Sm-Nd AND Rb-Sr AGES OF METAMORPHIC ROCKS FROM THE SØR RONDANE MOUNTAINS, EAST ANTARCTICA

K. SHIRAISHI1 and H. KAGAMI2

1National Institute of Polar Research, 1-9-10, Kaga, Itabashi-ku, Tokyo 173, Japan
2Institute for Study of Earth’s Interior, Okayama University, Misasa, Tottori-gun, Tottori 682-02, Japan

Abstract: New Sm-Nd and Rb-Sr data are reported for the granulate facies metamorphic rocks from the Sør Rondane Mountains. The 87Rb/86Sr ratios for most whole-rock samples are low (0.02–0.15) and no meaningful isochron can be drawn due to isotopic scatter. Four enderbitic gneisses and two mafic granulites, however, define an isochron of 978 ± 52 Ma with initial 87Rb/86Sr ratio of 0.70426. The 143Nd/144Nd vs. 147Sm/144Nd ratios for all ten whole-rock samples define an isochron of 961 ± 101 Ma with an initial ratio of 0.51163 (εNd = +4.5). Model ages with respect to the depleted mantle range from 1102 to 1291 Ma. The Rb-Sr isochron yields the age of granulate facies metamorphism associated with pronounced Rb-depletion. If the Sm-Nd data are indicative of protolith age, it means there was a short time from crustal formation to granulate facies metamorphism. The Sm-Nd internal mineral isochron for an enderbitic gneiss yields 624 ± 18 Ma with an initial ratio 0.51193. The Rb-Sr internal mineral isochron for the same sample without biotite data is 556 ± 26 Ma with an initial ratio 0.70510; the age recalculated without hornblende data is 483 ± 12 Ma with an initial ratio 0.70520. These ages are attributed to the successive thermal events associated with granite intrusion.

Key words: dating, Sm-Nd, Rb-Sr, granulite, Sør Rondane

Introduction

The Sør Rondane Mountains (71.5°–72.5°S, 22°–28°E) consist of medium- to high-grade metamorphic rocks, together with various plutonic and minor dyke rocks (Van Autenboer and Loy, 1972; Shiraishi et al., 1991). Most of the available geochronological data indicate an intense thermal event which is assigned to plutonic activities in the early Paleozoic (e.g. Picciotto et al., 1964). The oldest age (2700 Ma) has been determined by U-Pb on detrital zircon from gneisses; however the age of the main phase of regional metamorphism remained uncertain (Pastels and Michot, 1970). The aim of this study was to determine the ages of protoliths, of the main phase of the granulite facies metamorphism, and of succeeding tectonothermal events. A preliminary report of these results was made by Shiraishi and Kagami (1989).

Description of the Samples

Geological setting

The metamorphic rocks in the northern and eastern parts of the Sør Rondane Mountains consist of pelitic to semipelitic gneisses, intermediate gneisses that may be derived from igneous rocks, and mixtures of sedimentary and volcanic rocks. Thin layers and lenses of calcareous and basic rocks occur in many places. Tonalite associated with mylonitic schists of basic, semipelitic and calcareous compositions occupies the southwestern part of the area.

In the central and eastern parts of the mountains, orthopyroxene-bearing granulite facies mineral assemblages occur in the basic to intermediate gneisses, and also in acidic charnockitic gneisses. However, a definite metamorphic zonation has not been established. Sillimanite-bearing pelitic gneisses in the eastern Sør Rondane contain relict kyanite, suggesting that the metamorphic facies series is of medium-pressure type (Grew et al., 1989). Physical conditions of the peak granulite facies metamorphism of the analyzed gneisses were estimated by Shiraishi and Kojima (1987) to be 800°C and 7–8.5 kbar. The metamorphic rocks show retrograde effects due to plutonic intrusions and mylonitization, retrograde kyanite having been formed in sillimanite-bearing pelitic gneiss (Asami and Shiraishi, 1987). Sakaiyama et al. (1988) divided the widespread plutonic activity in the Sør Rondane into two stages based on intrusive relations and timing relative to the regional mylonitization. Previous geochronological work established that the younger intrusives are early Paleozoic (Shiraishi et al., 1991).

Sampling

Ten whole-rock samples were selected from the northeastern part of Brattipene in the central Sør Rondane Mountains (Fig. 1). They were collected from a 200 m high cliff, which is predominantly composed of enderbitic (tonalitic) gneisses with thin layers of mafic granulite. Conspicuous granite-pegmatite dykes intrude the enderbitic gneisses. This resulted in a bleached light gray gneiss zone up to a few meters wide in the surrounding enderbitic gneisses. However the preexisting gneissic foliation is not affected.

Four enderbitic gneisses (1503B, 1503D, 1602D, 2502A) and two interlayered mafic granulite boudins (20 cm wide, 1503C, 2502B), were collected from a single outcrop a few meters across. The analyzed retrograde gneisses include weakly foliated (1602A) and well-foliated gneisses (1602B, 1601C) and a 10 cm wide mafic layer (1601A). Two of the retrograde gneisses (1602A, 1602B) crop out 50 m above...
Fig. 1. Simplified geological map of the western and central parts of the Sør Rondane Mountains, showing the sample locality.

### Table 1. Rb-Sr isotopic compositions of metamorphic rocks from the Sør Rondane Mountains.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Mineral Assemblages*</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>$^{87}$Rb/$^{86}$Sr</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Enderbitic gneisses</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85011503B</td>
<td>(Pl-Qtz-Hbl-Cpx-Bt-Opx)</td>
<td>2.47</td>
<td>291.8</td>
<td>0.0245</td>
<td>0.70436(4)**</td>
</tr>
<tr>
<td>1503C</td>
<td>(Pl-Hbl-Opx-Cpx-Bt)</td>
<td>3.59</td>
<td>238.2</td>
<td>0.0436</td>
<td>0.70484(6)</td>
</tr>
<tr>
<td>1503D</td>
<td>(Pl-Qzt-Opx-Hbl-Bt-Cpx-Grt)</td>
<td>8.93</td>
<td>207.7</td>
<td>0.1244</td>
<td>0.70615(3)</td>
</tr>
<tr>
<td>Hbl</td>
<td></td>
<td>10.85</td>
<td>43.21</td>
<td>0.7269</td>
<td>0.71085(12)</td>
</tr>
<tr>
<td>Bt</td>
<td></td>
<td>162.8</td>
<td>16.30</td>
<td>29.47</td>
<td>0.90786(1)</td>
</tr>
<tr>
<td>Pl</td>
<td></td>
<td>4.44</td>
<td>186.0</td>
<td>0.0692</td>
<td>0.70559(4)</td>
</tr>
<tr>
<td>1602D</td>
<td>(Pl-Qzt-Hbl-Opx-Kfs-Cpx-Bt)</td>
<td>10.78</td>
<td>212.4</td>
<td>0.1468</td>
<td>0.70643(2)</td>
</tr>
<tr>
<td>9022502A</td>
<td>(Pl-Qzt-Opx-Bt)</td>
<td>38.30</td>
<td>163.5</td>
<td>0.6710</td>
<td>0.71356(1)</td>
</tr>
<tr>
<td>2502B</td>
<td>(Pl-Hbl-Opx-Bt-Cpx)</td>
<td>5.34</td>
<td>357.2</td>
<td>0.0433</td>
<td>0.70494(1)</td>
</tr>
<tr>
<td><strong>Retrograde gneisses</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85011601A</td>
<td>(Hbl-Pl-Bt)</td>
<td>6.78</td>
<td>193.0</td>
<td>0.1016</td>
<td>0.70456(2)</td>
</tr>
<tr>
<td>1601C</td>
<td>(Qzt-Pl-Hbl-Bt-Kfs)</td>
<td>9.33</td>
<td>207.3</td>
<td>0.1302</td>
<td>0.70637(2)</td>
</tr>
<tr>
<td>1602A</td>
<td>(Pl-Qzt-Hbl-Cpx)</td>
<td>1.36</td>
<td>218.7</td>
<td>0.0180</td>
<td>0.70412(2)</td>
</tr>
<tr>
<td>1602B</td>
<td>(Pl-Qzt-Hbl-Bt-Cum-Ep)</td>
<td>2.98</td>
<td>327.9</td>
<td>0.0263</td>
<td>0.70358(2)</td>
</tr>
</tbody>
</table>

* Mineral abbreviations after Kretz (1983) ** Numbers in parentheses for the $^{87}$Sr/$^{86}$Sr ratios refer to the 2σ error in the last digit.

The sampled enderbitic gneisses. The other two (1601A, 1601C) were collected from a point about 300 m along strike, adjacent to a one meter wide pegmatite dyke.

**Petrography**

Mineral assemblages of the analyzed samples are given in Table 1. The petrography and mineral chemistry of the enderbitic gneisses were reported by Shiraishi and Kojima (1987). The enderbitic gneisses are dark-colored medium-to coarse-grained rocks which partly show distinct foliation owing to elongated quartz grains and aggregates of mafic minerals. The gneisses commonly contain two pyroxenes and bear up to 40 volume % of quartz, a mafic granulite being an exception. The dark-color is largely due to quartz
and plagioclase. Brownish pargasitic hornblende is the other dominant mafic mineral. The most quartzose gneiss (1503D) contains a trace amount of garnet (Mg/(Mg+Fe) = 0.16). The enderbitic gneisses are overprinted by retrograde textures: yellowish brown biotite associated with quartz partly replaces orthopyroxene, and greenish hornblende occurs along cracks in clinopyroxene.

The retrograde gneisses have no orthopyroxene and show intense retrograde textures as follows: Hornblende usually shows strong color zoning; brownish green cores and pale green to bluish green on the outside. Locally green hornblende and plagioclase form symplectic pseudomorphs after orthopyroxene. 1601C contains cummingtonite which is surrounded by pseudomorph fine aggregates of bluish green tschermakitic hornblende and quartz. 1602B contains fine cummingtonite which is surrounded by bluish-green tschermakitic hornblende and fine epidote with quartz at the fringe of hornblende.

**Bulk chemical composition**

Chemical compositions of the ten samples including trace elements and REE have been analyzed (Table 2). There is no significant difference in major and trace elements composition for the non-retrograde and retrograde gneisses at similar SiO₂ contents. It is noteworthy that Rb is consistently low relative to K (K/Rb = 952–2991) and to Sr (Rb/Sr = 0.006–0.051). U and Th are also low. All chondrite-normalized REE patterns except for 1601A show relatively smooth and moderately fractionated patterns. However, spidergrams for incompatible element abundances in the retrograde gneisses are irregular relative to those for the non-retrograde enderbitic gneisses.

**Isotopic Data**

**Analytical procedure**

Extraction of Rb, Sr, Sm and Nd from rock and mineral powders are described by Kagami et al. (1987). Mass spectrometric analyses follow the procedure of Kagami et al. (1987, 1989). $^{87}$Sr/$^{86}$Sr ratios were normalized to $^{86}$Sr/$^{88}$Sr = 0.1194 and $^{143}$Nd/$^{144}$Nd ratios were normalized to $^{146}$Nd/$^{144}$Nd = 0.7219. Blanks for the whole procedure are <0.3 ng Rb, <1 ng Sr, <0.3 mg Sm and <1 ng Nd.

Average errors for $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd ratios were 0.005% and 0.006%, respectively at the 2σ level. Rb and Sr concentrations of samples were obtained by $^{87}$Rb/$^{86}$Rb mixed spike. Sm and Nd concentrations of each sample were determined using a $^{150}$Sm/$^{150}$Nd mixed spike. Based on reproducibility of data we estimate an error of 1% for the Rb/Sm and Sm/Nd ratios of each sample.

**Rb-Sr data**

Rb-Sr isotopic data for the analyzed samples are given in Table 1 and plotted in Figs. 2 and 3. No meaningful isochron can be drawn for all whole-rock samples due to the considerable scatter of the data. Four enderbitic gneisses and two mafic granulites from within a few meters of each other, however, define an isochron of 978 ± 52 Ma with an initial ratio 0.70426. Among the four retrograde gneisses, two pairs occur adjacent to each other: 1601A occurs as a mafic
Fig. 2. Rb-Sr whole-rock isochron diagram of metamorphic rocks from the Sør Rondane Mountains. Calculated errors are within the scale of symbols.

Fig. 3. Rb-Sr mineral isochron diagram for enderbitic gneiss 1503D. *W.R.*; whole-rock, *Hbl*; hornblende, *Bt*; biotite, *Pl*; plagioclase.

Layer in the gneiss 1601C, and 1602B is a well-foliated gneiss adjacent to the weakly foliated gneiss 1602A. In Fig. 2, neither pair makes a meaningful isochron. Taking the mode of occurrence, petrographic and chemical characteristics into account, it is suggested that Rb-Sr isotopic compositions of the retrograde gneisses were disturbed by the retrogression. Deviation of six enderbitic gneiss analyses from the isochron could also have resulted from later isotopic disturbance, since these gneisses also contain minor quantities of retrograde minerals.

The internal mineral isochron for an enderbitic gneiss (1503D) yields 489 ± 30 Ma with an initial ratio 0.70536 (Fig. 3). However, the age is controlled by biotite with high $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{87}\text{Rb}/^{86}\text{Sr}$ ratios. The isochron age without biotite data is 556 ± 26 Ma with an initial ratio 0.70510. Without the hornblende, the isochron age is 483 ± 12 Ma, with an initial ratio 0.70520.

**Sm-Nd data**

Sm-Nd isotopic data are given in Table 3 and plotted in Fig. 4. Sm and Nd contents of biotite and hornblende are very high relative to typical values for these minerals, possibly due to inclusions of accessory minerals such as apatite. The $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{147}\text{Sm}/^{144}\text{Nd}$ ratios for all ten whole-rock samples define an isochron of 961 ± 101 Ma, with an initial ratio of 0.51163 (eNd = -4.5). The calculated
Table 3. Sm-Nd isotopic compositions and model ages of metamorphic rocks from the Sør Rondane Mountains.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>$^{147}$Sm/$^{144}$Nd</th>
<th>$^{143}$Nd/$^{144}$Nd</th>
<th>$T^{*}_{DM}$ (Ma)</th>
<th>$E_{Nd}$ (1000 Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enderbitic gneisses</td>
<td>85011503B</td>
<td>4.93</td>
<td>20.03</td>
<td>0.1485</td>
<td>0.51256(2)**</td>
<td>1387</td>
</tr>
<tr>
<td></td>
<td>1503C</td>
<td>3.14</td>
<td>12.19</td>
<td>0.1554</td>
<td>0.51262(1)</td>
<td>1394</td>
</tr>
<tr>
<td></td>
<td>1503D W.R.</td>
<td>2.73</td>
<td>12.00</td>
<td>0.1376</td>
<td>0.51249(2)</td>
<td>1328</td>
</tr>
<tr>
<td></td>
<td>Hbl</td>
<td>94.78</td>
<td>288.0</td>
<td>0.1989</td>
<td>0.51275(2)</td>
<td>1346</td>
</tr>
<tr>
<td></td>
<td>Bt</td>
<td>9.29</td>
<td>28.60</td>
<td>0.1945</td>
<td>0.51273(1)</td>
<td>1220</td>
</tr>
<tr>
<td></td>
<td>Pl</td>
<td>0.83</td>
<td>5.07</td>
<td>0.0990</td>
<td>0.51234(2)</td>
<td>1354</td>
</tr>
<tr>
<td></td>
<td>1602D</td>
<td>3.44</td>
<td>13.94</td>
<td>0.1491</td>
<td>0.51254(2)</td>
<td>1446</td>
</tr>
<tr>
<td></td>
<td>9022502A</td>
<td>2.37</td>
<td>12.50</td>
<td>0.1145</td>
<td>0.51236(2)</td>
<td>1558</td>
</tr>
<tr>
<td></td>
<td>2502B</td>
<td>3.31</td>
<td>14.60</td>
<td>0.1370</td>
<td>0.51247(2)</td>
<td>1443</td>
</tr>
<tr>
<td>Retrograde gneisses</td>
<td>85011601A</td>
<td>1.22</td>
<td>4.28</td>
<td>0.1716</td>
<td>0.51272(2)</td>
<td>1304</td>
</tr>
<tr>
<td></td>
<td>1601C</td>
<td>3.77</td>
<td>14.48</td>
<td>0.1574</td>
<td>0.51262(1)</td>
<td>1361</td>
</tr>
<tr>
<td></td>
<td>1602A</td>
<td>6.56</td>
<td>27.69</td>
<td>0.1432</td>
<td>0.51255(2)</td>
<td>1443</td>
</tr>
<tr>
<td></td>
<td>1602B</td>
<td>4.86</td>
<td>20.42</td>
<td>0.1439</td>
<td>0.51253(1)</td>
<td>1558</td>
</tr>
</tbody>
</table>

* $T^{*}_{DM} = \frac{1}{\lambda} \ln \left[ \frac{1 + (\varepsilon_{Nd} - 1) \lambda / \alpha_{Nd}}{1 - (\varepsilon_{Nd} - 1) \lambda / \alpha_{Nd}} \right]$ \( \lambda = 6.54 \times 10^{-12} \text{ yr}^{-1} \)
** Numbers in parentheses for the $^{143}$Nd/$^{144}$Nd ratios refer to the 2σ error in the last digit.

Fig. 4. Sm-Nd whole-rock and mineral isochron diagram of metamorphic rocks from the Sør Rondane Mountains.

uncertainty is high due to the very small range in $^{147}$Sm/$^{144}$Nd ratios. The internal mineral isochron for 1503D yields 624 ± 18 Ma, with an initial ratio 0.51193.

Discussion

Ages of the protoliths and granulite facies metamorphism

The Sm-Nd and Rb-Sr whole-rock isochron ages are consistent within analytical uncertainties, viz. about 1000 Ma. This could either represent the age of crust formation or else metamorphism of even older crust. Although REE mobility during metamorphism is still controversial (e.g. Grauch, 1989), there is no distinct disturbance of REE patterns between the enderbitic gneisses and the retrograde gneisses. Model ages based on $\varepsilon_{Nd} = +10.0$ and $^{147}$Sm/$^{144}$Nd = 0.2136 at present age with respect to the depleted mantle (DM), range between 1220 and 1568 Ma (Table 3). However, the use of $\varepsilon_{Nd} = +8.5$ as depleted mantle yields younger model ages between 1102 and 1291 Ma. These are similar to the isochron ages. Moreover, $\varepsilon_{Nd} = +4.5$ at 1000 Ma suggests that the protoliths were derived from a depleted mantle source. Hence, it is reasonable to assume that the whole-rock Sm-Nd data for the metamorphic rocks define the crust formation age. The higher values of $^{147}$Sm/$^{144}$Nd ratios of the analyzed samples (mean 0.15) relative to those of the average continental crust (about 0.12: Moorby and Taylor, 1986) support this assumption.

Alternatively, resetting of Sm-Nd whole-rock isochrons
may have been possible under the estimated conditions of granulite facies metamorphism (800°C, 7–8.5 kbar) (McCulloch and Black, 1984). Re-equilibration of isotopic ratios during metamorphism depends on the scale of redistribution relative to sampling. Since the samples are obtained from one outcrop (within 300 meters), re-distribution of the Sm-Nd system is a plausible explanation, if dehydration reactions during the granulite facies metamorphism released fluids bearing LREE. In summary, we currently have no conclusive evidence to determine whether the Sm-Nd isochron age dates the protolith or the metamorphism. If the Sm/Nd ratios of the enderbitic gneisses before the 1000 Ma granulite facies metamorphism were lower than the present values, the model ages for depleted mantle give the maximum age of the protoliths.

On the other hand, the enderbitic gneisses are depleted in Rb as well as U and Th, and have very high K/Rb and low Rb/Sr ratios relative to the average continental crust. It is assumed that a large Rb-depletion cannot represent a primary feature, but may be a consequence of granulite facies metamorphism coupled with partial melting or fluid migration. Therefore, the Rb-Sr whole-rock isochron for the enderbitic gneisses yields the age of granulite facies metamorphism. Rb-depletion during granulite facies metamorphism has been reported from many Precambrian terrains (e.g. Mooibath and Taylor, 1986). If Sm-Nd data indicate the age of the protolith, it means that the time of granulite facies metamorphism closely followed the emplacement of the protoliths, which we infer to be possibly no more than 100 Ma (the precision of our analyses). The close time relationship between crustal formation and granulite facies metamorphism is similar to that of the eastern Sør Rondane Mountains (Grew et al., 1991) and it has been reported from many other granulite terrains of both Archean and Proterozoic age (Jahn and Zhang, 1984; Mooibath and Taylor, 1986).

Successive thermal events

Internal mineral isochrons for Rb-Sr and Sm-Nd systems are potentially useful for dating the successive thermal events which reset isotopic ratios on the mineral scale. Sm-Nd closure temperatures in minerals are considered to be 620–660°C and those for Rb-Sr in biotite and hornblende are considered to be about 320 and 530°C, respectively (Burton and O’Nions, 1990). Therefore, the thermal event at 624 ± 18 Ma might be significant. Retrograde textures are attributed to this event. U-Pb dating of zircon from granites near the present sample locality indicates two post-tectonic intrusive phases: 600 ± 30 and 520 ± 20 Ma (Pasteels and Michot, 1970). The older phase appears to be contemporaneous with the Sm-Nd mineral age of 624 ± 18 Ma, whereas the younger one is close to the Rb-Sr mineral ages of 560 Ma and 480 Ma.

Conclusion

The geological history established for the central Sør Rondane Mountains on the basis of available isotope data is as follows:

1. Precursors of enderbitic gneisses were emplaced at around 1000 Ma, followed shortly afterwards by granulite

facies metamorphism.

2. Pronounced depletion of Rb, U and Th was associated with the granulite facies metamorphism.

3. The Sm-Nd system was reset on a mineral scale at 620 Ma, possibly because of granite intrusion.

4. Successive granite intrusions reset the Rb-Sr mineral ages at 560 and 480 Ma.

Acknowledgements

The authors would like to thank E. S. Grew and L. R. K. Perera for useful discussions and comments during the preparation of this paper.

REFERENCES


