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Discussion on Rb-Sr Isochron Ages of Granitoids in the Hengduan Mountains①

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Abstract

Based on the Rb-Sr isotopic study of the granitoids in the Hengduan Mountains, the classification and geologic significance of whole-rock Rb-Sr isochrons as well as the factors influencing homogenization of the isotopic systems are discussed. Usually, there is no good linear correlation of isochrons for diorites and alkali-rich intrusive rocks (including alkaline rock and alkalic granite). But by means of the external isochron of monominerals from the rocks, isochrons with good linear correlation as well as ages and Sr initial ratios with a high confidence can be obtained. In order to obtain a satisfactory isochron, the discriminant parameters should be calculated from the Rb / Sr ratios and estimated ages of samples. Only those that meet the requirements can be used as the Rb-Sr isochrons. The quality of an isochron should be judged from three factors, i.e. correlation coefficient, MSWD and homogenization degree.

Rb-Sr method has been widely used in geochronology, but sometimes it can not give an isochron with good linear correlation because a wide and complicated range of objects are needed for the determination. Every method has its advantages and shortages, and is applicable only to a limited field. In this paper Rb-Sr isochron ages and its applicability to rocks and minerals are discussed with reference to granitoids in the Hengduan Mountains area.

Rb-Sr Isochron Age

Isochron ages include those of whole rock, interior and exterior. There are three cases for the formation of a whole-rock isochron: 1) true isochron: its samples were gathered from a geological system of isotopic homogenization, and it represents a true age; 2) mixing isochron: its samples were collected from a binary mixing system formed in a certain time, it has a good linear correlation but its age is not true; 3) medley isochron: its samples came from more than two kinds of rocks formed in different phases, or from rock systems with different initial ratios; due to the great difference in Rb / Sr value, isochrons with a good linearity can be formed but represent different geological meanings.

①Also known as the "Transverse Range" of SW China.

(1) Examples of whole-rock isochron

Since the Rb / Sr values for well crystallized and differentiated acid granites (e.g. porphyritic and equigranular biotite-granite, two-mica-granite and light-coloured granite) are high and vary within a wide range (1–1000), isochrons with a good linear correlation are easily obtained. On the contrary, the values for granodioritic rocks (including diorite, tonalite and granodiorite) are low and vary within a limited range (generally less than 1), and the heterogeneity of initial ratios of rocks and errors of measurements cause a scattered distribution of data points, usually leading to the formation of an unsatisfactory isochron. Similar case exists for alkali-rich intrusive rocks, especially hypabyssal and ultra-hypabyssal alkaline rocks and alkali granites.

Table 1. Contents of Rb and Sr for Diorite from the Tongde Pluton

No.	Sample No.	Rb%	Sr%	Rb / Sr
1	83–577	0.0033	0.0702	0.05
2	83–580	0.0021	0.0674	0.03
3	83–582	0.0006	0.0872	0.0068
4	83–584	0.0009	0.0784	0.01
5	83–576	0.0028	0.0794	0.04
6	83–579	0.0024	0.0800	0.03
7	83–581	0.0022	0.0672	0.03
8	83–457	0.0007	0.0834	0.0084

Table 2. Rb and Sr Isotopic Data for Diorite from the Tongde Pluton

No.	Sample No.	$^{87}Rb(\mu mol / g)$	$^{86}Sr(\mu mol / g)$	$^{87}Rb / ^{86}Sr$	$^{87}Sr / ^{86}Sr$
1	83–577	0.10100	0.78246	0.12908	0.70638 ± 6
2	83–580	0.07851	0.71814	0.10494	0.70515 ± 1
3	83–582	0.03148	0.96921	0.03248	0.70554 ± 2
4	83–584	0.03780	0.87968	0.04297	0.70665 ± 3

Table 3. Whole-Rock Rb and Sr Isotopic Data for Granite from the Shenxianshui Pluton

No.	Sample No.	$^{87}Rb(\mu mol / g)$	$^{86}Sr(\mu mol / g)$	$^{87}Rb / ^{86}Sr$	$^{87}Sr / ^{86}Sr$
1	82–S–1	1.448	0.1567	9.247	0.72169
2	82–S–6	1.503	0.1108	13.561	0.72537
3	82–S–8	1.581	0.1134	13.941	0.72764
4	82–S–9	2.921	0.01301	224.48	0.97503
5	82–S–8a	2.838	0.01036	273.90	1.04395
6	82–S–10	2.625	0.01996	131.52	0.85247
7	82–S–4	1.546	0.1078	14.342	0.72749

The Rb and Sr analysis of eight diorite samples form the Tongde pluton at Dukou shows that the Rb / Sr values are not only all less than 0.05 but also very close to each other (Table 1). Four (Nos. 1–4) of them were selected for isotopic determination but could not form an isochron (Table 2). Calculation indicates that the accumulation of radiogenic strontium has caused a $^{87}Sr/^{86}Sr$ value increase of less than 0.0004, while the heterogeneity of initial ratios of granitoid is up to 0.001, thus an isochron is not available.

Table 4. Whole-Rock Rb and Sr Isotopic Data for Granites from the Hager Pluton

No.	Determined object	$^{87}Rb(\mu mol/g)$	$^{86}Sr(\mu mol/g)$	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
1	Inequigranular biotite-granite	1.31996	0.04007	32.9413	0.76922
2	Inequigranular biotite-granite	1.03727	0.07373	14.0685	0.73399
3	Inequigranular biotite-granite	1.19403	0.04627	25.8057	0.75839
4	Inequigranular biotite-granite	1.10967	0.05180	21.4222	0.75183
5	Inequigranular biotite-granite	1.31030	0.05774	22.6931	0.75318
6	Inequigranular biotite-granite	1.28606	0.07595	16.9330	0.74074
7	Inequigranular biotite-granite	1.36254	0.05964	22.8461	0.75227
8	Leucocratic granite	0.85396	0.09214	9.2681	0.72618
9	Leucocratic granite	0.82368	0.12480	6.6000	0.72222
10	Leucocratic granite	0.75302	0.15068	4.9975	0.71946

The $^{87}Rb/^{86}Sr$ values of porphyritic biotite granite from Longchahe, Gejiu, evenly vary within the range of 0.87–2.86, which means that the samples are synchronous and have the same source region; the $^{87}Sr/^{86}Sr$ values evidently vary within the range of 0.71202–0.71616. Thus a good isochron can be formed. Its age (150 Ma) should represent the true age of the rock (Wu Qinsheng et al., 1984).

The abundances of Rb and Sr as well as $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios (Wu Qinsheng et al., 1984) for equigranular biotite-granites from the Shenxianshui pluton fall in two groups different in order of magnitude. Therefore the samples are not from the same rock, or some of the samples are from the same rock but with isotopic components added from other systems. For one of the groups, the $^{87}Rb/^{86}Sr = 9.247–14.342$ and the $^{87}Sr/^{86}Sr = 0.72169–0.72764$, whereas for the other, the $^{87}Rb/^{86}Sr = 131.52–273.90$ and $^{87}Sr/^{86}Sr = 0.97503–1.04395$ (Table 3). If we regard the samples of equigranular biotite-granite as being of the same source and synchronous genesis, then the calculating results are as follows: the age $t = 84.2$ Ma, the Sr initial ratio $a = 0.7083$ and the correlation coefficient $r = 0.9988$. although there seems to be a good linear correlation, the age obtained is actually an artificially mixed whole-rock Rb-Sr isochron age. According to the fact that rocks derived from the same source and formed or intruded at the same time should have similar concentrations of ^{87}Rb and ^{86}Sr as well as similar $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios, two groups of samples can be distinguished. One group consists of samples 1, 2, 3 and 7, of which the isochron age $t = 79$ Ma, with $a = 0.7112$ and $r = 0.9606$. Although its linear correlation is not fully satisfactory, the isochron age still can reflect the formation age, and the Sr initial ratio is concordant with that of composite rock body in this area. Both the Longchahe and Shenxianshui plutons belong to the composite rock body in western Gejiu: the former intruded earlier and its $a = 0.7101$, while the latter intruded later and its $a = 0.7112$. This phenomenon is also in agreement with the theory of isotopic evolution. The other group consists of samples 4, 5 and 6, of which the isochron age t = 94 Ma, with a = 0.6754 and r = 0.9998. Though the isochron has a good linear correlation, the Sr initial ratio is very low, which is impossible for Mesozoic granites. This further proves that it is a medley isochron (Fig. 1).

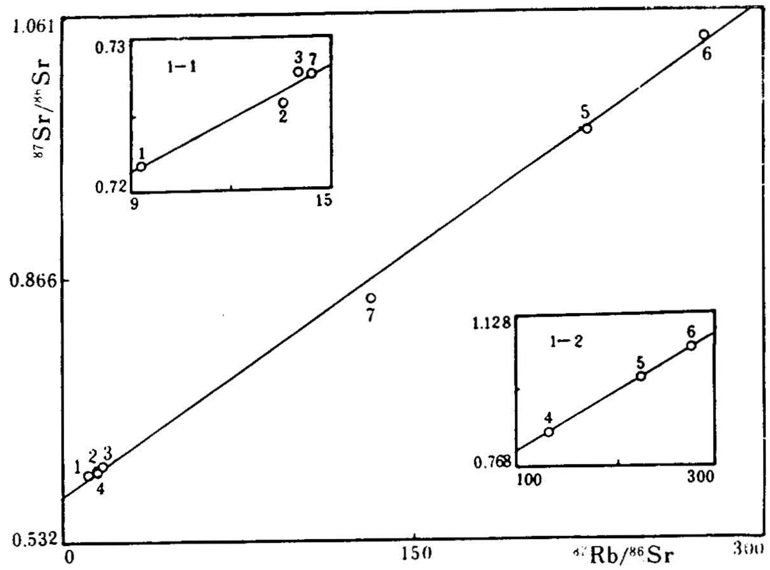

Fig. 1. Whole-rock Rb-Sr isochron for equigranular biotite-granite from the Shenxianshui pluton.
t = 84.4 ± 1.1 Ma; b = 0.000120 ± 2; a = 0.7102 ± 8.
1-1, whole-rock Rb-Sr isochron (samples 1, 2, 3 and 7);
1-2, whole-rock Rb-Sr isochron (samples 4, 5 and 6).

(2) Medley whole-rock Rb-Sr isochron age

A medley isochron may reflect the age of early intruded rock, the age of late intruded rock, or the roughly average value of the two, depending on the difference of Rb / Sr value and number of samples of the two groups of rocks. Obviously, those rocks which have high Rb / Sr value and a large number of samples control the age. For example, the inequigranular biotite-granite intruded early and the light-coloured granite intruded late in the Hagala pluton were determined. The Rb and Sr isotopic determination results are shown in Table 4 and Fig. 2. It can be seen that the Rb and Sr contents as well as the $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios have a very narrow range and are similar for all the samples from the same rock but are quite different for the samples from different rocks. Calculation using 10 samples from two kinds of rocks gives the following results: t = 130.8Ma, a = 0.7097, and r = 9971. If we calculate separately the age of two different kinds of rocks, then the whole-rock Rb-Sr isochron age for the inequigranular biotite-granite (samples 1–7) t = 130.9 Ma, with a = 0.7097 and r = 0.9910 (Fig. 2–1), and that for the light-coloured granite (samples 8–10) t = 110.1 Ma, with a = 0.7117 and r = 0.9992 (Fig. 2–2). These results suggest that the age and Sr initial ratio for inequigranular biotite-granite which intruded earlier, calculated either separately or mixedly, remain unchanged. As for the light-coloured granite which intruded later, its true age and Sr initial ratio can only be obtained by separate calculation, while a calculation combining the earlier intruded rock gives a useless result, because the age and initial ratio are both controlled by the inequigranular biotite-granite. The reason is that the later has a wide range of $^{87}Rb / ^{86}Sr$ and $^{87}Rb / ^{86}Sr$ values, and therefore occupies the positions of controlling points. In addition, much more data of its samples are used in the calculation.

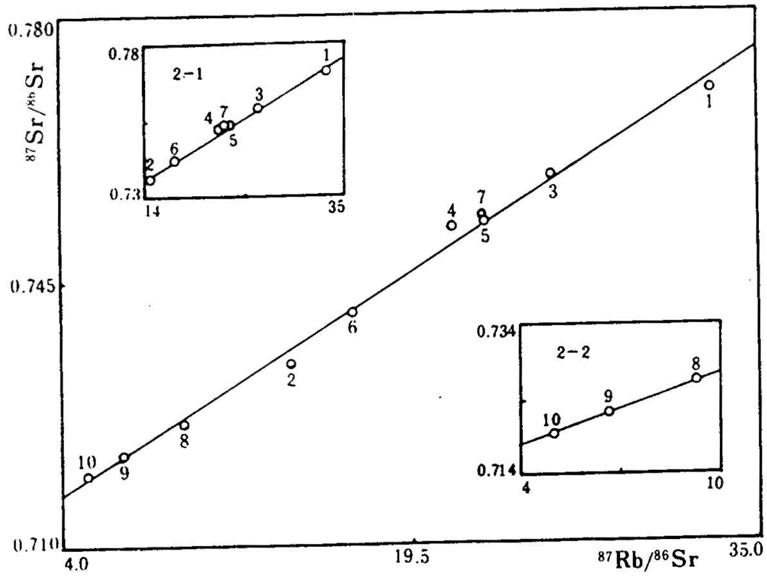

Fig. 2. Medley whole-rock Rb-Sr isochron of the Hagala pluton.

t = 130.8 ± 3.2 Ma; a = 0.7097 ± 8; b = 0.00185 ± 5.

2–1, whole-rock Rb-Sr isochron for the inequigranular biotite-granite of the Hagala pluton;

2–2, whole-rock Rb-Sr isochron for the light-coloured granite of the Hagala pluton.

Another example is the Lailishan pluton, which consists of an earlier porphyritic monzonitic-biotite granite and an equigranular biotite-granite intuded later. The mixed calculation of relevant data shows that the medley whole-rock Rb-Sr isochron age is t = 54.8 Ma, with a = 0.7125 and r = 0.9993 (Fig. 3). However, the separated calculation suggests that the whole-rock Rb-Sr isochron age for the former (samples 1–3) is t = 84.2 Ma, with a = 0.7112 and r = 0.9278 (Fig. 3–1), while that for the latter (samples 4–7) is t = 51.9 Ma, with a = 0.7135 and r = 0.9997 (Fig. 3–2). It can be seen from the results of age calculation that the medley whole-rock isochron age is close to the whole-rock isochron age for the latter. Though the number of their samples are about the same, yet the latter has a larger spacing of data points which control the low and high positions of the isochron. Thus the medley whole-rock Rb-Sr isochron has the age and Sr initial ratio close to those for the latter.

The isotopic data of an earlier porphyritic monzonitic- biotite granite and a later equigranular biotite-granite of the Guyong pluton give a medley whole-rock Rb-Sr isochron age of t = 76.2 Ma, with a = 0.7107 and r = 0.9983 (Fig. 4), a whole-rock Rb-Sr isochron age for porphyritic biotite monzonitic granite (samples 1–7) of t = 83.6 Ma, with a = 0.7093 and r = 0.9773 (Fig. 4–1), and a whole- rock Rb- Sr isochron age for biotite granite (samples 8–11), t = 71.4 Ma, with a = 0.7156 and r = 0.9989 (Fig. 4–2). The medley age is essentially the average of the two groups of samples and is influenced by the larger number of samples of the earlier intruded rock type.

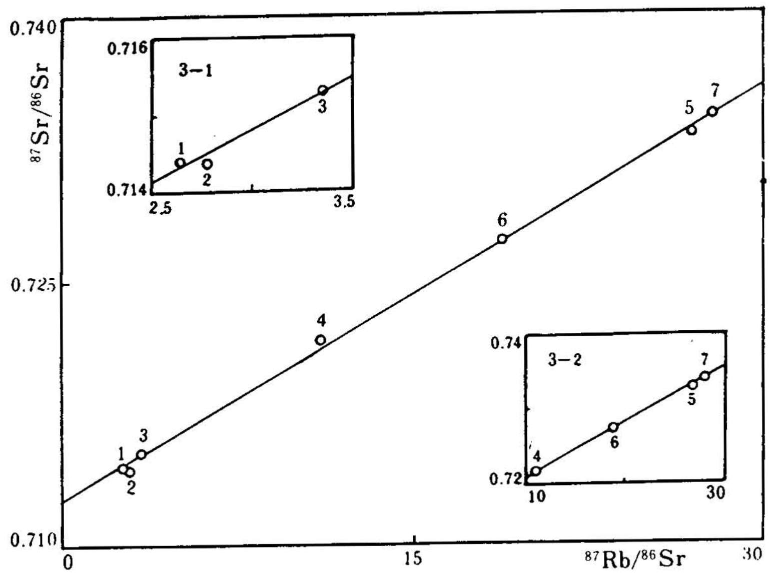

Fig. 3. Medley whole-rock Rb-Sr isochron for granite from the Lailishan pluton.
t = 54.8 ± 1.7 Ma; a = 0.7125 ± 0.0004; b = 0.00077 ± 9.
3–1, Whole-rock Rb-Sr isochron for porphyritic monzonitic biotite-granite;
3–2, whole-rock Rb-Sr isochron for equigranular biotite-granite.

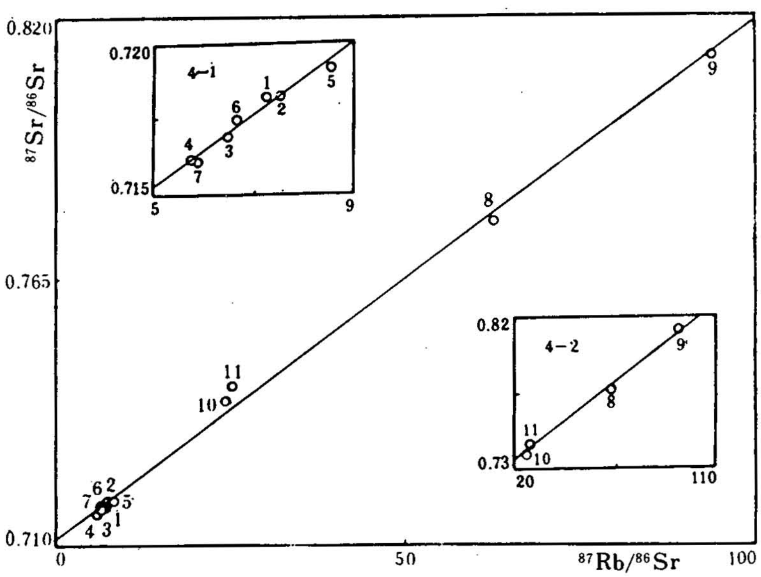

Fig. 4. Medley whole-rock Rb-Sr isochron for granite from the Guyong pluton.
t = 76.2 ± 0.8 Ma; a = 0.7107 ± 3; b = 0.00108 ± 8.
4–1, Whole-rock Rb-Sr isochron for porphyritic biotite monzonitic granite;
4–2, whole-rock Rb-Sr isochron for biotite granite.

(3) Interior Rb-Sr isochron age

In interior isochron determination, whole rock and monominerals (including rock-forming and accessory minerals) are usually used, and isochron with good linear correlation can be obtained for all kinds of rocks mentioned above. Generally, there are two situations for their age values: one is that the determined rock was not markedly influenced by late geologic process and its age value approximately reflects the rock formation age; the other is that the rock was influenced by late metamorphism and its age value generally represents the metamorphic time. In addition, the interior isochron age is usually equal to the K-Ar age listed in Table 5.

Table 5. Comparison of Rb-Sr Interior Isochron Ages with K-Ar Ages of Mica for Hornblende-Syenite Porphyry of the Tengchang Pluton

No.	Determined objects	Age (Ma)	Method	Reference
1	Whole-rock+biotite+k-feldspar	33.9	Rb-Sr	Tan Xuechun, 1985
2	Whole-rock+biotite+K-feldspar+ plagioclase	35.1	Rb-Sr	Tan Xuechun, 1985
3	Whole-rock+biotite+K-feldspar+ plagioclase+apatite	36.1	Rb-Sr	Tan Xuechun, 1985
4	Biotite	36.8	K-Ar	This paper

The interior isochron age calculated from five samples (two whole-rocks, two biotites and one muscovite) of two-mica-granite from the Mengsong pluton is $t=238.7$ Ma, with $a=0.7605$ and $r=0.9974$. The age calculation from three samples, i.e. the whole-rock (S_{1-1}), biotite (S_{1-2}) and muscovite (S_{1-3}), gives the isochron parameters as follows: $t=235.7$ Ma, $a=1.1937$ and $r=0.9972$. The age calculated from five samples is approximately identical to that from three samples, with the only exception that the presence of muscovite makes the initial ratio larger in the case of three samples.

The above data indicate that usually a good interior isochron can be obtained when one whole-rock sample and 2–3 monomineral samples are employed.

(4) Monomineral Rb-Sr isochron age

A Rb-Sr monomineral or mineral isochron is constructed using one of the single minerals such as feldspar (K-feldspar and plagioclase), mica and amphibole. It is applicable to rocks with low degree of isotopic homogenization, but has not been studied intensively. A few available data show that for the same rock, the data points of whole rock are scattered and can not form a good isochron, making the obtained age unreliable but in the case of monominerals, an isochron with good linear correlation and a formation age with high confidence can usually be acquired. For example, when whole- rock samples of the granodiorites from the southern part of the Lincang pluton are used to construct an isochron, the data points are very scattered ($r=0.1361$), but when biotite samples are used, the obtained isochron not only has a good linear correlation ($r=0.9944$) but also gives a formation age ($t=256$ Ma) with high confidence. This age is close to the whole-rock Rb-Sr isochron age (263 Ma) for granodiorites from the middle part of this pluton.

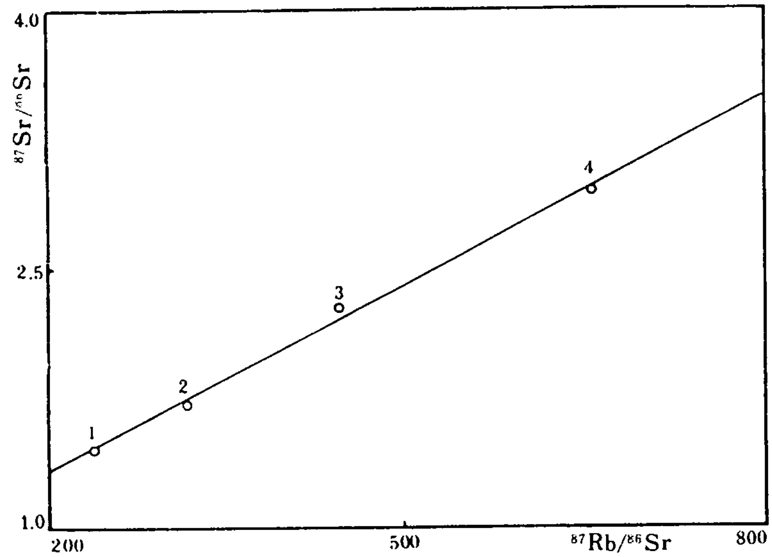

Fig. 5. Biotite Rb-Sr isochron of granodiorite from the southern part of the Lincang pluton.

Discussion

(1) Factors influencing isotopic homogenization

As a product of partial melting, the granitic magma was probably isotopically homogenized in a deep closed system. But during the upward intrusion and emplacement of the magma, the isotopic homogeneity could be disturbed to various degrees due to the addition of components of host rock or xenoliths as well as the difference in assimilation. For example, in dioritic rocks, inclusions and xenoliths of different sizes and complicated composition are usually found. Some of them have retained the features of the protolith, but some have lost such features and become similar in appearance to the host rocks (of the inclusions and xenoliths). Although the xenoliths have already been altered, yet their isotopic compositions may not have been completely changed. This is also true for alkaline rocks. For example, six samples from the syenite-porphyry at Shigu, Xiaoqiaotou, were analyzed, of which five have similar isotopic abundance and composition, that is: ^{87}Rb = 0.3983–0.4576 μmol/g, ^{86}Sr = 1.3557–1.6031 μmol/g, $^{87}Rb/^{86}Sr$ = 0.2612–0.3104, and $^{87}Rb/^{86}Sr$ = 0.7061–0.7069; sample 81–913 is obviously abnormal: its ^{87}Rb = 0.5378 μmol/g, ^{86}Sr = 0.1264 μmol/g, $^{87}Rb/^{86}Sr$ = 4.2548, and $^{87}Sr/^{86}Sr$ = 0.7436. This is because sample 81–913 contains inclusions. Although the inclusions visible to the naked eye had been removed before analysis, the isotopic composition of the rock around them had already been influenced. This influence can only be identified by isotopic composition analysis, rather than by the naked eye or elemental analysis. Five samples from the porphyritic biotite-granites in Xiangcheng were analyzed, four of which have similar isotopic composition: $^{87}Rb/^{86}Sr$ = 1.8778–2.7383, and $^{87}Sr/^{86}Sr$ = 0.71011– 0.71176. Only one sample, which is near the contact zone, has high ratios: $^{87}Rb/^{86}Sr$ = 3.2438, and $^{87}Sr/^{86}Sr$ = 0.72674. This further indicates that the rocks near the contact zone were disturbed in isotopic composition. Nine samples from the granodiorite at Taiyingong were also analyzed, eight of which have similar isotopic composition: $^{87}Rb/^{86}Sr=1.3217-3.7096$, and $^{87}Sr/^{86}Sr=0.7257-0.7415$. Only one sample, which is greisenized, has remarkably abnormal ratios: $^{87}Rb/^{86}Sr=16.445$, and $^{87}Sr/^{86}Sr=0.7883$. This suggests that late hydrothermal alteration has a great influence on the isotopic composition or the degree of isotopic homogenization.

(2) Selection of isochron samples

Since the formation temperature for granite (600–700℃) is lower than that for volcanic and other basic rocks (1200–1300℃), the isotopic initial ratio during granite formation is more heterogeneous than volcanic rocks. Generally, the $^{87}Rb/^{86}Sr$ value of modern volcanic rocks from the same source region varies from 0.0003 to 0.0005. According to the relationship between diffusion coefficient and temperature, the heterogeneity of initial ratio of granites from the same source region is estimated to be up to 0.001. The calculation based on this order-of-magnitude heterogeneity shows that an isochron with an age error less than 10% can be obtained only when the following equation is satisfied:

$$K=t\cdot\sqrt{\frac{N-2}{N}\sum_{i=1}^{N}u_i^2}>0.4 \tag{1}$$

where t is the rock age, $\sum_{i=1}^{N}u_i^2$ is the square sum of deviation of $^{87}Rb/^{86}Sr$ values for a group of samples (if replaced by Rb / Sr value, the obtained K value should be multiplied by 2.8). For a given t, in order to satisfy equation (1), the Rb / Sr value must be large enough, the deviation fully high or the samples adequately numerous. Dioritic rocks usually can not satisfy this equation, and this thus can not yield a good isochron. On the contrary, biotite and two-mica-granites readily satisfy it. Therefore, whether a group of samples can form an isochron depends on a discrimination based on equation (1). If this equation is not satisfied, there is no need to make a further isotopic analysis. For example, the K value of eight samples from the Tongde pluton is only 0.1 (even the age is in Ga), and hence they can not form an isochron. The biotite-granite at Longchahe, Gejiu, has a K value of 1.4, thus yielding an isochron.

Besides satisfying the above equation, a discrimination for homogeneity coefficent must be performed.

$$H=\sum_{i=1}^{N}(P_{i-1})^2/N-2 \tag{2}$$

Dividing the domain between the maximum and minimum Rb / Sr values of N samples into N equidistance intervals, P_i is the number of samples which fall into the ith interval. Generally, if H value is less than 2, then the isochron age obtained is more creditable; if H is higher then 2, then probably a medley isochron is obtained, or there exist one or two isotopically abnormal samples which should be eliminated.

(3) Evaluation of isochron quality

After the selection of samples by using Rb / Sr ratios, an isotopic analysis is conducted, and an isochron drawn. Meanwhile, the following calculations must be done in order to evaluate isochron quality:

a. Correlation coefficient: If $H\leqslant 2$, the correlation coefficient is closer to 1 and the isochron is more reliable. If $H\geqslant 2$, then the correlation coefficient is not the major factor for discrimination.

b. *MSWD* (Mean Standard Weight of Deviation):

$$MSWD = \sum_{i=1}^{N} W_i (Y_i - bX_i - a)^2 / N - 2 \tag{3}$$

where $W_i = \dfrac{1}{b\sigma X_i^2 + \sigma Y_i^2}$, ($\sigma X_i$ and σY_i are the measurement errors for $^{87}Rb / ^{86}Sr$ and $^{87}Sr / ^{86}Sr$ respectively); b is the slope and a is the initial ratio. For an isochron which is not influenced by other factors, the deviation between sample point and isochron line should be approximately equal to measurement error. Therefore the *MSWD* value is preferably less than 2.

c. Slope error: It is a direct measure of age error. Generally, the isochrons which have a good linear correlation and a small *MSWD* value certainly have a small slope error.

$$\Delta b = \sqrt{\sum_{i=1}^{N} (Y_i - bX_i - a)^2 / (N-2) \sum_{i=1}^{N} W_i u_i^2} \tag{4}$$

d. Initial ratio: The size of initial ratio should approximately be consistent with the variation range of $^{87}Sr / ^{86}Sr$ in different times of the earth's evolution. For instance, if the ratio is less than 0.7, a mixing or medley isochron usually occurs, suggesting that neither the age nor the initial ratio is confident.

This study was financially supported by the National Science Foundation of China.

Chinese manuscript received Dec. 1988
accepted Apr. 1989

Reference

Wu Qinsheng et al., 1984. Sr Isotopic characteristics of the Gejiu Sn-bearing granite and ore prospecting indicators. *Geochimia*, No.4, pp.293–302.