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Resetting and closing condition of Rb-Sr whole-rock isochron system: some samples of metamorphic and granitic rocks from the Gondwana super-continent and Japan Arc

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Abstract: The closure temperature of the Rb-Sr whole-rock system for felsic rocks has been generally considered to be *ca.* 700°C, but it falls to *ca.* 400°C, as a result of efficient action of fluids, especially H_2O. Thus, the Rb-Sr whole-rock ages obtained by rocks collected from a single outcrop to specimen-size are not always coincident with those of emplacement of granitic magma or partial melting under high grade metamorphism. Although the Rb-Sr whole-rock isochron ages of metamorphic rocks collected from a wide area have been sometimes interpreted as those of metamorphism, careful consideration for these ages is needed.

key words: Rb-Sr whole-rock isochron age, metamorphism, Sr isotopic homogenization, partial melting, fluids, closure temperature

1. Introduction

Hofmann (1979) discussed the difficulty of determination of metamorphic age of the Rb-Sr whole-rock system on the basis of his own and other author's studies, even if thin slabs were used. On the other hand, Faure (1986) and Attendorn and Bowen (1997) pointed out that Sr isotopic homogenization takes place under metamorphism. Actually, the linear relationship obtained from metamorphic rocks in a Rb-Sr isochron diagram has been sometimes interpreted as indicating metamorphic age (*e.g.* Shibata *et al.,* 1986; Dalrymple, 1991). In contrast, Dickin (1995) and Shimura *et al.* (1998) stated that such a homogenization does not take place regionally under metamorphism. Moreover, Dickin (1995) emphasized that, even if the linear relationship in the Rb-Sr isochron diagram can be obtained from metamorphic rocks, its line does not mean an isochron. Thus, although the fundamental Rb-Sr whole-rock system of metamorphic rocks is not fully understood yet, partial melting and existence of fluids probably holds the key to solution of the question (*e.g.* Pan *et al.,* 1999).

The closure temperature of the Rb-Sr whole-rock system for felsic igneous rocks has been generally considered to be *ca.* 700°C (*e.g.* Harrison *et al.,* 1979), which corresponds to the solidus temperature of felsic magmas (Nakajima *et al.,* 1990). Shirahase and Gorai (1968) emphasized that the linear relationship in the Rb-Sr isochron diagram obtained from several representative felsic igneous masses (*i.e.* sample with mean chemical composition of each felsic igneous mass) indicates a large-scale separation of magmas from the source. We sometimes use representative samples collected from each zoned portion of a zoned pluton for age determination using the Rb-Sr whole-rock system. In such a sampling method, the age calculated from the line probably indicates a temperature higher than *ca.* 700°C and in the magma separation process. On the other hand, there is a possibility that the closure temperature of the Rb-Sr whole-rock system for felsic rocks falls to much lower than *ca.* 700°C.

In this paper, we discuss the resetting condition of the Rb-Sr whole-rock system for metamorphic rocks and fall of the closure temperature for the Rb-Sr whole-rock system of migmatite and granitic rocks on the basis of age data from the Gondwana supercontinent and the Japan Arc. In order to discuss these, we newly analyzed major and minor chemical compositions and Sr isotopic ratios of migmatite from the Okiep Copper district in Namaqualand, South Africa (*e.g.* Yuhara *et al.,* 2001, 2002).

2. Analyzed samples

The migmatite (99082202B) analysed for chemical compositions and Sr isotopic ratios was collected from the Okiep Copper district (Fig. 1). A rock block, which is 40 cm×40 cm×15 cm, including paleosome, leucosome and melanosome, was taken out from the outcrop (Figs. 2A and B). A rock piece (18 cm long, 2 cm width) was cut away from the block (Fig. 2C). Samples C1, C10 and C11 are paleosome; C3 and C8 melanosome; C5 and C6 leucosome.

The paleosome is relatively fine-grained and forms light gray layers, and has schistosity shown by arrangement and shape of constituent minerals. The mineral assemblage is biotite+plagioclase+quartz+K-feldspar. Sometimes 1 mm size clots, which consist of epidote+albite+biotite, are observed. The leucosome is a medium-grained leucocratic layer in the migmatite. It shows granitic texture and has no schistosity. The mineral assemblage is biotite+plagioclase+quartz+K-feldspar, and is richer in K-feldspar than other portions. In many cases, the leucosome is rimmed by melanosome. The melanosome consists of medium-grained melanoclatic portions and mainly has biotite, plagioclase and quartz. This portion is relatively rich in biotite, titanite, and zircon, and poor in K-feldspar. Sometimes melanosome contains 1–2 mm size clots which consist of epidote+biotite+albite, and of biotite+titanite+epidote (Fig. 3). The former shows a round shape, and it is composed of euhedral epidote and unhedral biotite and albite. On the other hand the latter shows a diamond-like shape. These clots are probably pseudomorphs after amphibole or pyroxene considering their chemical compositions.

Major and minor chemical compositions for the paleosome, leucosome and melanosome are given in Table 1 and shown in Harker's diagram (Fig. 4). This figure shows that the melanosomes plot on the lower SiO_2 concentration side, whereas the leucosomes

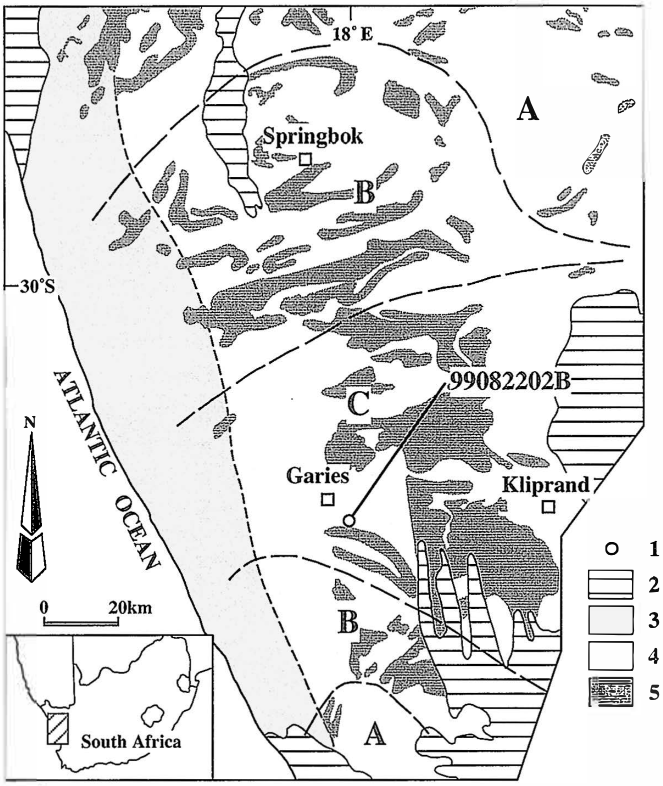

Fig. 1. Simplified geological map of the Bushmanland Subprovince of the Namaqualand Metamorphic Complex, modified after Andreoli et al. (1994). 1: location "99082202B" of analyzed sample, 2: late Precambrian to early Paleozoic Nama Group, 3: the Namaqualand Metamorphic Complex reworked during the Pan-African event, 4: granitic intrusive rocks of the Namaqualand Metamorphic Complex, 5: supracrustal enclaves of the Namaqualand Metamorphic Complex. A: upper-amphibolite zone, B: lower-granulite zone, C: upper-granulite zone.

are higher SiO_2 on the side. One of the paleosome (C11) plots in the middle between the melanosomes and leucosomes and the other two (C1, C10) are overlapped with the leucosomes. Approximate relations between each element and SiO_2 are recognized. These can be explained as addition- and subtraction-relationships implying a genetic connection among rock samples (*e.g.* White and Chappell, 1977; Osanai *et al.,* 1992). Figure 5 shows normalized patterns of each sample calculated by chemical compositions of the paleosome (C11, Table 1). A supplemental relationship between the melanosomes and leucosomes is recognized, which also implies a genetic connection among them.

3. Analytical Procedures

Extraction procedures for Sr from rock powders have been described in Kagami *et*

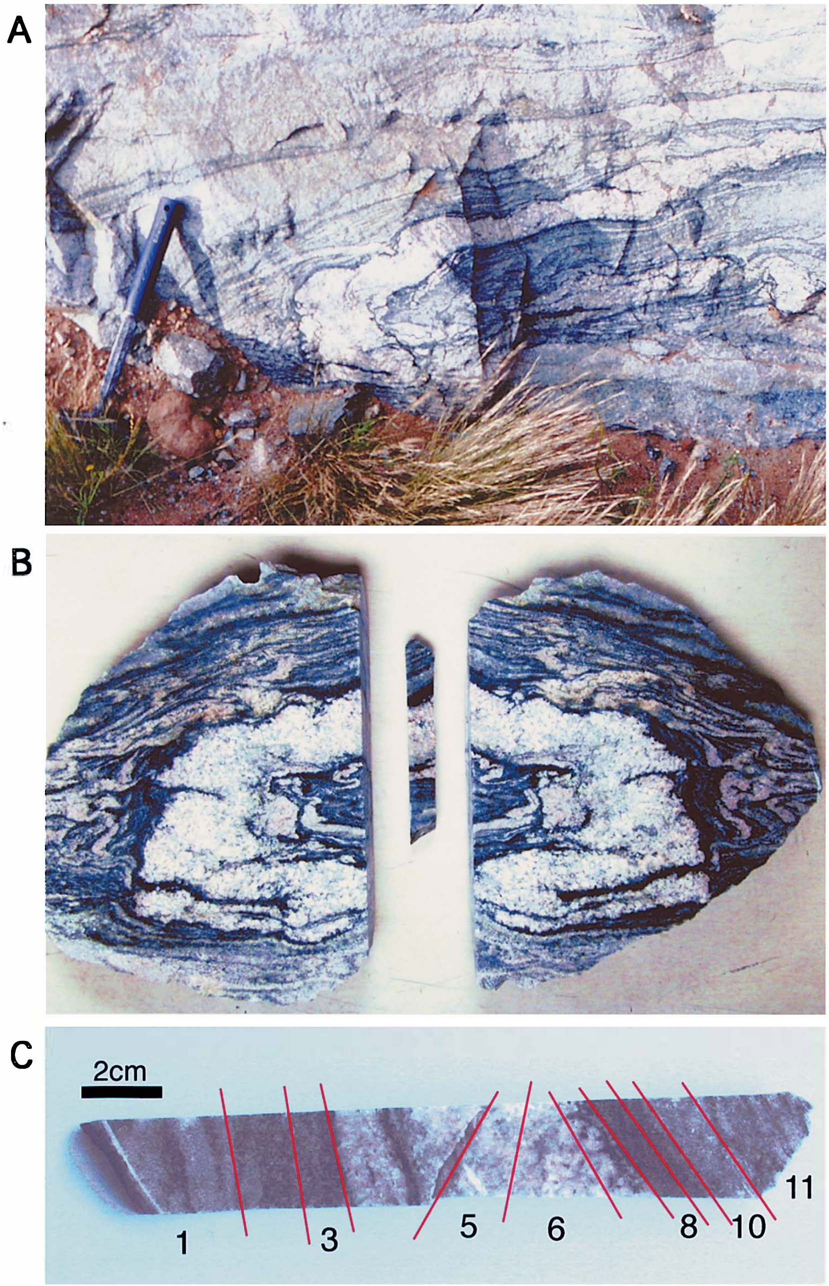

Fig. 2. Mode of field occurrence of migmatite and analyzed samples.
A: mode of field occurrence of migmatite, B: three rock pieces were cut away from the rock block, C: analyzed samples and their names (C1, C10, C11: paleosomes, C3, C8: melanosomes, C5, C6: leucosomes).

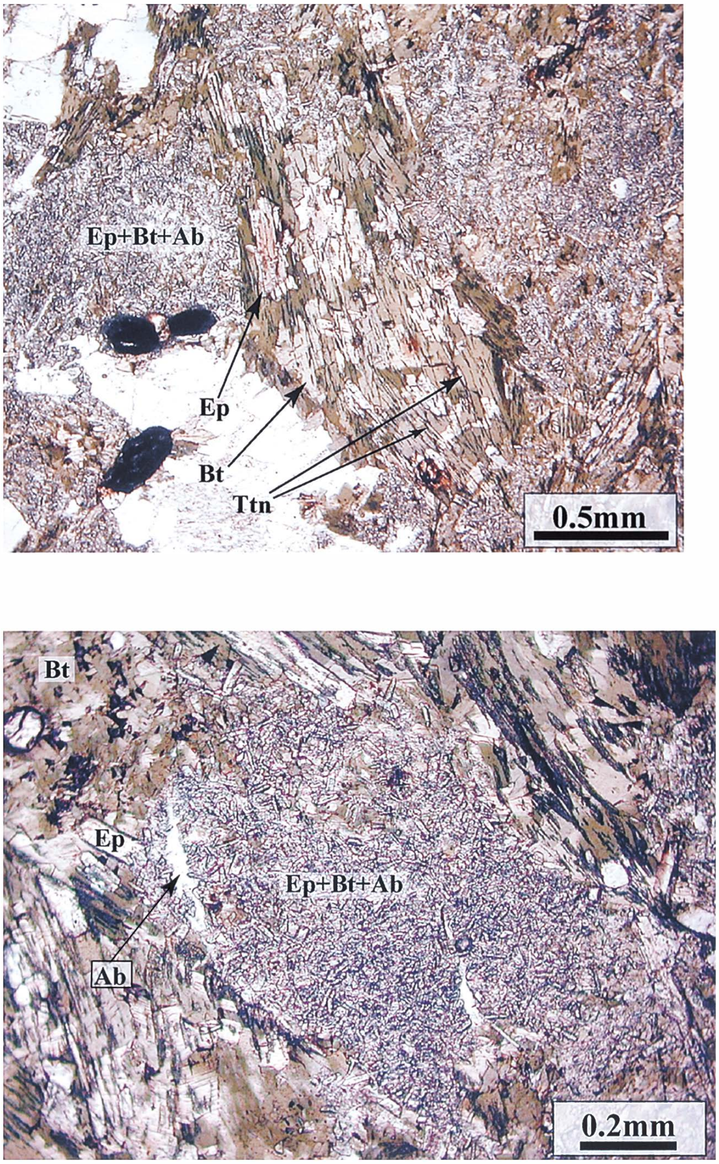

Fig. 3. Photomicrographs of clots constituing of epidote + biotite + albite and biotite + titanite + epidote in melanosome. Ab: albite, Bt: biotite, Ep: epidote, Ttn: titanite.

al. (1987). Isotopic analyses were performed on a MAT262 mass spectrometer at Niigata University. $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$. The $^{87}Sr/^{86}Sr$ ratio of NBS987 during this study was 0.710188 ± 0.000032 (2σ, n = 3). The $^{87}Sr/^{86}Sr$ ratios of C6 (leucosome), C8 (melanosome), C10 and C11 (paleosome) were measured (Table 1). The Sr isotopic ratio of each sample has an error of 0.0018% as

Table 1. Major and minor chemical compositions and $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios of migmatite.

	C1 paleosome	C3 melanosome	C5 leucosome	C6 leucosome	C8 melanosome	C10 paleosome	C11 paleosome
SiO_2	75.37	66.89	76.61	75.46	57.05	76.65	73.26
TiO_2	0.58	1.23	0.10	0.08	3.94	0.42	0.88
Al_2O_3	12.44	13.41	12.90	13.20	12.03	12.37	11.87
Fe_2O_3	3.07	6.35	0.73	0.73	11.97	2.89	4.01
MnO	0.04	0.08	0.01	0.01	0.19	0.03	0.05
MgO	1.04	1.74	0.23	0.20	2.91	0.82	1.20
CaO	2.39	2.21	0.97	0.98	5.23	1.89	1.89
Na_2O	1.73	2.09	2.19	2.28	1.18	1.41	2.21
K_20	3.36	5.07	6.34	7.01	3.39	3.19	4.07
P_2O_5	0.14	0.25	0.04	0.07	0.81	0.23	0.20
Total	100.16	99.32	100.12	100.02	98.70	99.90	99.64
V(ppm)	42.9	91.0	11.0	7.5	207.1	23.6	45.4
Cr	332.1	313.8	87.3	136.1	311.2	214.2	172.0
Ni	16.0	20.0	0.0	0.0	39.7	0.9	10.3
Rb	173.3	255.4	179.6	191.5	296.6	171.3	184.1
Sr	123.1	161.7	160.5	153.7	164.0	92.0	141.6
Y	13.5	22.9	5.7	7.6	77.7	20.4	24.6
Zr	279.6	575.4	73.7	49.3	2052	219.0	447.9
Nb	8.3	16.6	1.4	1.2	66.7	5.6	12.4
Ba	605.3	1103	1300	1441	290.5	579.3	916.0
$^{87}Rb/^{86}Sr$				3.63	5.27	5.42	3.50
$^{87}Sr/^{86}Sr$				0.769769	0.777184	0.777918	0.768443

the 2σ level. Concentrations of major and minor elements including Rb and Sr were determined by XRF (RIX3000; Niigata University) following the procedure of Takahashi and Shuto (1997). The ages and initial $^{87}Sr/^{86}Sr$ ratios were calculated by the computer program of Kawano (1994) using the equation of York (1966) and the following decay constant: $\lambda^{87}Rb = 1.42 \times 10^{-11} y^{-1}$ (Steiger and Jäger, 1977). The estimated relative errors in the age calculation of $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios are 5% (1σ) and 0.015% (1σ), respectively.

4. Results

Four whole-rock samples give a line with a Rb-Sr age of 338 ± 36 Ma with an initial $^{87}Sr/^{86}Sr$ isotopic ratio of 0.7519 ± 0.0021, which is shown in Fig. 6. This Rb-Sr whole-rock isochron age is much younger than the ages of igneous and metamorphic rocks occurring in the study area, which are *ca.* 1230 Ma~*ca.* 720 Ma and *ca.* 1200 Ma~*ca.* 950 Ma, respectively (Yuhara *et al.,* 2001, 2002). As described in analyzed samples, the melanosomes consist of biotite, plagioclase and quartz and sometimes contain clots constituting of epidote+biotite+albite and biotite+titanite+epidote,

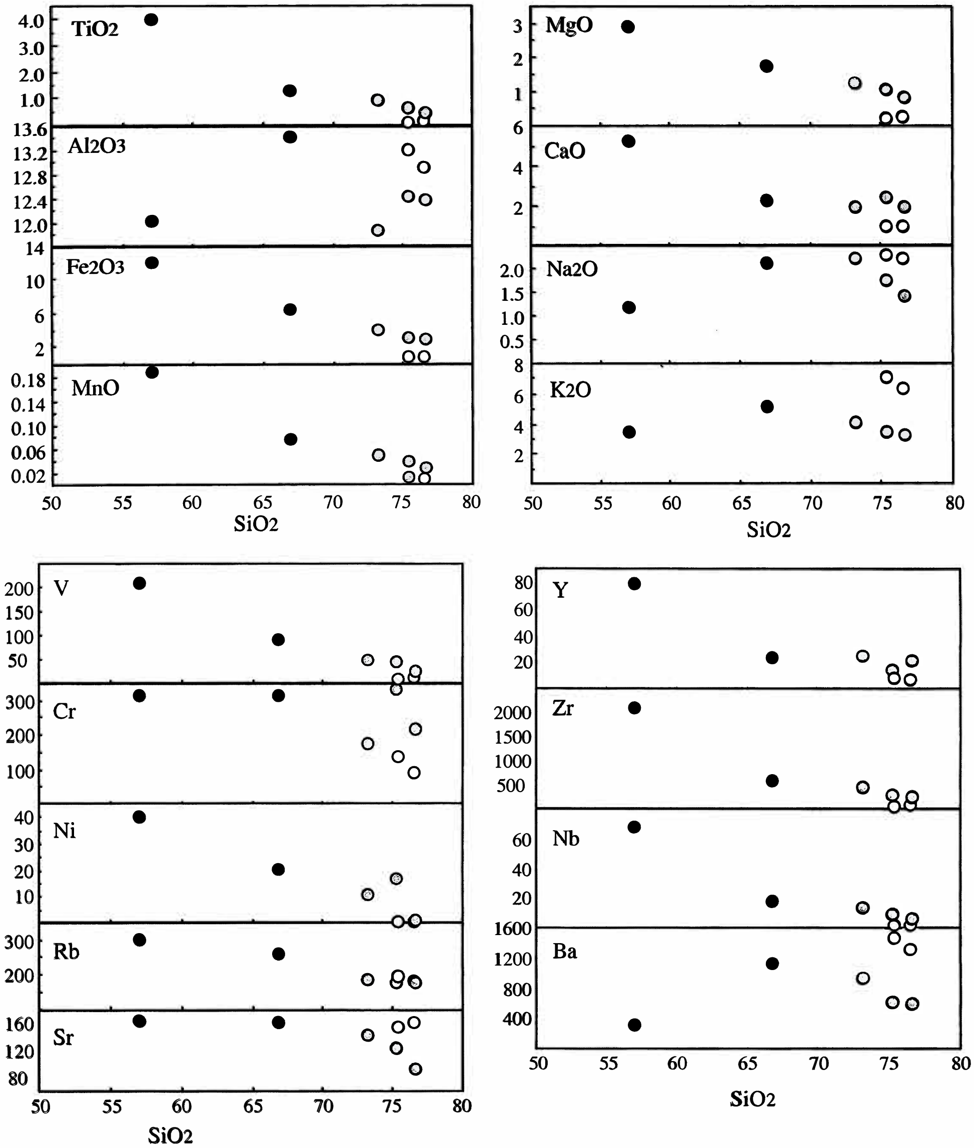

Fig. 4. Harker's diagrams of migmatite.
Closed circles: melanosomes, shaded circles: paleosomes, open circles: leucosomes.

which are quite different from orthopyroxene bearing mineral assemblages of melanosome as discussed by Owada *et al.* (1992), Shimura *et al.* (1998) and Miyamoto *et al.* (2002). The age of 338±36 Ma will be mentioned in the discussion (5.4) in connection with closure of the Rb-Sr whole-rock system and the existence of fluids.

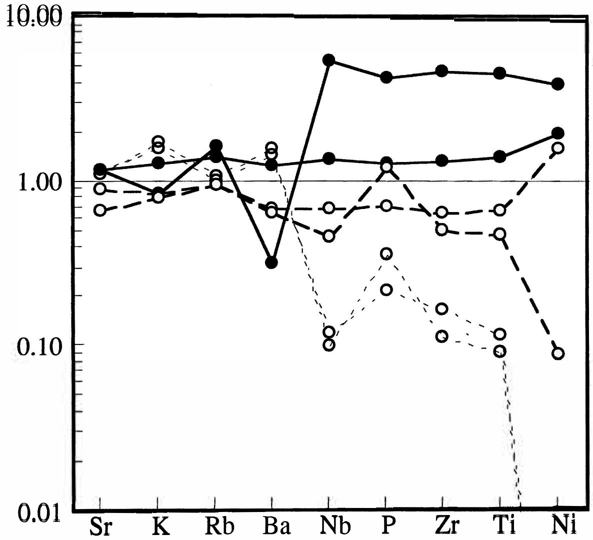

Fig. 5. Paleosome-normalized patterns of leucosome and melanosome. The normalizing factors are from paleosome "C11", which are given in Table 1. Closed circles: melanosomes, shaded circles: paleosomes, open circles: leucosomes.

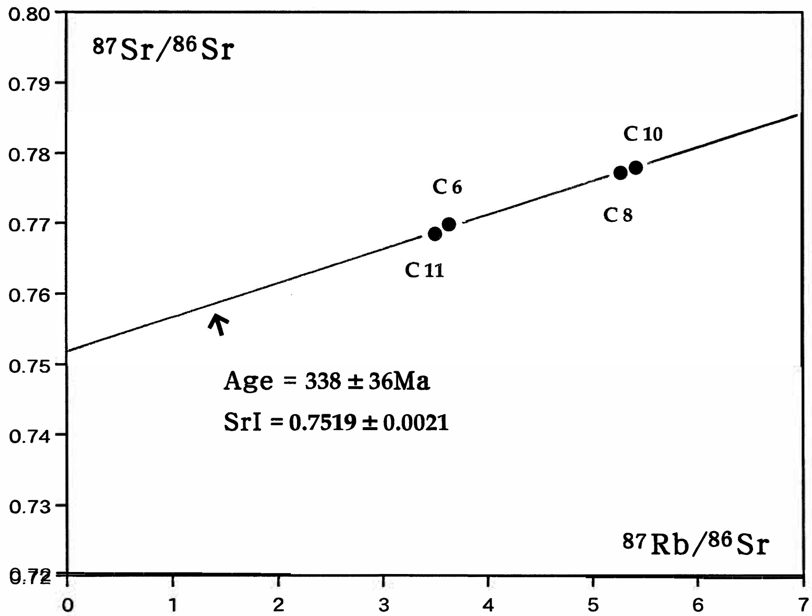

Fig. 6. Rb-Sr whole-rock isochron diagram of migmatite. SrI: initial $^{87}Sr/^{86}Sr$ ratio.

5. Discussion

5.1. Necessity of reexamination of metamorphic age defined by the Rb-Sr whole-rock system

Straight lines in the Rb-Sr isochron diagram obtained from metamorphic rocks have been reported from several areas in the world, and they have been sometimes interpreted as the meaningful isochron metamorphic age. However, Sr isotopic homogenization would not occur regionally at the middle to upper crustal level. This matter is probably understood as a case of igneous mass with a well defined Rb-Sr whole-rock isochron age.

As discussed by Jäger (1979), Faure (1986), Attendorn and Bowen (1997) and others, such igneous mass had a homogeneous Sr isotopic composition in its magma stage. The magma had ascended from deep crust (or upper mantle) and was emplaced at the middle to upper crustal level and rapidly made up a mass. According to a fundamental explanation about the Rb-Sr whole-rock isochron system (*e.g.* Jäger, 1979; Faure, 1986; Attendorn and Bowen, 1997), each member of the rock suite has the same $^{87}Sr/^{86}Sr$ ratio just after closure of the Rb-Sr whole-rock system. With the passage of time after the mass formation, each member acquires a different Sr isotopic ratio with the addition of radiogenic ^{87}Sr (disintegration product of ^{87}Rb). If the rock suite retrains its Rb-Sr isotopic system without any geologic disturbance from the formation to the present time, a reliable Rb-Sr whole-rock isochron age can be obtained using each member. Such ages are not cited in this paper as there are too many to enumerate.

The closure temperature of the Rb-Sr whole-rock system for felsic rocks has been stated as *ca.* 700°C (*e.g.* Harrison *et al.,* 1979). However, if the rock suite is heated again at *ca.* 700°C, its Sr isotopic composition would not be homogenized totally. Sr isotopically homogenized temperature for the rock suite (or mass) is probably close to that of original magma though its temperature may fall if the formed magma and fluid act efficiently. Taking account of this case, it is expected that the Sr isotopic composition for the composite consisting of various rocks (igneous, metamorphic and sedimentary rocks) would not be regionally homogenized at the middle- to upper-crust level by metamorphism. Moreover, it seems to be difficult to attain regional Sr homogenization, even under lower crustal level metamorphism. However, contrary to this expectation, Rb-Sr whole-rock isochrons interpreted as metamorphic ages have sometimes been reported, using samples collected from regional area (a few kilometer square and over). As to these age data, it is necessary to reexamine in detail whether they are meaningful metamorphic ages or not. If they are recognized as meaningful ages, it is necessary to know several important agents (*e.g.* fluids, *P-T* condition) for the metamorphism and scale (in field) will cause Sr isotopic homogenization. This information will significantly contribute to better understanding of the Rb-Sr whole-rock system of metamorphic rocks.

5.2. Resetting of Rb-Sr whole-rock system under partial melting process

Shiraishi and Kagami (1992) analyzed Rb-Sr and Sm-Nd systematics of the enderbitic gneisses from the Sør-Rondane Mountains, East Antarctica. Enderbitic gneisses except for retrograde rocks define a Rb-Sr whole-rock isochron age of 961±101

Ma. All gneisses including retrograde rocks define a Sm-Nd whole-rock isochron age of 978±52 Ma. Recalculation of the Rb-Sr age of 950±6 Ma using felsic enderbitic gneisses of igneous origin collected from a single outcrop was reported by Nishi *et al.* (2002). A Sm-Nd mineral age using hornblende, biotite and plagioclase is 624±18 Ma, which is interpreted as the main metamorphic age in the study area. Rb and Sr isotopic data of retrograde gneisses are randomly scattered on the right side of an isochron indicating 961±101 Ma, whose isotopic disturbance was caused by geologic events with an age of 630 Ma. Thus, Sr isotopic homogenization for the enderbitic gneiss did not occur in a single outcrop under the high-grade metamorphism (*ca.* 800°C, 7–8.5 kb: Shiraishi and Kojima, 1987).

Kagami *et al.* (1995) analyzed Rb-Sr and Sm-Nd systematics of charnockites from Gampola-Nuwara Eliya located in the Highland Complex, Sri Lanka. The Rb-Sr whole-rock isochron age using biotite-free rocks from a single outcrop of Nuwara Eliya is 2415±2 Ma. Biotite-free rocks from Gampola also plot on this isochron. Rb-Sr isotopic data of biotite-bearing rocks are scattered on the right side of the 2415 Ma isochron. Sm-Nd whole-rock isochron ages and mineral age using garnet, mafic fraction and felsic fraction of Gampola charnockites are 2330±30 Ma and 525.1±5.8 Ma, respectively, though the samples from Nuwara Eliya are scattered and did not give a reliable Sm-Nd isochron. These age data indicate that the Gampola-Nuwara Eliya rocks were affected by Pan-African orogeny. The straight line in Rb-Sr system connecting two-mica granite occurring as sheet-like to network dyke with various widths and the charnockite which is one of the main rock facies in the Nuwara Eliya outcrop is coincident with that of the Sm-Nd system, whose inclination corresponds to an age of *ca.* 485 Ma. *P-T* conditions of metamorphism of Nuwara Eliya are >9 kb and *ca.* 800°C (Schumacher and Faulhaber, 1994). The two-mica granite with an age of *ca.* 485 Ma was formed by partial melting of charnockite during the latest stage of the Pan-African orogeny (Kagami *et al.,* 1990). This suggests that partial melting causes Sr isotopic homogenization at least on a local scale. Actually, metamorphic rocks formed by such a process generally give a meaningful Rb-Sr whole-rock isochron age using samples collected from a single outcrop or separated from a rock block (*e.g.* Owada *et al.,* 1992; Shimura *et al.,* 1998; Miyamoto *et al.,* 2002).

Pan-African migmatite from Breidvågnipa, East Antarctica, was formed under the condition of *ca.* 870°C and 8 kb and has a Rb-Sr whole-rock isochron age of 570±46 Ma (Shimura *et al.,* 1998). Peraluminous granite, which occurs as dykes (3 cm–1 m wide) or irregularly shaped pools (50 cm–5 m in diameter), also plots on the 570 Ma isochron. All samples including the migmatite and granite define an age of 576±39 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.71016±0.00057. And Archean migmatite from Howard Hills, East Antarctica was formed at *ca.* 1120–1200°C (Yoshimura *et al.,* 2000) and has Rb-Sr and Sm-Nd whole rock isochron ages of 2.63±0.03 Ga and 2.66±0.05 Ga, respectively (Miyamoto *et al.,* 2002). The samples used for this dating were collected from a single outcrop. On the other hand, Hidaka migmatite from Hokkaido, Japan was formed at 870°C and 7.3 kb (Osanai *et al.,* 1991). Paleosomes, leucosomes and melanosomes for the dating are separated from a specimen-size block and give a well defined Rb-Sr whole-rock age of 54.9±5.5 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70570 ±0.00004 (Owada *et al.,* 1992). Orthopyroxene bearing tonalites, collected regionally from the Hidaka Metamorphic Belt, also plot on the 54.9±5.5 Ma isochron. This age is coincident with the previous published one of 56.0±6.1 Ma (Owada *et al.,* 1991) within an error.

Thus, the age data from the migmatite imply that Sr isotopic homogenization has been achieved on a local scale (*i.e.* single outcrop to specimen-size) under metamorphism which accompanies partial melting.

5.3. Closure temperature of Rb-Sr whole-rock system on a local scale

The closure temperature of Rb-Sr whole-rock system of granitic rocks has generally been fixed at *ca.* 700°C. However, it is likely that closing of the system still continues to much lower than 700°C depending on the samples (sampling methods). We discuss this possibility using the felsic igneous rock occurring in the Japan Arc.

Ryoke migmatite, Central Japan occurs around the Hisori and Ikuta granitic masses and is intruded by the Hisori granitic mass though it is not clear if there is an intrusive relation between migmatite and the Ikuta granitic mass (Yuhara, 1995). Major and minor chemical compositions of the migmatite completely overlap with those of Ryoke pelitic- to psammitic-derived metamorphic rocks but are totally different from those of Ryoke granitic rocks. This migmatite was formed at >820°C and >5.8 kb (Yuhara, 1995). Rb-Sr whole-rock systems of the migmatite were studied using samples from a single outcrop and slabs separated from a rock block, whose isochron ages are 74.2±6.4 Ma, 58.7±10.4 Ma, 56.4±18.6 Ma (Yuhara *et al.,* in preparation), 55.2±19.1 Ma and 49.7±1.7 Ma (Yuhara, 1995). Most of these ages are younger than K-Ar hornblende ages of 74.3±0.7 Ma~ 68.8±0.7 Ma and Rb-Sr biotite ages of 65.2±0.3 Ma~60.5±0.2 Ma obtained from Hisori and Ikuta granitic masses (Yuhara *et al.,* 2000b). Furthermore, Rb-Sr whole-rock ages of the migmatites are close to or younger than Rb-Sr biotite ages (61.3±1.0 Ma, 57.8±1.1 Ma) obtained from Ryoke metamorphic rocks (Yuhara *et al.,* 2000b). As described above, the Hisori granitic mass with K-Ar hornblende age of 74.3±0.7 Ma distinctly intrudes into migmatite. Judging from closure temperatures of K-Ar hornblende (*ca.* 500°C; Harrison, 1981) and Rb-Sr biotite (*ca.* 330°C; Wagner *et al.,* 1977), and the field relationship between Hisori granitic mass and migmatites, Rb-Sr whole-rock isochron ages do not indicate formation of the migmatites but cooling age down to *ca.* 400°C.

Hiji tonalite, which is one of the oldest granitic masses occurring in the Ryoke Belt, has various ages ranging from 495 Ma (U-Pb zircon; Sakashima *et al.,* 2000) to *ca.* 10 Ma (fission track apatite ages; Tagami and Shibata, 1993) though most ages cluster between 165 Ma and 50 Ma (Yuhara *et al.,* 2000a). Rb-Sr and K-Ar biotite ages of this mass range from 65.2±2.0 Ma to 59.1±0.1 Ma and K-Ar hornblende ages are 72.3±3.0 Ma and 70.4±0.7 Ma. Rb-Sr whole-rock ages using slab pieces of two rock specimens collected from two different outcrops are 69.9±8.1 Ma and 63±10 Ma (Yuhara *et al.,* 2000a). Every rock sample collected from each of these outcrops plots on the isochron obtained from slab pieces, and the recalculated ages using slab pieces and rock samples are 69.5±7.3 Ma and 63±10 Ma. Considering the K-Ar hornblende and Rb-Sr biotite ages, the closure temperature of the Rb-Sr whole-rock system using samples collected from a single outcrop is estimated at *ca.* 400°C.

Kagashima (1999, 2001a, b) and Shimura *et al.* (2002) studied the petrology and

Rb-Sr geochronology of layering of the late Cretaceous granitic mass occurring in the Northeast Japan Arc. The layering was formed as a marginal facies in accordance with emplacement of magma. Slab pieces separated from one layer (30 cm long) define an age of 89.5±1.9 Ma, which is close to or slightly older than the Rb-Sr biotite age of 88.9 ±0.3 Ma. Adding other age data for several layered and homogeneous granitic samples, they discussed the relation between the emplacement process of granitic magma and formation of the granitic layer, and estimated that closure temperatures of the Rb-Sr system using layering which was formed by rapid cooling at margin of the mass is close to *ca.* 400°C.

The age data described above strongly suggest that Rb-Sr whole-rock ages obtained using samples collected from a single outcrop of granitic mass are considerably younger than the emplacement age of the mass except for the ages using layering (Kagashima, 1999, 2001a, b; Shimura *et al.,* 2002). In other words, the Rb-Sr whole-rock isochron ages obtained from samples which are collected in a single outcrop are not generally coincident with those of formation of migmatite or emplacement of felsic magma.

5.4. Causes of fall of closure temperature for the Rb-Sr whole-rock system

Melts and fluids in the rocks play important roles in Sr isotopic homogenization (Pan *et al.,* 1999). The rate of diffusion of Sr and other elements in melts rapidly falls in accordance with decreasing of temperature (Hofmann and Hart, 1978; Dickin, 1995). Hofmann and Hart (1978) support local Sr isotopic heterogeneity even in a completely crystalline mantle. Considering these, it is estimated that the Rb-Sr whole-rock system is closed at high-temperature by removal of melts. And under the subsolidus condition, closing of the Rb-Sr whole-rock system on a local scale may be related to the efficient action of fluids, especially H_2O. If the fluids are released rapidly after the formation of migmatite, the Rb-Sr whole-rock system would be closed at high-temperature. Breidvågnipa (East Antarctica), Howard Hills (East Antarctica) and Hidaka Belt (Hokkaido) granulitic rocks consisting of anhydrous minerals as described above may support such cases.

Burton and O'Nions (1990) studied the Rb-Sr and Sm-Nd systematics of charnockite from Kurunegala, Sri Lanka and obtained reliable Rb-Sr and Sm-Nd whole-rock isochron ages with 535.4±4.5 Ma and 535.1±36.1 Ma, respectively, using slab pieces separated from small samples (14 cm long). They stated that the granulite-facies metamorphism was caused by dehydration melting. Kagami *et al.* (1990) and Santosh *et al.* (1992) collected a hornblende-biotite gneiss, which seems to be incipient charnockite, from Kurunegala, and they reported a Rb-Sr whole-rock age of 422±91 Ma using five portions separated from the gneiss (20 cm long). This age is distinctly younger than that of charnockite reported by Burton and O'Nions (1990). The young age of 422±91 Ma is probably due to the fall of closure temperature caused by the hydrous condition.

The ages data described above are slightly younger than those of main geologic events. However, if the migmatite retains the fluids at high-temperature for a long time, its Rb-Sr whole-rock system will not be closed easily and would yield a meaningless age. We studied migmatite in the upper granulite-facies zone of the Okiep Copper district, Namaqualand, South Africa (Figs. 1 and 2A~C). Four rocks separated from one migmatite piece (Fig. 2C) define a line indicating an age of 338±36 Ma (initial $^{87}Sr/^{86}Sr = 0.7519 \pm 0.0021$) on the Rb-Sr isochron diagram (Fig. 6). This age is too young in comparison with that of igneous activity (*ca.* 1230 Ma–*ca.* 720 Ma) and metamorphism (*ca.* 1200 Ma–*ca.* 950 Ma) in the Okiep Copper district (Yuhara *et al.,* 2001, 2002). In view of the field occurrence, the formation of migmatite is probably related to granulite-facies metamorphism (*ca.* 1200 Ma–*ca.* 1050 Ma; Robb *et al.,* 1999). As mentioned in the descriptions of analyzed melanosome samples, epidote+biotite+albite clots and biotite+titanite+epidote clots may be pseudomorphs after amphibole or pyroxene. Although the meaning of *ca.* 340 Ma is not clear at present, the Rb-Sr whole-rock system was not closed immediately after the formation of migmatite, caused by the influence of H_2O. We need more detailed petrological, petrochemical, Rb and Sr isotopic analyses for *ca.* 340 Ma rocks in order to clarify the timing of this influence.

As discussed above, closure temperature of migmatites and granites falls to *ca.* 400°C under the efficient action of fluids, especially H_2O. This speculation leads to a conclusion that the Rb-Sr whole-rock system of rocks fully affected by fluids under greenschist-facies metamorphism will be reset on a local scale. However, even if one is using such metamorphic rocks collected from a single outcrop, it is difficult to obtain reliable Rb-Sr whole-rock isochrons. This discrepancy is probably caused by heterogeneous Sr isotopic compositions for every part of a series of rocks using age determination.

6. Summary

Sr isotopic homogenization in a single outcrop to specimen-size took place during metamorphism which accompanied partial melting. The closure temperature of Rb-Sr whole-rock system for felsic rocks falls to *ca.* 400°C, as a result of efficient action of H_2O. The Rb-Sr whole-rock isochron ages using samples collected from a single outcrop of granitic mass are probably not coincident with that of emplacement of magma except for the ages of layering formed by rapid cooling of magma. The temperature of *ca.* 400°C suggests that the Rb-Sr whole-rock ages of migmatites do not always indicate that of partial melting under metamorphism at the highest grade.

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