Isotope geochronology of Dapingzhang spilite-keratophyre formation in Yunnan Province and its geological significance

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Received July 26, 1999

Abstract On the basis of the geological field investigations and isotope geochronological studies the Sm-Nd isochron age (513 Ma±40 Ma), Rb-Sr isochron age (511 Ma±8 Ma) and K-Ar age (312−317 Ma) of the Dapingzhang spilite-keratophyre formation in Yunnan Province are presented. From these geochronological data it is evidenced that this suite of volcanic rocks was formed in the Cambrian and the parent magma was derived from a depleted mantle, which was influenced by crustal contamination and/or seawater hydrothermal alteration. During the Late Carboniferous the volcanic rocks experienced relatively strong geological reworking. This study provides geochronological evidence for the occurrence of Cambrian volcanic rocks in the Sanjiang (three-river) area.

Keywords: **spilite-keratophyre formation, isotope geochronology, Cambrian, Dapingzhang, Yunnan.**

The Sanjiang (three-river) area of southwestern China is located at the juncture of the Eurasian and Indian plates, where there are widespread various types of intrusive rocks and volcanic rocks. Owing to the unique geological setting and materials, studies of the tectonic evolution of the lithosphere have been attracting more and more attention of geological scholars both at home and abroad. At the present time, the focus of study is placed on the evolution and development of the Paleo-Tethys since the Carboniferous. Relatively speaking, little work has been done in this respect for the time prior to the Carboniferous. Whether there occurred volcanic activities during the Cambrian in this area has long been an open question as there have been no reliable isotope geochronology data available. With the Dapingzhang spilite-keratophyre formation in Yunnan Province as an object of study, this paper provides strong isotope geochronological evidence for the presence of Cambrian volcanic rocks in this area.

1 Geological setting

The Dapingzhang mining district is located at the edges of the Simao Basin in the Sanjiang area of Yunnan Province, sandwiched between the NW-striking Liziqing fault and the Jiufang fault in the east and west (fig.1). Mainly exposed in this area is a suite of rocks dominated by acid rocks such as quartz keratophyre and basic rocks such as spilite. The major rock types include

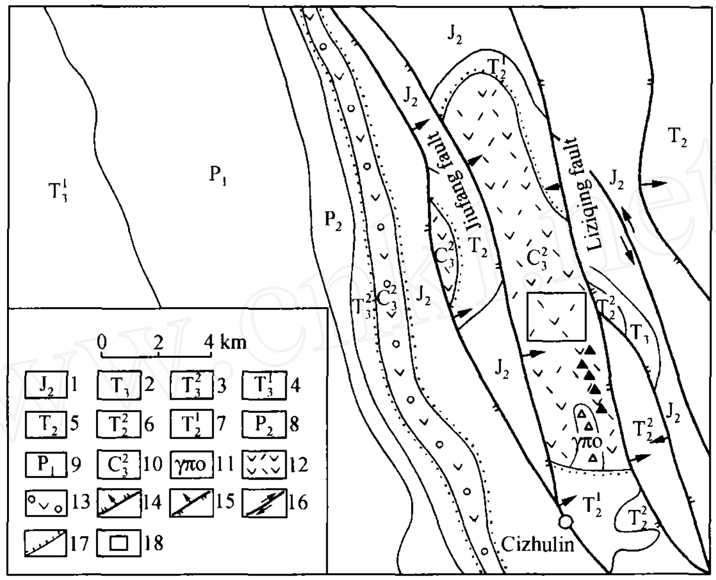

Fig. 1. Regional geological sketch map of the Dapingzhang mining district (simplified after No. 5 Geological Party of Yunnan Province). 1, Sandstone, shale intercalated with marl; 2, clastic rocks intercalated with limestone; 3, sandstone, mudstone intercalated with coal seams; 4, sandstone, shale and limestone; 5, carbonate rocks intercalated with sandstone and shale; 6, limestone, marl and mudstone; 7, limestone, dolomitic limestone; 8, limestone, sandy mudstone; 9, sandstone, mudstone and shale; 10, Longdonghe Formation volcanic rock (upper part ?); 11, granodioritic porphyry; 12, spilite-keratophyre formation; 13, intermediate pyroclastic rock; 14, measured and deduced normal fault; 15, measured and deduced reversed fault; 16, slip fault; 17, unconformable boundary; 18, Dapingzhang mining district. ▲, Spilite-keratophyre sample locality; △, granodioritic porphyry sample locality.

quartz keratophyre, spilite, keratophyre and granodioritic porphyry with recognizable siliceous rock interbeds, and the spilite-keratophyre formation is intruded by the granodioritic porphyry. The large and super-large volcanic rock-type massive sulfide Cu-polymetallic ore deposit at Dapingzhang, which was found three years ago, is hosted in this spilite-keratophyre formation.

2 Sample description

The Sm-Nd, Rb-Sr and K-Ar isotopic compositions of the whole-rock samples of spilite, keratophyre and granodioritic porphyry were analyzed in this study. Fresh samples were collected from the locations far away from the mineralized horizons, which are shown not to have been affected by mineralization alteration.

The spilite occurs as moderate to thin layers, which are grayish-green, yellowish-green and dark grayish-green in color and exhibit porphyritic texture and pillow and massive structures. The rock is composed dominantly of albite (An=3－6), chlorite, clinozoisite, biotite and minor quartz. The albite is present in the form of subhedral slaty and striped crystals and albite twins are commonly seen with Carlsbad twin and Carlsbad albite twin occasionally observed. The albite lattice is filled by chlorite and biotite. The albite exhibits skeletal crystal structure, indicating that it was formed under quenching condition[1,2].

Keratophyre accounts for a small portion of the volcanic rocks in this area and it is light brown and light green in color and mostly exhibits porphyritic texture and compact massive structure. The phenocrysts are dominated by albite (An=2—5) with pyroxene and biotite occasionally observed. The matrix is cryptocrystalline and compact crystalloid. Albite is the main mineral present in the matrix in addition to K-feldspar, chlorite, epidote and minor carbonate minerals.

The granodioritic porphyry exhibits porphyritic texture and phenocrysts are composed mainly of quartz, oligoclase (An=28—32) and K-feldspar. The oligoclase is slaty in form and highly euhedral with well developed albite twins. Quartz phenocrysts show signs of resorption and are racteal drop-shaped, indicating that they were formed at high temperatures. The matrix consists of fine-grained mosaic quartz and plagioclase.

3 Analytical methods

The Sm-Nd and Rb-Sr isotopic compositions of the rock samples were analyzed at the Modern Analysis Center of Nanjing University after they were purified and separated by using high-pressure sealing fusion method and cation exchange techniques, followed by mass spectrometric analysis on a VG-354 mass spectrometer[3]. The La Jolla standard samples gave a $^{143}Nd/^{144}Nd$ ratio of 0.511 860±6(2σ) and the background value of Nd in the whole procedure was $(5-7)\times 10^{-11}$ g. The standard sample NBS-987 gave a $^{87}Sr/^{86}Sr$ ratio of 0.710 243×15(2 σ) and the background value of Sr in the whole procedure was $(1-2)\times 10^{-9}$ g. The $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotopic ratios are normalized on the basis of $^{143}Nd/^{144}Nd$=0.721 9 and $^{87}Sr/^{86}Sr$=0.119 4. The analytical errors involved in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ measurements (2 σ) are ±1% and ±0.5%, respectively. The K-Ar isotopic compositions were analyzed at the Isotope Research and Analysis Center of Yichang Institute of Geology, Chinese Academy of Earth Sciences by using the whole-rock isotope spiking method.

The Rb-Sr and Sm-Nd isochron ages were computed using the Ludwig's ISOPLOT program (Version 2.90) and the age errors are expressed in 2 σ. The decay constants adopted in this work are $\lambda_{Rb}=1.42\times 10^{-11}a^{-1}$, $\lambda_{Sm}=6.54\times 10^{-12}a^{-1}$ and $\lambda_{^{40}K}=5.543\times 10^{-10}a^{-1}$.

4 Results and discussion

4.1 Isotopic ages

The Sm-Nd, Rb-Sr and K-Ar isotope data obtained experimentally are presented in tables 1—3 and the corresponding Sm-Nd and Rb-Sr isochrons are shown in figs. 2 and 3.

4.1.1. Sm-Nd isochron age. $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios in the spilite and keratophyre samples were estimated at 0.120 4—0.200 3 and 0.512 516—0.512 786, respectively. As can be seen in fig. 2, the five data points show a better linear correlation. From this we worked out t=513

$\pm 40(2\sigma)$ Ma, $\varepsilon_{Nd}(t)$=+2.7$\pm$0.8, I_{Nd}=0.512 113$\pm$40(2σ), and MSWD=0.151.

Table 1 The Sm-Nd isotopic analyses of volcanic rocks in the Dapingzhang mining district

Sample No.	Rock type	Sm$\times 10^{-6}$	Nd$\times 10^{-6}$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd(2\sigma)$	$(^{143}Nd/^{144}Nd)_i$	$\varepsilon_{Nd}(t)$
DP_5-7	spilite	1.654	5.886	0.169 9	0.512 682$\pm$15	0.512 114	2.6
DP_5-7′	keratophyre	1.421	6.845	0.120 4	0.512 516$\pm$14	0.512 114	2.6
DP_6-3	keratophyre	4.285	16.21	0.157 8	0.512 645$\pm$19	0.512 118	2.7
DP_6-5′	spilite	2.867	8.659	0.200 3	0.512 786$\pm$17	0.512 117	2.7
DP_6-6	spilite	2.256	8.694	0.151 3	0.512 625$\pm$12	0.512 120	2.7

Analyst: Wang Yinxi with the Modern Analysis Center of Nanjing University.

Table 2 The Rb-Sr isotopic analyses of volcanic rocks in the Dapingzhang mining district

Sample No.	Rock type	Rb$\times 10^{-6}$	Sr$\times 10^{-6}$	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr(2\sigma)$	$(^{87}Sr/^{86}Sr)_i$	$\varepsilon_{Sr}(t)$
DP_5-7	spilite	0.413 4	6.752	0.179 95	0.709 102$\pm$19	0.707 794	55.2
DP_5-7′	keratophyre	4.836	4.608	3.023 7	0.729 806$\pm$25	0.707 829	55.7
DP_6-3	keratophyre	15.12	48.47	0.913 01	0.714 504$\pm$18	0.707 868	56.3
DP_6-5′	spilite	2.736	110.5	0.073 75	0.708 405$\pm$16	0.707 879	56.4
DP_6-6	spilite	1.514	165.7	0.026 75	0.708 008$\pm$27	0.707 814	55.5

Analyst: Wang Jinxi with the Modern Analysis Center of Nanjing University.

Table 3 The K-Ar isotopic analyses of volcanic rocks and supergene intrusive rocks in the Dapingzhang mining district

Sample No.	Rock type	K(%)	$^{40}Ar\times 10^{-6}$	$^{40}Ar/^{40}K$	Age/Ma	Air argon
DP_5-7′	spilite	0.267	0.006 340	0.019 905	313.7	26.3
DP_6-6	spilite	0.085	0.002 005	0.019 773	311.8	36.4
DP_6-3	keratophyre	0.534	0.012 815	0.020 115	316.7	19.9
$\eta_{0\pi}$-1	granodioritic porphyry	0.872	0.020 135	0.019 355	305.7	18.5
$\eta_{0\pi}$-2	granodioritic porphyry	0.511	0.011 382	0.018 671	295.7	22.9
$\eta_{0\pi}$-3	granodioritic porphyry	0.534	0.011 854	0.018 607	294.8	9.7

Analytical unit: The Isotope Research and Analysis Center of Yichang Institute of Geology, Chinese Academy of Earth Sciences.

4.1.2 Rb-Sr isochron age. $^{87}Sr/^{86}Sr$ ratios in the spilite and keratophyre samples vary over the ranges of 0.026 75$-$3.023 7 and 0.708 008$-$0.729 806, respectively. As can be seen in fig. 3, the five data points possess a better linear correlation (r=0.999 9). From this we can work out t=511$\pm$8(2σ)Ma, I_{Sm}=0.707 833$\pm$70(2σ) and MSWD=13.7.

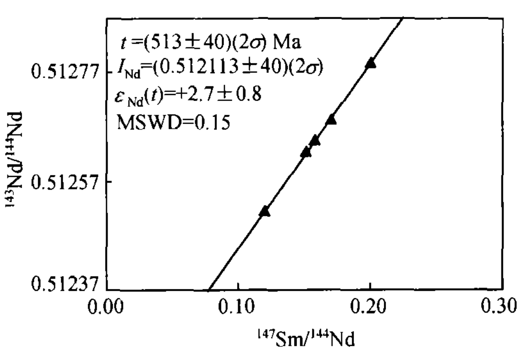

Fig. 2. The Sm-Nd isochron of volcanic rocks in the Dapingzhang mining district.

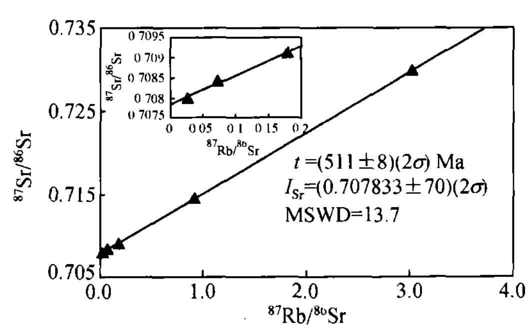

Fig. 3. The Rb-Sr isochron of volcanic rocks in the Dapingzhang mining district.

4.1.3 K-Ar isotopic age. As can be seen from table 3, the K-Ar ages of spilite-keratophyre samples are 311.8$-$313.7 Ma and 316.7 Ma while those of granodioritic porphyry samples are within the range of 294.8—305.7 Ma.

4.2 Forming age of the volcanic rocks and magma source

The data available[4] indicate that the areas studied were affected by two tectono-thermal events. One occurred during the formation of the spilite-keratophyre formation and the other at the time of intrusion of the granodioritic porphyry into the formation. After the emplacement of the contamination in petrogenesis, high $(^{87}Sr/^{86}Sr)_i$ values could be caused by crustal contamination and/or seawater hydrothermal alteration, the former having been evidenced by Nd isotopic characteristics[5—9]. Also, as the seawater contains as much as 8×10^6 Sr and has a high $^{87}Sr/^{86}Sr$ ratio (about 0.709)[11], Sr isotope fractionation between the two in the process of seawater hydrothermal alteration which took place at the time when or immediately after the rocks were formed could also lead to an increase in $(^{87}Sr/^{86}Sr)_i$ values (fig. 4) (cf. refs. [10—14]). In conjunction with the geological setting of this area, the dating characteristics of various isotope dating systems and the above geochronological results, it can be seen clearly that (i) the Rb-Sr and Sm-Nd isochron ages of the spilite-keratophyre formation should represent the forming age of this formation, i.e. this formation should be the product of mantle-source magma eruption during the Cambrian, although the magma was affected by crustal contamination and/or seawater hydrothermal alteration; (ii) its K-Ar age should represent the time when this formation was geologically reworked during the Carboniferous or the intrusion and cooling of the granodioritic porphyry till the K-Ar isotopic system was closed. The K-Ar age of the spilite-keratophyre formation (312—317 Ma) is slightly greater than that (295—306 Ma) of the granodioritic porphyry, which seems to be related to the temperature difference between Ar diffusion and its closeness or the losses of K from fragile K-rich feldspars in acid rocks.

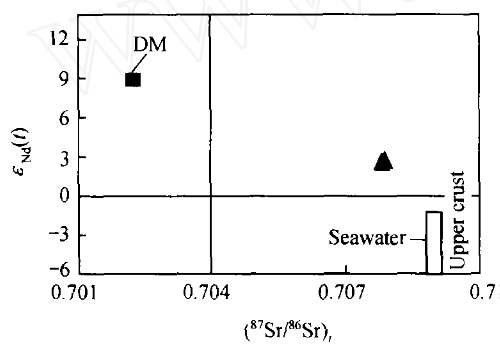

Fig. 4. $\varepsilon_{Nd}(t)$-$(^{87}Sr/^{86}Sr)_i$ diagram of the Dapingzhang spilite-keratophyre. (Seawater values deduced after Jacobsen et al.[18]; upper crust values represent the deduced range. ▲— Dapingzhang spilite-keratophyre).

Little geological work has been done in the Dapingzhang mining district and the reliable geochronological information is rare on the forming age of the spilite-keratophyre formation. On the other hand, the rocks are cut through by the faults. Consequently, it is hard to determine the forming age of the spilite-keratophyre formation merely on the stratigraphic contact relations. Previous scientific workers assigned this formation to the Longdonghe Formation of the Carboniferous system (fig. 1). As a matter of fact, this conclusion is not tenable as is evidenced by the following aspects: (i) The Dapingzhang mining district is significantly different in rock assemblage from that in the Longdonghe Formation, the latter consisting of limestone, sandy conglomerate, volcanic tuff, intermediate-acid volcanic lava and radiolarian siliceous rocks while the spilite-keratophyre formation in the Dapingzhang mining district being composed mainly of basic, acid volcanic lavas with minor amounts of limestone, sandy conglomerate, and siliceous rocks which occur locally as the hanging-wall rocks of orebodies in most cases. (ii) According to the Regional Geology of Yunnan Province (1990), the Longdonghe Formation is assigned to the late Late Carboniferous[15] in consideration of the fact that the lower member of the Longdonghe Formation contains fusulinid fossils. Feng Qinglai (1992) discovered Early Permian radiolarian fossils in siliceous rocks in the upper member of the Longdonghe Formation, providing strong evidence that the Longdonghe Formation is late Late Carboniferous-Early Permian in age[16]. The age of the Dapingzhang volcanic sequence determined by previous workers lacks reliable fossil evidence. Even up to now, there has been no report about the discovery of fossils in the siliceous rocks. (iii) The conclusion is inconsistent with the isotope geochronological data available.

The isotope geochronology data in this paper provide reliable chronological evidence for the Cambrian volcanic rocks in the Sanjiang (three-river) area of Southwest China. In fact, previous investigators did find some scattered Cambrian volcanic rocks in this area on the basis of geological investigations (fig. 5). For instance, metamorphic intermediate-basic volcanic rocks are found outcropping in the Gongyanghe Group ($\in_{1-2}$) of the southern segment of the Gaoligong Mountains, Luxi, which are assigned to the spilite-keratophyre formation by Li (1984)[17]. In addition, in the areas of Chayu and Ranwu are exposed basic volcanic rocks in the Guqin Group ($\in_3$), basic volcanic rocks are exposed in the areas of Batang and Derong ($\in_1$-S_3), and basic volcanic rocks in the Shigu and Cangshan groups in the areas of Shigu and Cangshan[18]. Among them, sedimentary rock intercalations in the Shigu Group contain Cambrian-Ordovician trilobite fossils[18]. All these findings provide strong geological evidence for the above isotope geochronological studies.

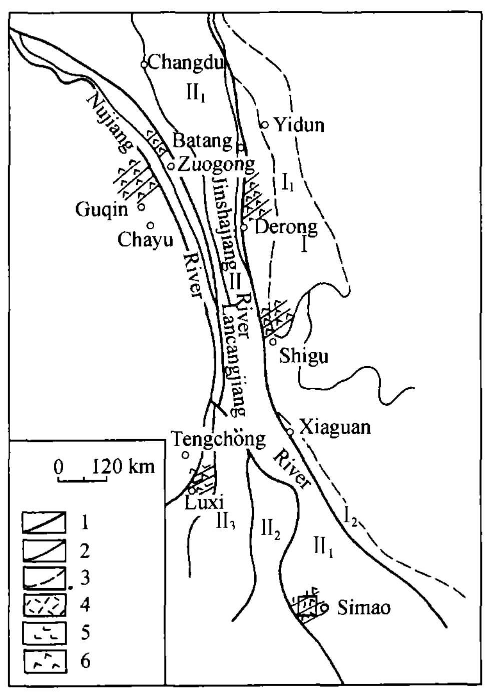

Fig. 5. Sketch map showing the distribution of Cambrian volcanic rocks in the Sanjiang area (stratigraphic division after Luo Jianning, 1992).

Granodioritic porphyry has not witnessed any thermo-reworking process. It is well known that the rocks which underwent later thermal events would yield the ages differing in geological significance on the basis of different isotopic dating systems. This depends mainly on the closing temperature of the isotopic dating system. Generally speaking, the closing temperatures of whole-rock Rb-Sr and Sm-Nd isotopic systems may be as high as up to 650℃ or even higher[10−14], while those of the K-Ar isotopic system are much lower[15]. Therefore, the Rb-Sr and Sm-Nd isotopic systems, especially the latter, have a strong capability of being resistant against turbidance[16, 17], but the K-Ar isotopic system just shows an opposite trend. As for those rocks which have experienced strong geological reworking (or transformation), the K-Ar method would not be powerful enough to give the forming age of the rocks. Instead, it can give the age of the last episode of thermal event.

As viewed from the Rb-Sr, Sm-Nd isochron ages and K-Ar age of the spilite-keratophyre formation, it is found that (i) the Rb-Sr (511 Ma$\pm$8 Ma) and Sm-Nd(513 Ma$\pm$40 Ma) isochron ages of the spilite-keratophyre formation are almost consistent with each other within the error limit; (ii) the K-Ar age of the spilite-keratophyre formation is far smaller than its Rb-Sr and Sm-Nd isochron age, but is equivalent to those of the granodioritic porphyry which intruded the formation; (iii) $(^{87}Sr/^{86}Sr)_i$=0.707 8 and $\varepsilon_{Nd}(t)$=2.7 for the spilite-keratophyre formation indicate that its ore-forming materials were derived mainly from a depleted mantle. But on the $\varepsilon_{Nd}(t)$-$(^{87}Sr/^{86}Sr)_i$ diagram (fig. 4), the data points of the Dapingzhang spilite-keratophyre obviously deviate from the values of the depleted mantle at the time the rocks were formed, and they are close to the values of seawater and upper crust at that time, suggesting that this suite of rocks was precisely affected by contamination.

As the seawater is low in Nd content (3×10^{6}) and, on the other hand, Nd can be retained for a short time in the seawater (<300 years), seawater hydrothermal alteration could not cause a great change in $\varepsilon_{Nd}(t)$ of the rocks[18], so $\varepsilon_{Nd}(t)$ values are indicative of the importance of crustal contamination.

5 Conclusions

From the above discussions, the following conclusions are drawn: the spilite-keratophyre formation in the Dapingzhang mining district, Yunnan is the product of mantle-source magma eruption during the Cambrian, affected by crustal contamination and/or seawater hydrothermal alteration; and the rocks were affected by relatively intense tectono-thermal events during the Late Carboniferous, which seems to be related mainly with the intrusion of the Late Carboniferous granodioritic porphyry in the area studied. It is strongly evidenced that there do occur Cambrian volcanic rocks in the Sanjiang area of Southwest China.

Acknowledgements Thanks are given to the leaders and colleagues of the No.5 Geological Party and the No.3 Team of Yunnan Province for support and help in field work. This work was jointly supported by the "Western Light" Program of the Chinese Academy of Sciences and the Collaboration Program between the Chinese Academy and Sciences and the Yunnan Provincial Academy of Sciences.

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