The thermal history of the miarolitic granite at Xincun, Fujian Province, China

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Abstract The thermal history of the late Mesozoic miarolitic granite has been studied based on zircon U-Pb dating, whole rock Rb-Sr dating and K-Ar dating of muscovite, biotite and K-feldspar from the same rock sample. From the beginning of zircon crystallization to the closure of K-Ar system of biotite, the granite body had a slow cooling rate (11.0℃/Ma) and an ascending rate (0.07 mm/a). From the end of this stage to the closure of K-Ar system of K-feldspar, the granite body increased its cooling rate (45℃/Ma) and ascending rate (0.36 mm/a). The thermal history of the Xincun granite with a slow cooling rate at the early stage and a fast cooling rate at the late stage may have been related to the fact that the Fujian coastal area had very high geothermal gradient in the late Mesozoic and evident decrease in geothermal gradient in the early Cenozoic.

Keywords: **closure temperature, thermal history, paleothermal gradient, Xincun miarolitic granite.**

Since Dodson[1] put forward the theory of closure temperature of isotope systems, great progress has been made in reconstructing cooling and ascending history of igneous bodies by dating different minerals at the same elevation or dating the same kind of minerals from different elevations[2—9]. However, great attention has not been paid to the thermal history of miarolitic granites, as they have been regarded as shallow intrusions and having a short cooling period. Thermal history study on the Laoshan miarolitic composite granite in Qingdao by Zhao et al.[5] suggested that the miarolitic granite and associated calc-alkali granite had a similar long cooling history of more than 10 Ma. We choose the Xincun miarolitic granite of the Zhangzhou complex in Fujian Province to further study the thermal evolution of miarolitic granites.

1 Geological setting

The late Yanshanian Zhangzhou complex in Fujian Province, with an exposed area of 900 km^2, consists of gabbro-norite (Shangfang body), quartz-diorite (Zudi and Yunshan bodies), granodiorite (Changtai body), monzonitic granite (Gunong body), fine-grained granite (Yanqian body), miarolitic alkali-feldspar granite (Xincun body) and alkali-feldspar granite-porphyry (Guokeng body) (fig. 1). The Xincun miarolitic granite body is exposed as a belt with NE trend, intruding into the Zudi body and Nanyuan Formation volcanic rock, at the eastern part of the complex (fig. 1). The miarolitic granite body has intermediate grain size within its central phase and fine-grained size at its edge phase. The rock is composed of K-feldspar (45%—50%), quartz (25%—35%), acidic plagioclase (16%—20%), and minor biotite and muscovite. Accessory minerals include magnetite, ilmenite, zircon, monazite, fluorite, garnet, apatite and minor aegirine, arfvedsonite. The granite has an evident miarolitic texture with different sizes and shapes. Chemically, the granite has high SiO_2 (75.69%—77.23%) and alkali components (8.23%—9.10%) with K slightly higher than Na, low Al_2O_3 (12.14%—12.93%), and high ε_{Nd} values (−4.8), high Zr/Hf (24), Nb/Ta (13.2) ratios, intermediate LREE/HREE ratio (4.15), low

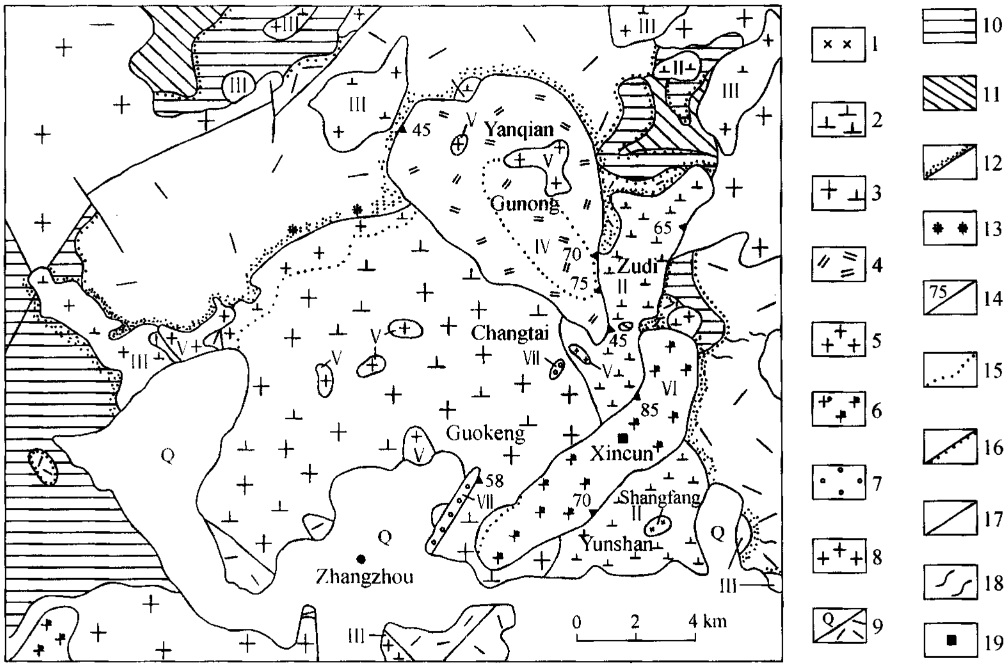

Fig. 1. Geological sketch map of Zhangzhou composite granite body. 1, Gabbro-norite; 2, quartz monzodiorite; 3, granodiorite; 4, rapakivi-adamellite; 5, fine-grained granite; 7, alkali-feldspar granoporphyry; 8, early Yanshanian granite; 9, Quaternary System and Nanyuan Formation volcanic rocks of Upper Jurassic series; 10, Wenbinshan Formation of Upper Triassic series and Lishan Formation of Lower Jurassic series; 11, Dalong Formation of Permian series and Xikou Formation of Lower Triassic series; 12, Hornfelsed zone; 13, greisenization zone; 14, occurrence of intrusive contact of the granite; 15, facies boundary; 16, stratigraphic uncomformity boundary; 17, fault; 18, schistosity; 19, sampling location.

REE concentration (111.3×10^{-6}), low δEu (0.15), $\delta^{18}O$ (5.8‰—8.0‰) values and low initial $^{87}Sr/^{86}Sr$ ratio (0.704 5)[10]. These geochemical parameters suggest that the Xincun alkali granite was formed by mixing of material from the crust and the mantle.

2 Samples and analytic method

Mineral separates with different closure temperatures such as zircon, muscovite, biotite and K-feldspar were selected by mechanic methods and purified by hand-picking to purity better than 98%. Single zircon U-Pb dating was performed at Isotope Laboratory, Institute of Geology and Mineral Deposits, the Ministry of Land and Resources, with mixed ^{205}Pb-^{235}U spike. Pb and U blanks of the analytic procedure were 0.05 and 0.002 ng, respectively. K-Ar dating for muscovite, biotite and K-feldspar was fulfilled with the spiking method at Isotope Laboratory, Institute of Geology, the Chinese Academy of Geological Sciences. The analytic results are presented in tables 1 and 2.

Table 1 Single zircon U-Pb dating results of Xincun granite

No.	Weight/μg	Content/μg · g^{-1}		Unradiogenic Pb in granite/ng
		U	Pb	
1	20	6 809	1 420	0.500
2	10	2 440	565	0.170

Isotope ratios

No.	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
1	300	13.55	0.016 19±22	0.107 4 ±41	0.048 13 ±166
2	165	15.16	0.016 00±28	0.106 1 ±36	0.048 09 ±129

Apparent ages/Ma

No.	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
1	103.5	103.6	105.7
2	102.3	102.4	103.7

Sample No. 1: Yellow brown long crystal of zircon; sample No. 2: light yellow short crystal of zircon.

Table 2 K-Ar isotopic ages for mineral separates from Xincun granite

Mineral	Weight/g	K(%)	$^{40}Ar^*(\times 10^{10})$/mol • g^{-1}	$^{40}Ar_a$(%)	$^{40}Ar^*/^{40}K$	Apparent age/Ma
Muscovite	0.0414	8.16	9.086	12.5	0.003731	63.1±1.4
Biotite	0.0435	7.63	7.736	10.8	0.003397	57.5±1.2
K-feldspar	0.1394	5.68	5.375	23.2	0.003171	53.8±1.3
K-feldspar	0.1279	5.67	5.567	23.6	0.003289	55.7±1.5

3 Results and discussion

(i) Isotopic dating and closure temperature. As shown in table 1, zircon U-Pb apparent ages of $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$, $^{207}Pb/^{206}Pb$ for the same zircon grain are very similar, suggesting that the zircon isotope system has maintained not being disturbed since the zircon crystallized. Thus the three apparent ages for a zircon grain represent the crystallization time of the zircon grain. However, the $^{206}Pb/^{238}U$ apparent age is more precise than $^{207}Pb/^{235}U$ apparent age for Mesozoic zircons, since the accumulation of radiogenic ^{206}Pb is one order of magnitude greater than that of radiogenic ^{207}Pb due to the difference in their decay constants. The average $^{206}Pb/^{238}U$ apparent age of 103.0 Ma±1.1 Ma of the two zircon grains is regarded as crystallization age of the zircon. K-Ar ages for muscovite (63.1 Ma±1.4 Ma), biotite (57.5 Ma±1.2 Ma) and K-feldspar (54.7 Ma±1.4 Ma) recorded the times when Ar stopped diffusion from the minerals. The Rb-Sr isochron consisting of three whole rock samples and three minerals of biotite, K-feldspar and plagioclase of the Xincun granite yields an age of (97.1±2.3) Ma, measured by Isotope Laboratory, Beijing Institute of Uranium Geology. Good correlation coefficient of the isochron and consistency in K-Ar dating results for the two K-feldspars suggest that the isotope systems have not been disturbed since the granite was formed.

There has been consensus about closure temperatures for different isotope systems. The closure temperatures for different isotopic systems used in this note are: (700±50)℃ for zircon U-Pb system, (350±50)℃ for muscovite, (300±50)℃ for biotite and (150±30)℃ for K-feldspar[4]. The closure temperature for whole rock Rb-Sr system is similar to the crystallization temperature of the granite[6]. The melting temperature of solid inclusion of Xincun granite is 600℃, measured by Zhou and Wu[10]. Crystallization temperature estimated from the diagram of $\lg f\,O_2$-T for biotite is 620℃[10]. Thus 600℃ is regarded as the closure temperature for the whole rock Rb-Sr isotope system of the Xincun granite.

(ii) Thermal evolution feature of granite. The above dating results and closure temperature estimates are plotted in fig. 2 and cooling rates at different stages can be calculated from them. The cooling rate was 16.9℃/Ma within a period from 103.0 to 97.1 Ma, 7.3℃/Ma from 97.1 to 63.1 Ma, 8.9℃/Ma from 63.1 to 57.5 Ma and 53.6℃/Ma from 57.5 to 54.7 Ma. The low cooling rate (7.3—16.9℃/Ma with average of 11.0℃/Ma) at the early stage (103—57 Ma) is consistent with the conclusion drawn from Ar-Ar study that the period between 107 and 70 Ma was a slow cooling period for the ambient Changlu-Nanao ductile shear zone. From 57 Ma on, the granite increased its cooling rate to 53.6℃/Ma. In a word, the Xincun granite had a slow cooling rate at the early stage and a relatively fast cooling rate at the late stage.

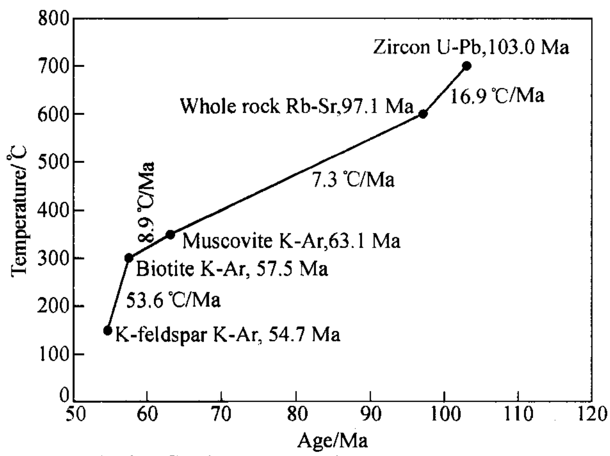

Fig. 2. Cooling rate curve for the Xincun granite.

There are many hot springs with temperature of 40—97℃[13] in the coastal area of Fujian. This area has intermediate-high geothermal gradients (40—80℃/km)[14]. If 60℃/km is taken as the geothermal gradient when the Xincun granite was emplaced, the calculated depth would be 10 km when the granite was crystallized (600℃). This estimate differs significantly from the emplacement depth of the granite body estimated by other calculation (3 km)[10]. Generally, for miarolitic granite, such a great emplacement depth is not reasonable. Thus the Mesozoic geothermal gradient mustn't have been similar to the present-day one. In the late Mesozoic, the coastal area of Fujian was located at the continental margin where there was severe magmatism due to the subduction of the paleo-Pacific plate under the continental plate of southeast China. This area must have had a high geothermal gradient in the Mesozoic under the influence of heat from the subduction friction, magmatic emplacement or eruption, and underplating of basalt magma. According to Zhou[13], the geothermal gradient in the late Yanshanian period was greater than 150℃/km. If this is correct, the calculated emplacement depth of the granite body would be 4 km, similar to the result (3 km) calculated by other methods[10]. This suggests that the geothermal gradient in the Mesozoic would be around 150℃/km. Thus the thermal history could be described as follows:

The initial emplacement depth of the granite body may have been 4.7 km where the zircon had crystallized but the magma had not completely solidified at temperature about 700 ℃ (fig. 3). As the magma ascended to 4 km 97.1 Ma ago, it solidified and the Rb-Sr o'clock started. During this period, the ascending rate was 0.12 mm/a and the cooling rate was 16.9℃/Ma. The granite body continued ascending and cooling as the crust was elevated by tectonic force. From 97.1 to 63.1 Ma, with an ascending rate of 0.05 mm/a and a cooling rate of 7.3℃/Ma, the granite was elevated to the depth of 2.3 km where the K-Ar o'clock of muscovite started. From 63.1 to 57.5 Ma, the body was moved to the depth of 2 km with an ascending rate of 0.05 mm/a and a cooling rate of 8.9℃/Ma, where K-Ar o'clock of biotite started. From 57.5 to 54.7 Ma, the ascending rate and the cooling rate of the body increased to 0.36 mm/a and 53.6℃/Ma, respectively, and removed to the depth of 1 km where K-Ar o'clock of K-feldspar started. The reason for increasing in the ascending rate and the cooling rate may have been related to the weakening of magmatism and basalt underplating and thus decreasing in geqthermal gradient.

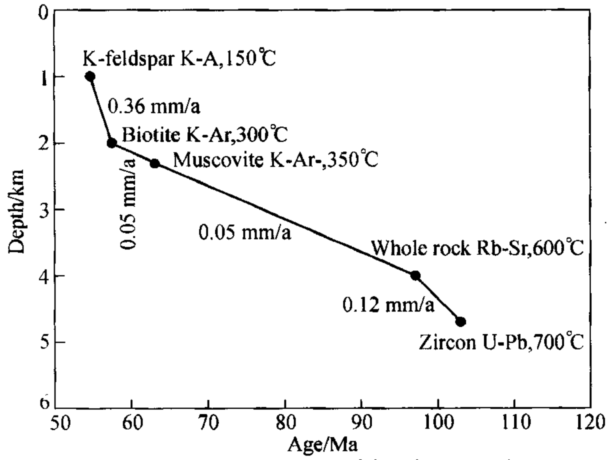

Fig. 3. Ascending rate curve of the Xincun granite.

The above study suggests that the Xincun miarolitic granite had a long cooling period (>40 Ma). During its early period of emplacement and solidification (103—58 Ma), the magma had slow cooling and ascending rates, suggesting that there was a very high geothermal gradient in the late Cretaceous Period in the coastal area of Fujian. Afterwards, the geothermal gradient decreased and the cooling and ascending rates of the granite body increased.

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