19.6	19.7	58.1	55.4	56.7
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Ni	24.20	9.43	282.26	377.92	269	269	246	234	219	242	243	106	106	325	311	319
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Cu	24.19	31.23	16.95	62.66	12.2	13.7	15.4	13.1	15.9	14.1	15.2	46.8	47.6	60.2	57.7	59.4
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Zn	54.94	53.73	149.61	165.00	81.9	85.4	78.6	84.6	81.8	76.4	88.8	77.1	79.6	106	105	105
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Ga	29.50	52.80	84.10	131.70	19	19.4	19	17.8	17.6	16.2	17.9	19.8	19.4	15.7	15.8	16.1
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Rb	45.47	141.39	547.10	383.06	113	105	108	113	107	96.7	102	73.8	74.8	56.4	70.4	72.2
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Sr	5967.00	1037.34	9809.50	8965.21	738	725	771	694	730	981	991	684	690	1162	1182	1213
Ba 2814.60 1651.00 3597.10 6457.00 2199 2008 2032 2177 2017 2188 2536 740 753 1705 1751 1801 Ta 2.53 1.73 0.41 0.47 0.33 0.33 0.35 0.37 0.34 0.36 0.48 0.45 3.34 3.34 3.57 Pb 30.48 17.15 17.39 29.17 10.4 11.2 11.6 10.7 12 10.1 11 29.8 28.2 15 15.3 15.4 U 8.01 1.68 1.81 1.72 1.67 1.73 1.63 1.68 4.87 4.65 11.05 10.8 11.2 Th 23.98 49.72 6.50 9.81 200 20.7 20.4 19.5 19.7 20.1 20.2 36.2 34.9 6.75 18.2 18.1	Cs	2.12	0.75	9.66	6.74	6.13	5.65	5.79	6.8	6.34	4.89	5.77	1.79	1.82	63.9	67.9	70.6
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Ba	2814.60	1651.00	3597.10	6457.00	2199	2008	2032	2177	2017	2188	2536	740	753	1705	1751	1801
Pb 30.48 17.15 17.39 29.17 10.4 11.2 11.6 10.7 12 10.1 11 29.8 28.2 15 15.3 15.4 U 8.01 1.68 1.81 1.72 1.67 1.73 1.63 1.68 4.87 4.65 11.05 10.8 11.2 Th 23.98 49.72 6.50 9.81 20 20.7 20.4 19.5 19.7 20.1 20.2 36.2 34.9 6.75 18.2 18.1	Ta	2.53	1.73	0.41	0.47	0.33	0.33	0.33	0.35	0.37	0.34	0.36	0.48	0.45	3.34	3.34	3.57
U 8.01 1.68 1.81 1.72 1.67 1.73 1.63 1.68 4.87 4.65 11.05 10.8 11.2 Th 23.98 49.72 6.50 9.81 20 20.7 20.4 19.5 19.7 20.1 20.2 36.2 34.9 6.75 18.2 1.81	Pb	30.48	17.15	17.39	29.17	10.4	11.2	11.6	10.7	12	10.1	11	29.8	28.2	15	15.3	15.4
The 23.98 49.72 6.50 9.81 20 20.7 20.4 19.5 19.7 20.1 20.2 36.2 34.9 6.75 18.2 18.1	Ū	8.01				1.68	1.81	1.72	1.67	1.73	1.63	1.68	4.87	4.65	11.05	10.8	11.2
111 20.70 7.72 0.00 7.01 20 20.7 20.7 17.7 17.7 20.1 20.2 0.2 0.7 0.7.7 10.2 10.1	Th	23.98	49.72	6.50	9.81	20	20.7	20.4	19.5	19.7	20.1	20.2	36.2	34.9	6.75	18.2	18.1

Table 1. Major, trace and rare earth element (REE) compositions for the lamprophyres.

Table 1. Cont.	

Sample	20CS15	21CS03	21CS01	21CS01A	11SF01	11SF02	11SF03	11SF04	11SF05	SF1-1	SF1-2	11SZ05-01	11SZ05-02	11SZ02-01	11SZ02-02	11SZ02-03
Data Source		This	Study							Yang e	et al. [42]					
Y	20.18	20.92	89.29	50.29	24.3	24.6	23.7	23.1	22.8	24.3	23.7	31.5	32.2	20.8	25.4	26.2
Sc	5.63	2.50	13.70	12.68	13.2	13.3	13.4	13.2	13.3	13.3	12.9	9.48	9.53	3.81	19.7	20
REE	1012.23	1070.03	1820.09	2793.61	871	883	851	853	841	834	882	1196	1165	707	740	740
LREEs	976.40	1037.23	1684.48	2712.10	847	858	828	827	815	807	856	1157	1129	678	709	709
HREEs	35.83	32.80	135.61	81.50	24.6	25	23.5	25.5	25.4	26.7	26.1	38.6	36.5	28.9	31.1	30.3
LREEs/HREEs	27.25	31.62	12.42	33.28	34.5	34.3	35.3	32.4	32.1	30.2	32.8	30	30.9	23.4	22.8	23.4
δCe	0.95	0.96	0.86	0.79	1.00	0.99	1.00	1.00	1.00	1.01	1.00	0.98	1.00	1.08	0.96	0.95
δΕυ	0.81	0.83	0.88	0.84	0.83	0.83	0.84	0.78	0.78	0.8	0.78	0.83	0.84	0.88	0.86	0.88
Lu/Yb	0.11	0.09	0.12	0.13	0.13	0.14	0.14	0.14	0.14	0.13	0.14	0.13	0.14	0.14	0.13	0.13
Nb/Yb	25.62	64.94	2.12	4.18	6.21	6.38	6.36	5.95	5.86	6.36	6.05	5.99	6.51	42.12	38.40	38.52
Th/Yb	18.48	52.08	2.01	4.79	15.15	15.80	15.69	15.12	14.81	15.58	15.30	19.89	20.65	4.62	11.17	11.17
La/Sm	11.34	17.50	12.24	25.85	9.34	9.47	9.59	8.96	9.17	8.96	8.96	7.99	8.35	6.53	6.67	6.61
Rb/Sr	0.01	0.14	0.06	0.04	0.15	0.14	0.14	0.16	0.15	0.1	0.1	0.11	0.11	0.05	0.06	0.06
Ba/Rb	61.90	11.68	6.57	16.86	19.5	19.2	18.9	19.3	18.9	22.6	24.8	10	10.1	30.2	24.9	25
Dy/Yb	4.72	4.02	3.04	3.00	26.40	26.60	26.94	24.57	27.08	24.38	25.02	16.50	17.87	17.51	15.93	16.03
K/(Ýb*1000)	14.12	46.69	12.27	18.86	4.14	4.31	4.21	4.12	3.99	4.53	4.17	4.38	4.56	4.58	4.37	4.27
Nb/U	3.38				4.88	4.62	4.8	4.61	4.52	5.02	4.76	2.23	2.37	5.56	5.8	5.58
Ba/Th	117.36	33.20	553.33	658.29	109.95	97.00	99.61	111.64	102.39	108.86	125.54	20.44	21.58	252.59	96.21	99.50
Th/Nb	0.88	0.68	0.61	0.81	2.44	2.48	2.47	2.54	2.53	2.45	2.53	3.32	3.17	0.11	0.29	0.29
La/Ta	97.96	165.39	1201.02	1995.94	642.42	654.55	633.33	568.57	535.14	585.29	572.22	581.25	608.89	44.01	47.90	44.26
Sr/Th	248.80	20.86	1508.96	914.01	36.90	35.02	37.79	35.59	37.06	48.81	49.06	18.90	19.77	172.15	64.95	67.02
Th/Ce	0.05	0.10	0.01	0.01	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.07	0.07	0.02	0.06	0.06
(La/Sm)N	7.13	11.01	7.70	16.26	6.04	6.12	6.20	5.79	5.92	5.79	5.79	5.17	5.40	4.22	4.31	4.27
(Gd/Yb)N	11.30	7.42	4.64	6.53	8.46	8.65	7.95	9.36	9.02	9.55	9.27	10.32	10.38	8.84	8.53	8.27
(La/Yb)N	157.95	171.33	65.79	220.46	115.25	118.32	115.37	110.70	106.83	110.70	111.99	110.01	116.35	72.25	70.44	69.99
(La/Lu)N	218.36	286.38	85.37	261.66	134.33	129.26	125.07	119.08	118.49	126.09	116.79	125.22	122.97	79.17	82.07	81.04

		14				ope aata N	or nerountite (200010/11	sin the meisik	in ureu.						
C t	C	ontents (pp	om)			Age (Ma)										
Spot -	Pb	Th	U	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	2σ	²⁰⁷ Pb/ ²³⁵ U	2σ	²⁰⁶ Pb/ ²³⁸ U	2σ	²⁰⁷ Pb/ ²⁰⁶ Pb	2σ	²⁰⁷ Pb/ ²³⁵ U	2σ	²⁰⁶ Pb/ ²³⁸ U	2σ
20CS15-01	47.63	938.03	1892.70	0.50	0.05206	0.00140	0.14416	0.00385	0.01992	0.00024	287.1	58.3	136.7	3.4	127.1	1.5
20CS15-02	36.40	562.41	1511.96	0.37	0.05259	0.00142	0.14286	0.00355	0.01963	0.00024	309.3	58.3	135.6	3.2	125.3	1.5
20CS15-03	54.33	1088.00	2162.34	0.50	0.05250	0.00127	0.14309	0.00316	0.01965	0.00021	305.6	55.6	135.8	2.8	125.4	1.3
20CS15-04	84.72	1999.20	3290.22	0.61	0.05169	0.00118	0.14165	0.00297	0.01973	0.00019	272.3	53.7	134.5	2.6	125.9	1.2
20CS15-05	44.25	853.09	1803.27	0.47	0.05221	0.00133	0.14189	0.00344	0.01953	0.00021	294.5	57.4	134.7	3.1	124.7	1.3
20CS15-06	44.30	974.70	1863.56	0.52	0.05075	0.00135	0.13469	0.00357	0.01908	0.00023	227.8	65.7	128.3	3.2	121.8	1.4
20CS15-07	37.20	673.85	1522.13	0.44	0.05266	0.00126	0.14469	0.00334	0.01977	0.00023	322.3	55.6	137.2	3.0	126.2	1.5
20CS15-08	41.76	850.65	1736.81	0.49	0.04988	0.00133	0.13640	0.00365	0.01966	0.00025	190.8	61.1	129.8	3.3	125.5	1.6
20CS15-09	45.63	763.78	1838.45	0.42	0.05226	0.00146	0.14132	0.00380	0.01948	0.00028	298.2	67.6	134.2	3.4	124.4	1.8
20CS15-10	43.32	710.59	1723.66	0.41	0.05079	0.00147	0.13872	0.00400	0.01964	0.00028	231.6	68.5	131.9	3.6	125.4	1.8
20CS15-11	42.12	750.29	1656.49	0.45	0.05309	0.00139	0.14495	0.00363	0.01966	0.00027	331.5	59.3	137.4	3.2	125.5	1.7
20CS15-12	55.06	972.20	2289.50	0.42	0.05292	0.00136	0.14069	0.00340	0.01920	0.00023	324.1	59.3	133.7	3.0	122.6	1.4
20CS15-13	45.31	853.08	1793.17	0.48	0.05321	0.00142	0.14380	0.00375	0.01953	0.00021	338.9	61.1	136.4	3.3	124.7	1.3
20CS15-14	35.08	544.69	1418.67	0.38	0.05240	0.00154	0.14184	0.00391	0.01966	0.00026	301.9	66.7	134.7	3.5	125.5	1.7
20CS15-15	40.32	578.15	1639.03	0.35	0.05073	0.00130	0.13719	0.00357	0.01956	0.00022	227.8	59.3	130.5	3.2	124.9	1.4
20CS15-16	36.25	605.66	1416.37	0.43	0.05085	0.00135	0.13878	0.00370	0.01978	0.00022	235.3	61.1	132.0	3.3	126.2	1.4
20CS15-17	36.46	617.81	1506.39	0.41	0.05189	0.00128	0.13761	0.00328	0.01928	0.00021	279.7	55.6	130.9	2.9	123.1	1.3

Table 2. LA-ICP-MS zircon U-Pb isotope data for kersantite (20CS15) from the Weishan area.

5.3. Zircon Lu-Hf Isotope

The Lu-Hf isotopic analysis of zircons from the lamprophyre (20CS15) (Table 3) show that the ¹⁷⁶Lu/¹⁷⁷Hf ratios for all measured results ranged from 0.0011 to 0.0015. The ¹⁷⁶Hf/¹⁷⁷Hf ratios of 17 zircons ranged from 0.282274 to 0.282442, with an average of 0.282359. Zircon ε Hf(t) values were all in the negative range, from –14.98 to –9.03 (Figure 9A) with an average of –11.98, and they were plotted between the lower crust and paleo-lower crust reconstruction lines (Figure 10). The single-stage-model and two-stage-model ages were 1.1–1.4 Ga and 1.7–2.1 Ga, respectively (Figure 9B).

Table 3. Zircon Lu-Hf isoto	ope data foi	: kersantite ((20CS15)) from the	Weishan area.
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Sample	Age (Ma)	¹⁷⁶ Lu/ ¹⁷⁷ Hf	¹⁷⁶ Hf/ ¹⁷⁷ Hf	2σ	εHf(0)	εHf(t)	T _{DM1}	T _{DM2}	f _{Lu/Hf}
20CS15-1	127.1	0.0013	0.282408	0.000037	-12.87	-10.20	1202	1824	-0.96
20CS15-2	125.3	0.0012	0.282411	0.000031	-12.77	-10.12	1195	1818	-0.96
20CS15-3	125.4	0.0012	0.282335	0.000033	-15.45	-12.80	1302	1987	-0.96
20CS15-4	125.9	0.0015	0.282274	0.000035	-17.61	-14.98	1398	2124	-0.95
20CS15-5	124.7	0.0011	0.282381	0.000029	-13.83	-11.18	1234	1884	-0.97
20CS15-6	121.8	0.0014	0.282436	0.000032	-11.88	-9.32	1166	1765	-0.96
20CS15-7	126.2	0.0012	0.282366	0.000032	-14.36	-11.69	1258	1918	-0.96
20CS15-8	125.5	0.0017	0.282335	0.000032	-15.45	-12.84	1319	1989	-0.95
20CS15-9	124.4	0.0012	0.282297	0.000030	-16.80	-14.17	1355	2072	-0.96
20CS15-10	125.4	0.0011	0.282363	0.000032	-14.46	-11.81	1259	1924	-0.97
20CS15-11	125.5	0.0014	0.282442	0.000030	-11.67	-9.03	1157	1750	-0.96
20CS15-12	122.6	0.0013	0.282367	0.000029	-14.32	-11.75	1260	1918	-0.96
20CS15-13	124.7	0.0011	0.282318	0.000030	-16.06	-13.42	1322	2025	-0.97
20CS15-14	125.5	0.0011	0.282349	0.000030	-14.96	-12.30	1278	1955	-0.97
20CS15-15	124.9	0.0014	0.282403	0.000029	-13.05	-10.43	1212	1837	-0.96
20CS15-16	126.2	0.0012	0.282334	0.000026	-15.49	-12.82	1303	1989	-0.96
20CS15-17	123.1	0.0014	0.282282	0.000031	-17.33	-14.75	1383	2107	-0.96



Figure 9. (A) Histogram of zircon ε Hf(t) values for the lamprophyre (20CS15). (B) Histogram of two-stage-model age for the lamprophyre.



Figure 10. (**A**,**B**) are ε Hf(t) vs. age (Ma) diagrams for lamprophyre (20CS15) from the Weishan area. (**A**) is enlarged from (**B**) to show the data variations.

6. Discussion

6.1. Early Cretaceous Intrusion of Lamprophyre Dike

Zircons from the lamprophyre of the Weishan area show obvious patchy, banded and sector zoning and high Th/U ratios of 0.38–0.61, indicating magmatic zircon. The analyzed spots yielded a weighted mean age of 125 Ma, which can be interpreted as the crystallization age of the lamprophyre. Qiu et al. [43] reported a K-Ar age of 120 Ma from the phlogopite of the lamprophyre in the Jingziyu area. Yang et al. [42] reported a zircon LA-ICP-MS U-Pb age of 126–132 Ma from the lamprophyre in the Xiaya and Jingziyu areas. The magma source of the lamprophyre from the Weishan, Jingziyu and Xiaya areas of the Luxi Terrane was an emplaced simultaneous source. Therefore, the mafic dike intrusions in the Luxi area were formed from 132–120 Ma, which is consistent with peak Early Cretaceous magmatic events in the eastern NCC.

Liang et al. [21] discussed the zircon LA-ICP-MS U-Pb age of Weishan alkaline rocks and showed that the crystallization age of the quartz syenite was 122 Ma and that of the aegirine quartz syenite porphyry was 130 Ma. Wei et al. [25] obtained zircon U-Pb ages of 127–126 Ma for the quartz syenite and alkali granite. Therefore, the alkaline and mafic magma were emplaced simultaneously during the Early Cretaceous.

6.2. Crustal Contamination

The lamprophyre from the Weishan area show low concentrations of SiO₂ (27.08–55.44 wt.%) and TiO₂ (0.52–0.80 wt.%); high concentrations of K₂O (1.80–7.39 wt.%), MgO (1.79–13.07 wt.%) and alkali (7.35–9.86 wt.%); and a high Mg# (29.49–79.83), which are characteristic of a deep mantle source [44]. Although crustal contamination shows only a limited influence on rapid upwelling and low viscosity magma [45,46], it is necessary to evaluate the effects of crustal contamination.

The crust-like trace element features included enrichment in LILEs (Rb, Ba) and LREEs, depleted HREEs and HFSEs (Nb, Ta, Ti, Zr), negative Nb-Ta and Ti anomalies, which may indicate continental crust material contamination from assimilation or a fractional crystallization process during the magma intrusion [47–49]. However, the lamprophyres show higher concentrations of Ba (1651–6457 ppm) and Sr (1037–9809 ppm) than the average continental crust (390 ppm Ba; 325 ppm Sr) [50], implying that the crust contamination had limited influence on the trace elements during the magma emplacement [51]. In addition, the low Lu/Yb ratios of 0.09–0.13 were close to the mantle-derived magmas (Lu/Yb, 0.14–0.15) rather than the continental crust (Lu/Yb, 0.16–0.18) [39], indicating the absence of crustal contamination. The geochemical evidence was consistent with the absence of inherited zircons within the lamprophyre. Previous studies have also suggested that crustal contamination has limited influence during mafic dike intrusion [52–55]. Therefore, the crust-like trace element features are not the result of crustal contamination from when the magma was ascending.

6.3. Nature of the Magma Source

The abundance of K₂O, alkali enrichment and low ε Hf(t) values (-14.98 to -8.69) suggest that the magma source of the lamprophyres was derived from an enriched mantle [56]. In the Th/Yb vs. Nb/Yb diagram, the lamprophyres also fell into the enriched mantle field (Figure 11A). The high LREE/HREE ratios of those alkaline lamprophyres imply that the enriched source was the lithospheric mantle [57]. Moreover, in the La/Sm vs. La diagram, the lamprophyres show an obvious positive correlation between La/Sm and La, suggesting that the main petrogenetic mechanism was controlled by partial melting rather than fractional crystallization (Figure 11B).



Figure 11. (**A**) Th/Yb vs. Nb/Yb diagram of the lamprophyre from the Weishan area [58]. (**B**) La/Sm vs. La diagram [59].

The lamprophyres exhibited high concentrations of K₂O and were enriched with LILEs and LREEs, which consistently indicate an enriched mantle source. Experimental petrology studies suggest that the volatile-rich minerals phlogopite and amphibole are the major host phases for a LILE-rich lithospheric mantle [60,61]. The compatible elements Rb, Sr and Ba are useful proxies for distinguishing phlogopite from amphibole [62]. The MELTS equilibria with phlogopite show higher Rb/Sr (>0.1) and lower Ba/Rb (<20) ratios. Comparatively, the MELTS equilibria with amphibole show a high Ba concentration and Ba/Rb (>20) ratio [63]. Therefore, there were low Rb/Sr (0.01–0.14) and high Ba/Rb (7–69) ratios in the lamprophyres from the Weishan area (Figure 12A), indicating that the magma source for the lamprophyre was formed by the partial melting of an amphibole-bearing lherzolite mantle. The Dy/Yb vs. K/(Yb*1000) diagram (Figure 12B) is a useful plot to distinguish the spinel-facies (low Dy/Yb ratio; <1.5) and garnet-facies (high Dy/Yb ratio; >2.5) of partial melting [64]. The lamprophyres show high Dy/Yb (3.00–4.72) ratios and K/(Yb*1000) (12.3–46.7) values and were plotted along the garnet-facies and garnet-facies amphibole-bearing lherzolite curve, which implies a low degree of partial melting (0.1-2%)in the garnet-facies. Experimental studies have suggested that the depth of the garnet transition zone is ~85 km [65]. In summary, the magma source of the lamprophyre from Weishan area originated in an enriched mantle through low-degree partial melting of an amphibole-bearing lherzolite mantle at garnet-facies of 85 km depth.



Figure 12. (**A**) Rb/Sr vs. Ba/Rb diagram. (**B**) Dy/Yb vs. K/(Yb*1000) diagram for the lamprophyres from the Weishan area [64].

6.4. Modification of the Mantle Source by Metasomatism

The lamprophyres exhibited higher Th/Yb ratios than MORBs and OIBs [66] (Figure 11A), implying that the mantle magma was enriched. High La/Ta ratios (>30) indicate that the lithospheric mantle enrichment is related to subduction [67]. The Nb/U ratio (3.38) of

lamprophyre was lower than the typical MORB and OIB compositions (Nb/U = 47 [68]; lower (Nb/U = 25) and upper (Nb/U = 4.5) crust [69]), which, together with the high Ba/Th (33.20–658.29) values, suggest that the enriched source was derived from slab dehydration fluids [70,71]. Previous studies have proposed that Early Cretaceous mafic rocks are characterized by high concentrations of H₂O (2–4 wt.%) [72] and suggest that the oceanic crust is the primary source [73]. In the Ba/Th vs. Th/Nb and Sr/Th vs. Th/Ce diagrams, the lamprophyre show large variations in the Ba/Th and Sr/Th ratios, indicating that the mantle source was metasomatized by a fluid source rather than melting [53] (Figure 13A,B). In addition, the new geochemical data from this study show a similar composition as that found for the Xiaya and Jingziyu, indicating that the magma source of the mafic dike in the Luxi Terrane was derived from an enriched mantle source.



Figure 13. (A) Ba/Th vs. Th/Nb diagram [53]. (B) Sr/Th vs. Th/Ce diagram [74].

We therefore propose that the magma emplacement of the 125 Ma lamprophyres from the Weishan area is consistent with Early Cretaceous (120–132 Ma) mafic dike intrusion in the Luxi Terrane [19,75]. The 120–110 Ma compression to extension tectonic transition regime in the eastern NCC triggered large-scale extension and lithosphere thinning [75–79] (Figure 14). The lithospheric mantle was metasomatized by dehydration fluids during the subduction process, and the magma source of the lamprophyre was emplaced during the subsequent extension process in the Early Cretaceous.



Figure 14. Tectonic schematism showing the formation of the lamprophyres in the Weishan area of Luxi Terrane [46,53,80].

7. Conclusions

(1) The parent magma of the lamprophyres in the Weishan area was formed by lowdegree partial melting of the amphibole-bearing lherzolite mantle at garnet-facies without crustal assimilation during its emplacement. The enriched mantle source of the parent magma was derived from the subducted slab dehydration fluids.

(2) The lamprophyre from the Weishan area was formed in an extensional tectonic setting and the mantle source was metasomatized during the subduction process in the Early Cretaceous.

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