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Nd AND Sr ISOTOPE CHARACTERISTICS OF THE PLUTONIC ROCKS IN THE SØR RONDANE MOUNTAINS, EAST ANTARCTICA

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Abstract: Plutonic rocks in the Sør Rondane Mountains, East Antarctica comprise early Paleozoic granitic rocks and late Proterozoic tonalite. The former is further classified into two types (volcanic arc type and within plate type). The initial εNd values for the analyzed granitic rocks (six samples from volcanic arc type and one from within plate type) fall in a limited range (-1.48 to $+0.62$) and Nd model ages (T_{DM}) for the granitic rocks were estimated to be 900-1000 Ma which agree well with the ages of basement rocks. Taking Sr isotope data and element compositions into account, volcanic arc type granites (Dufek, Lunckeryggen and Mefjell) are explained by a fractional crystallization from an isotopically homogeneous magma which was generated from late Proterozoic lower (to middle) crustal rocks, whereas the within plate type granites (Vikinghøgda, Rogerstoppane and Pingvinane) are assumed to have been formed mainly by mixing between crustal rocks with high Sr isotope ratios and mafic (to intermediate) parental magma originated in the upper mantle or lower crustal source. The presence of extremely high Sr isotope ratios for the within plate type granites suggests the involvement of more older crustal rocks (early to middle Proterozoic) beneath the Sør Rondane Mountains. Changes of magma sources and a dominant process of magma formation from within plate type granites (early) to volcanic arc type granites (late) reflect the change of tectonic situation in this region during the early Paleozoic. The late Proterozoic Nils Larsen tonalite was generated in a depleted mantle and evolved without large crustal contributions.

1. Introduction

The Sør Rondane Mountains, one of the large inland mountain ranges in East Antarctica, consist mainly of medium-to high-grade metamorphic rocks and plutonic bodies of various sizes (Fig. 1) (VAN AUTEMBOER and LOY, 1972; SHIRAISHI *et al*., 1991). Previous geochronological studies have revealed two main thermal and magmatic events: late Proterozoic (950-1000 Ma) granulite facies regional metamorphism and plutonism, and early Paleozoic (500-530 Ma) plutonism (PICCIOTTO *et al*., 1964; PASTEELS and MICHOT, 1970; TAKIGAMI *et al*., 1987; TAKAHASHI *et al*., 1990; SHIRAISHI and KAGAMI, 1992; TAINOSHO *et al*., 1992). Geological and petrological characteristics for the plutonic rocks were summarized by SAKIYAMA *et al.* (1988) and TAKAHASHI *et al.* (1990), and geochemical data for the rocks were presented by TAINOSHO *et al.*(1993). However, isotopic data (Sr and Nd isotope data) for the plutonic rocks, which offer important information on the intrusive age, origin and evolutional process of magmas that formed the plutonic bodies, are very limited to the Sør Rondane Mountains. In this report, we present new Nd isotope data for some of the plutonic bodies and discuss with the previously published Sr isotope data for further understanding of the nature of magmatism and crustal evolution in this area.

2. Geology and Geochemistry

2.1. *Outline of geology*

The basement metamorphic rocks are mainly composed of pelitic, psammitic and intermediate gneisses, associated with subordinate basic and calc-silicate gneisses which were metamorphosed under the amphibolite to granulite facies conditions in late Proterozoic (SHIRAISHI *et al.*, 1991). Plutonic rocks in the Sør Rondane Mountains are divided into late Proterozoic tonalite and early Paleozoic granitic rocks (TAKAHASHI *et al.*, 1990). The late Proterozoic tonalite (Nils Larsen tonalite) is exposed in the southern part of the Sør Rondane Mountains, and was affected by regional mylonitization with relatively

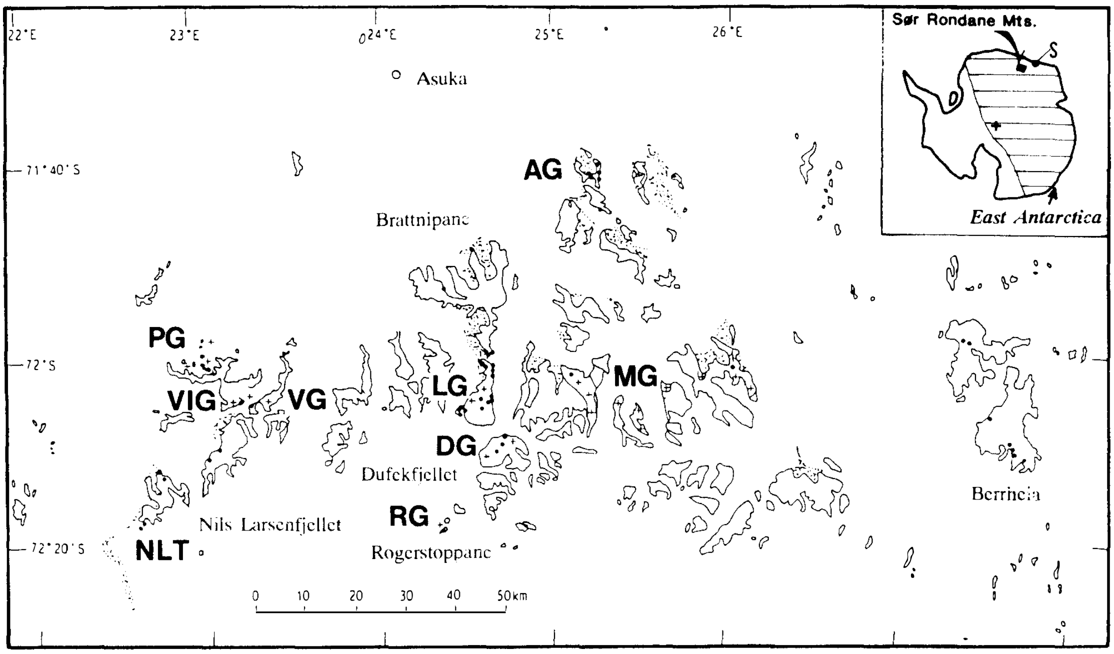

Fig. 1. Distribution of plutonic rocks in the Sør Rondane Mountains, East Antarctica (after TAINOSHO *et al., 1992). Inset map shows the locations of Sør Rondane Mountains and Syowa Station (S). Small dotted symbols show moraine, crossed symbols represent the granitic rocks, and the other parts bounded by solid line show outcrop areas of metamorphic rocks. Solid circles indicate sample locations. Symbols for granites are as follows : AG, Austokampane granite ; DG, Dufek granite ; LG, Lunckeryggen granite ; MG, Mefjell granite ; PG, Pingvinane granite ; RG, Rogerstoppane granite ; VG, Vengen granite ; VIG, Vikinghøgda granite ; NLT, Nils Larsen tonalite.*

low-grade metamorphic condition (KOJIMA and SHIRAISHI, 1986). The early Paleozoic granitic rocks are subdivided into two types (concordant type and discordant type) on the basis of their field relations with basement gneisses and the timing of regional mylonitization (SAKIYAMA *et al*., 1988 ; TAKAHASHI *et al*., 1990). The emplacements of the concordant granites predated those of the discordant granites. Petrographical characteristics for the late Proterozoic tonalite and early Paleozoic granitic rocks are described in TAINOSHO *et al*. (1992 ; 1993).

2.2. *Whole rock chemistry of plutonic rocks*

The plutonic rocks are classified by their petrochemical characteristics (TAINOSHO *et al*., 1993).

The late Proterozoic tonalite has high CaO, MgO, Ni and Cr, and low alkali, Ba and Rb contents ; this tonalite correlates to the M-type granite.

The early Paleozoic granitic rocks, mostly belonging to the A-type granite of the classification of LOISELLE and WONES (1979), are grouped into two types based upon major and trace element compositions (TAINOSHO *et al*., 1992, 1993). One is volcanic arc type granite which includes Dufek granite, Lunckeryggen granite and Mefjell granite (Fig. 1). The rocks in this type are characterized by relatively high alkalis, Ba, Sr, and low Y and Nb contents. The other type is within plate type granite which involves Austkanpane granite, Pingvinane granite, Rogerstoppane granite and Vikinghøgda granite, having low alkalis, Sr, Cr, and high Y and Nb, in comparison with the volcanic arc type granites. This classification (volcanic arc type and within plate type) almost coincides with the classification on the structure of the pluton (discordant type and concordant type), respectively, except the Mefjell granite. Characteristics of the isotope data, particularly for Sr isotope data of the rocks, are consistent with this classification.

3. Samples and Experiments

Seven samples for Nd isotope measurements were selected ; they are four samples from the Dufek granite, two from the Mefjell granite and one from the Pingvinane granite.

Extraction procedures of Sm and Nd from powdered rock samples are described in ARAKAWA (1992). The extracted Nd samples were loaded on Re filament using 3% HNO_3. The measurements were performed with a double Re filament mode, using a Finnigan MAT 262 mass spectrometer equipped with seven Faraday collectors at the University of Tsukuba. Data acquisition was done in the static mode with pre-measurement gain calibration of each Faraday collector. The measured $^{143}Nd/^{144}Nd$ ratios were normalized to the $^{146}Nd/^{144}Nd$ ratio of 0.7219. Total blanks in the whole procedure were less than 0.02 ng for Sm and 0.3 ng for Nd. Repeated measurements of the La Jolla Nd standard during this study gave an average $^{143}Nd/^{144}Nd$ of 0.511864 ± 0.000008 ($n=10$). Errors of the $^{143}Nd/^{144}Nd$ ratios for each sample range from 0.001% to 0.002% at 2σ level. Sm and Nd concentrations of each sample were determined by isotope dilution method using ^{149}Sm-^{146}Nd mixed spike. Based on the reproducibility of the data we estimate an error of 1% for the Sm/Nd ratio. The CHUR values used for εNd calculation are $^{147}Sm/^{144}Nd$ (present)=0.1966 and $^{143}Nd/^{144}Nd$ (present)=0.512638 (WASSERBURG *et al*., 1981). Isochron ages were calculated using the least-squares method of YORK (1969). The decay

Table 1. Sm and Nd isotopic compositions and model ages for the Paleozoic granitic rocks in the Sør Rondane Mountains.

Sample No.	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd_t (Ma)	T_{DM}*
Dufek granite						
B9001-2301A	6.91	44.70	0.0935	0.512302 (5)**	+0.406	944
2302A	10.71	69.11	0.0937	0.512297 (7)	+0.292	952
2303A	9.80	71.04	0.0834	0.512278 (7)	+0.615	900
2305B	7.58	61.32	0.0747	0.512230 (9)	+0.267	897
Mefjell granite						
2502	3.02	18.54	0.0984	0.512306 (7)	−0.126	978
2405C	18.77	197.38	0.0575	0.512101 (7)	−1.482	923
Pingvinane granite						
1406	15.65	84.31	0.1122	0.512381 (10)	+0.486	998

* Model age calculation (T_{DM}) follows FARMER and DEPAOLO (1983).
** Numbers in parentheses for the $^{143}Nd/^{144}Nd$ ratios refer to the $2\sigma_m$ error in the last digit.
Initial εNd values were calculated, based on the published Rb-Sr whole rock ages for Dufek and Mefjell granites (TAINOSHO *et al.*, 1992), and assuming an intrusive age of 510 Ma for the Pingvinane granite.

constant of ^{147}Sm used is 6.54×10^{-12}/y. The analyzed data are listed in Table 1.

4. Results and Discussion

4.1. Nd isotope data

Sm-Nd isotope data are plotted in Fig. 2. Four samples of Dufek granite yield an isochron indicating an age of 519 ± 98 (1σ) Ma with an initial ratio of 0.51198 ± 0.00006 (1σ). The large uncertainties of the age and corresponding initial ratio are due to the limited ranges of $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios for the samples (Fig. 2). This age is almost identical to the Rb-Sr whole rock age of 528 ± 31 Ma (2σ) for 6 samples from the same Dufek granite (TAINOSHO *et al.*, 1992), and this coincidence confirms the intrusive age of the granite.

Figure 3 displays the Nd isotope evolution lines for the analyzed granite samples together with the data of granulite facies gneisses at Brattnipane by SHIRAISHI and KAGAMI (1992). Our samples present relatively a narrow range of εNd values (−1.48 to +0.62) and are plotted near the CHUR evolution curve. Model ages with respect to the depleted mantle (DM) (DEPAOLO, 1981) for the granite samples fall in the limited range of 900–1000 Ma (Table 1, Fig. 3). These model ages are mostly equal to the Rb-Sr whole rock isochron age of 956 Ma for the Nils Larsen tonalite (TAKAHASHI *et al.*, 1990), and the Rb-Sr whole rock isochron age of 978 Ma and Sm-Nd whole rock isochron age of 961 Ma for the high grade gneisses in Brattnipane (SHIRAISHI and KAGAMI, 1992). Based on the high initial εNd values and Nd model ages (T_{DM}) of the gneisses, SHIRAISHI and KAGAMI (1992) concluded that the precursors of the gneisses were emplaced at around 1000 Ma, followed by granulite facies metamorphism with short time interval. Although the Nd isotope data for the gneisses are slightly off from the estimated evolution lines of the granites (Fig. 3), above coincidence of the ages leads us to assume the genetical relationships between the early Paleozoic granites, and basement gneisses and late Proterozoic tonalite.

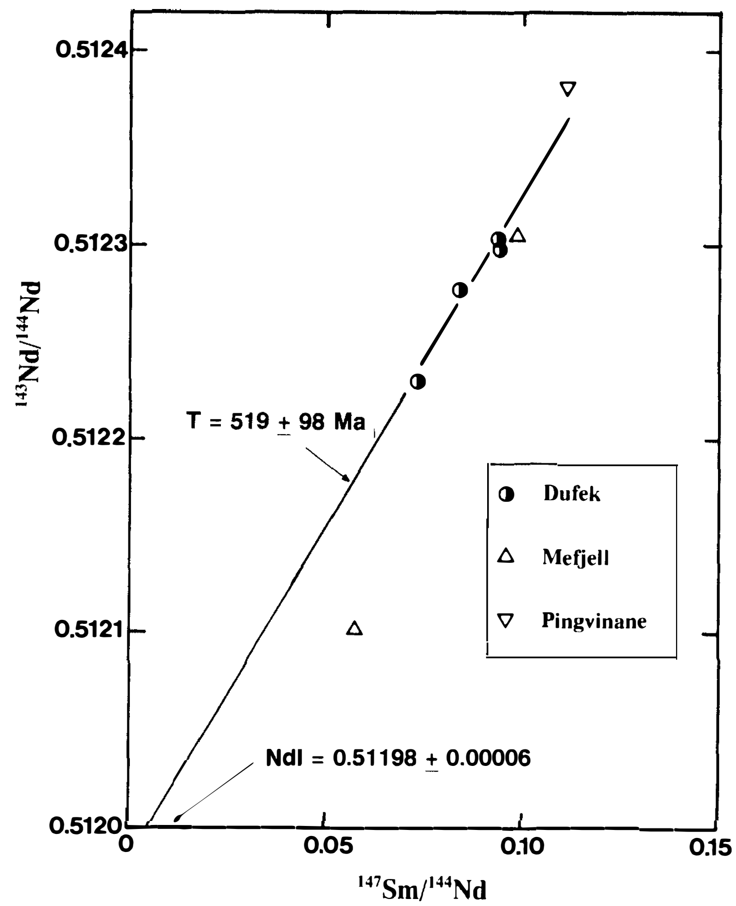

Fig. 2. Sm-Nd whole rock isochron diagram of early Paleozoic granitic rocks in the Sør Rondane Mountains. An isochron was quoted from four samples of the Dufek granite. Symbols are as follows : half-filled circles = Dufek granite, open triangles = Mefjell granite, open reverse triangle = Pingvinane granite.

As for the samples analyzed, there is no distinct difference of Nd isotope compositions between the volcanic arc type (Dufek and Mefjell) and the within plate type (Pingvinane).

4.2. *Sr isotope data*

The late Proterozoic Nils Larsen tonalite has an average initial Sr isotope ratio ($^{87}Sr/^{86}Sr$) of 0.7024 (TAKAHASHI *et al.*, 1990) which is clearly lower than those of the granulite facies gneisses at Brattnipane (0.7043) (SHIRAISHI and KAGAMI, 1992). This discordance of the ratios indicates the different origin between the two Proterozoic basement rocks, although there remains a possibility that the high Sr isotope ratios for the granulite facies gneisses resulted from later disturbance in the Rb-Sr isotope system (SHIRAISHI and KAGAMI, 1992). The low Sr isotope ratios for the Nils Larsen tonalite suggest their origin in a depleted mantle source.

In the case of early Paleozoic granites, the difference between two rock types (volcanic arc type and within plate type) is disclosed in the Sr isotope ratios. Figure 4 is a $^{87}Sr/^{86}Sr$-Rb/Sr diagram for the rocks from volcanic arc type (Dufek, Lunckeryggen and Mefjell granites) and within plate type (Pingvinane, Vikinghøgda and Rogerstoppane

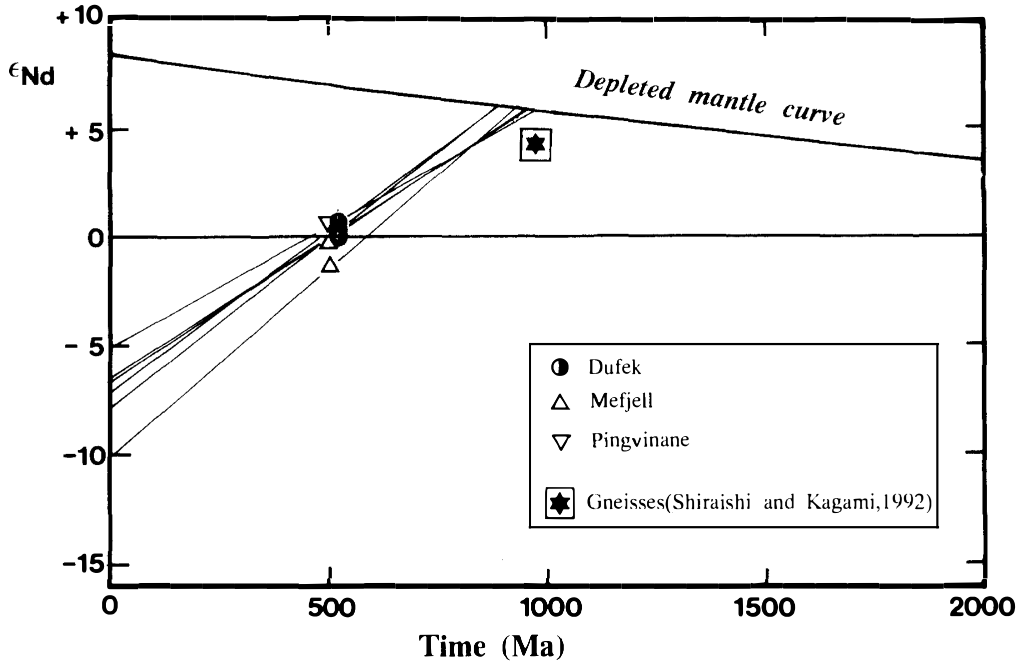

Fig. 3. Nd isotopic evolution diagram for the plutonic rocks and metamorphic rocks in the Sør Rondane Mountains. Nd isotopic evolution curve of the depleted mantle was cited from DEPAOLO (1981) and that of the chondritic uniform reservoir (CHUR) is after WASSERBURG et al. (1981). T_{DM} calculation followed FARMER and DEPAOLO (1983). Gneisses in the figure include enderbitic gneisses and retrograde gneisses at Brattnipane (SHIRAISHI and KAGAMI, 1992).

granites) (TAKAHASHI *et al.*, 1990; TAINOSHO *et al.*, 1992; unpublished data). Granitic rocks of the volcanic arc type show nearly horizontal trend without large scatter in $^{87}Sr/^{86}Sr$ ratios in individual pluton. The average Sr isotope ratios are 0.7037 for the Dufek, 0.7050 for the Lunckeryggen and 0.7056 for the Mefjell granite. In contrast, the rocks of the within plate type have high and wide range of Sr isotope ratios, specifically for the Vikinghøgda (0.7072–0.7200) and the Rogerstoppane granite (0.7302). Four of the Pingvinane granites exhibit a data range of 0.7035–0.7068 with narrow Rb/Sr ratios. The wide variations of Sr isotope values for the within plate type granites precludes the derivation of their parental magma from an isotopically unique source. Sr isotope ratios of late Proterozoic Nils Larsen tonalite (TAKAHASHI *et al.*, 1990) and granulite facies gneisses (SHIRAISHI and KAGAMI, 1992) are also plotted in the figure with age correction at the intrusive age of the plutons. The tonalites are characterized by low Rb/Sr ratios (mostly 0.006–0.159) and their Sr isotope values overlap those of some Paleozoic granites (Fig. 4).

4.3. Constraints on the origin and genesis of granitic magmas

The Nd and Sr isotopic results and chemical data suggest that the variations of lithology and chemistry of the volcanic arc type granites (Dufek, Lunckeryggen and Mefjell granites) were produced through crystal fractionation from an isotopically homogeneous magma with intermediate (or mafic) chemical composition. In this case, on the isotope basis, the Nils Larsen tonalite and granulite facies geneisses are plausible magma source for the volcanic arc type granites, although the Sr isotope data of the Mefjell granite are slightly

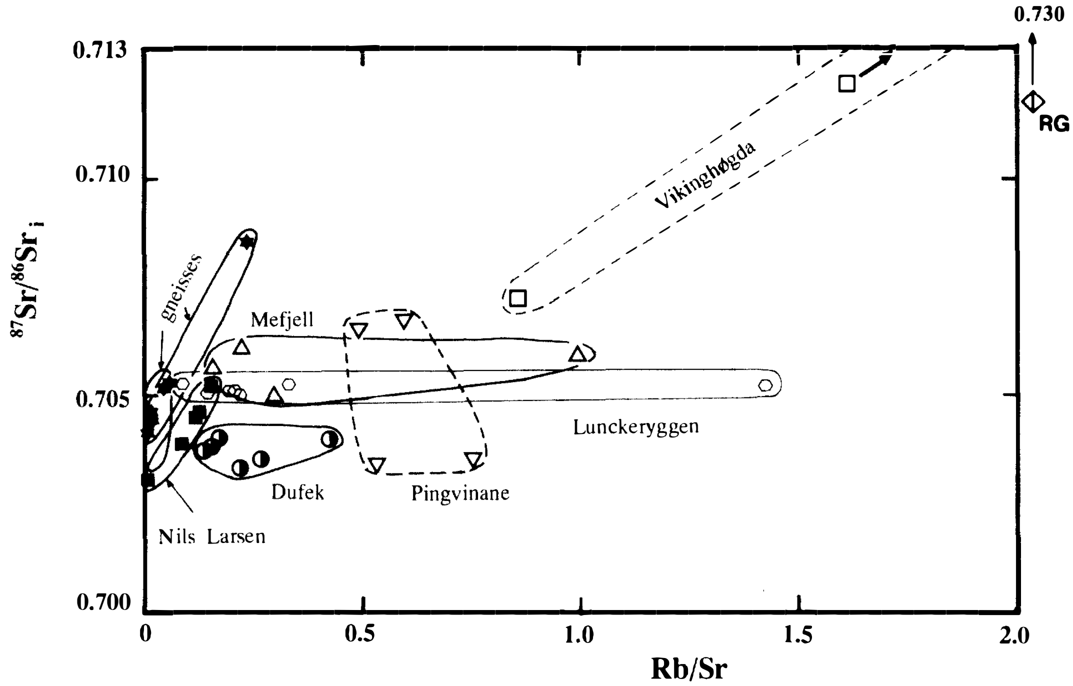

Fig. 4. Initial $^{87}Sr/^{86}Sr$ vs. Rb/Sr diagram for the plutonic rocks and metamorphic rocks in the Sør Rondane Mountains. Initial $^{87}Sr/^{86}Sr$ ratios were calculated at the published Rb-Sr whole rock ages (528 Ma for the Dufek, 525 Ma for the Lunckeryggen and 506 Ma for the Mefjell) (Takahashi et al., 1990 ; Tainosho et al., 1992), and other Paleozoic plutons and late Proterozoic tonalite and gneisses were calculated at 510 Ma. The data surrounded by solid lines indicate the volcanic arc type granites and those by broken lines are within plate granites. One Rogerstoppane granite (RG) is out of range of the figure.

higher than the majority of the data for the tonalites and gneisses (Fig. 5). Shiraishi and Kagami (1992) showed the extremely low Rb (and Rb/Sr) values for the gneisses at Brattnipane and interpreted them to be the result of a Rb (and some other elements) depletion event associated with fluid migration and partial melting during late Proterozoic regional metamorphism. Although these large-ion lithophile (LIL) element depleted basement rocks are generally recognized as magma sources for A-type (within plate type) granites (*e.g.*, Collins *et al.*, 1982), the chemical characteristics of the volcanic arc type granites are possibly explained by adopting a low degree of partial melting of the depleted sources. Therefore the late Proterozoic basement rocks including the Nils Larsen tonalite and granulite facies gneisses seem to be appropriate magma sources for the volcanic arc type granites (Dufek, Lunckeryggen and Mefjell), though magma contributions from a depleted mantle source cannot be excluded.

On the other hand, isotopically heterogeneous lithologies of the within plate type granites (Vikinghøgda, Rogerstoppane and Pingvinane granites) suggest the dominance of assimilation of crustal rocks (or crust-derived melt) with high Sr isotope values (>0.730) for the magma genesis (Fig. 4). Field occurrences support the assimilation of crustal rocks. The parental magma with low Sr (and high Nd) isotope ratios as one end member for the mixing process may have had mafic (to intermediate) chemical compositions and

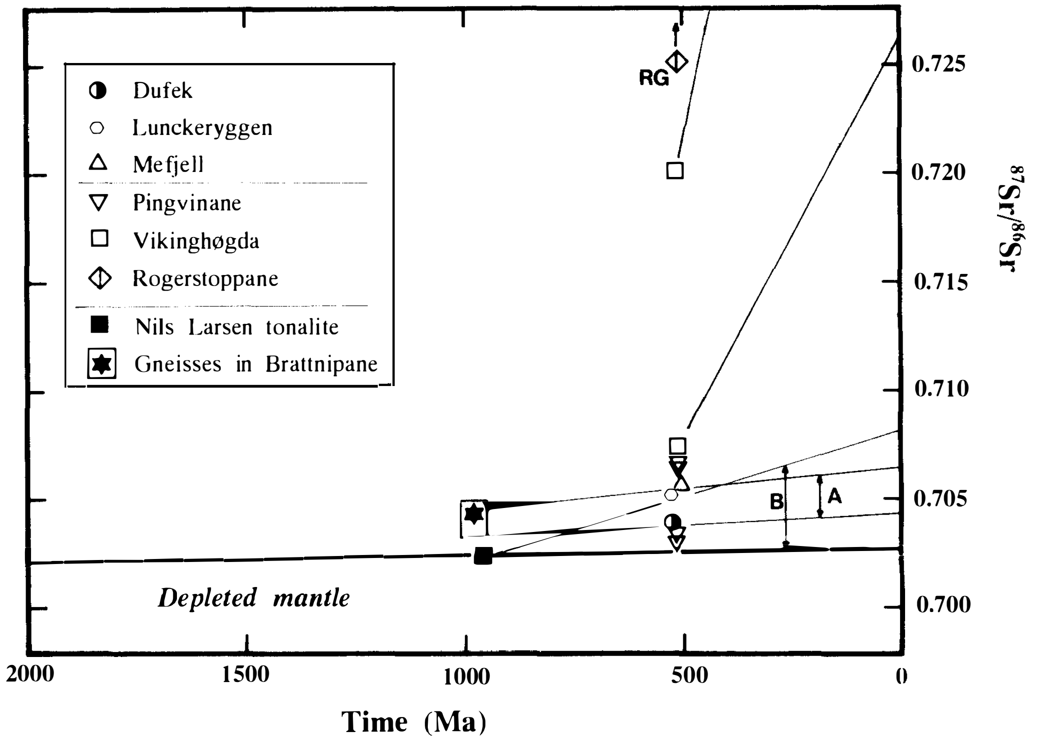

Fig. 5. Sr isotopic evolution diagram for the plutonic rocks and metamorphic rocks in the Sør Rondane Mountains. The depleted mantle curve was adopted from BEN OTHMAN *et al. (1984). The range labelled "A" in the figure shows an isotopic evolution range for most of the gneisses at Brattnipane, and "B" is the range for the Nils Larsen tonalite. The Dufek, Lunckeryggen and Mefjell granites are within the range of A or B, whereas some samples from other granites are clearly out of the ranges, toward high Sr initial ratios.*

might be originated from upper mantle or lower crust. Another crustal end member(s) with high Sr (and low Nd) isotope ratios is not defined precisely because of insufficient isotope data of basement crustal rocks. Similar crustal mixing processes were proposed for the genesis of some A-type (within plate type) granites (EBY, 1990 ; KERR and FRYER, 1993), although the A-type granites have been interpreted in general as anatectic derivatives of lower crustal rocks that were depleted by previous melt extraction (*e.g.*, COLLINS *et al.*, 1982 ; WHALEN *et al.*, 1987).

These two different types of granitic plutons developed in a limited space and time have been caused by the change of the tectonic situation around the Sør Rondane Mountains during early Paleozoic. In an early stage, progressive mixing of crustal rocks (or crust-derived melt) by parental mafic (to intermediate) magma resulted in the formation of within plate type granites, while in a late stage the differentiation by crystal fractionation of parental magma without large amounts of crustal assimilation produced the volcanic arc type granites.

Figure 5 shows a Sr isotope evolution diagram for the available rocks around Sør Rondane Mountains. Two magmatic and thermal episodes, being widely recognized also in Queen Maud Land, East Antarctica (*e.g.*, OHTA *et al.*, 1990 ; SHIRAISHI *et al.*, 1991), correspond to crust forming and evolutional processes in the Sør Rondane Mountains.

The presence of granitic rocks with markedly high Sr isotope ratios, especially Rogerstoppane and Vikinghøgda, strongly suggest the involvement of older crustal rocks (>1000 Ma), probably of early to middle Proterozoic. Plutonic rocks and dyke rocks with high Sr (and low Nd) isotope values were ascertained from the Mühlig-Höfmannfjella, East Antarctica (OHTA *et al.*, 1990) and from Transantarctic Mountains in the Ross Orogen (*e.g.*, BORG *et al.*, 1990) where early Paleozoic igneous activities occurred widely and the basement rocks are older.

The Nils Larsen tonalite representing Sr isotope values close to the depleted mantle value (Fig. 5) proves that its parental magma was generated in the depleted mantle and evolved with less crustal contribution.

5. Conclusions

The Nd-Sr isotope study of the plutonic rocks from the Sør Rondane Mountains revealed the following points.

Early Paleozoic granitic rocks are classified into two types (volcanic arc type and within plate type) based on trace element characteristics (TAINOSHO *et al.*, 1992); this classification is compatible with the Sr (and Nd) isotope signatures for the granitic rocks. Initial εNd values for the analyzed granite samples (Dufek, Mefjell and Pingvinane) are concentrated in a limited range (-1.48 to $+0.62$) close to the CHUR value. The Nd model ages (T_{DM}) for the granites are estimated to be 900–1000 Ma, and these ages coincide well with those of basement metamorphic rocks and Nils Larsen tonalite.

The parental magma for the Nils Larsen tonalite was generated in the depleted mantle in the late Proterozoic and evolved with less crustal influence.

These Sr and Nd isotope data suggest the different origin and process of magma evolution between the volcanic arc type and within plate type granites. Volcanic arc type granites (Dufek, Lunckeryggen and Mefjell) are interpreted in terms of fractional crystallization from an isotopically homogenous magma which originated mostly in late Proterozoic lower (to middle) crustal rocks similar to the basement gneisses and Nils Larsen tonalite. On the other hand, the within plate type granites (Vikinghøgda, Rogerstopane and Pingvinane) are explained mainly by the assimilation of crustal rocks with high Sr isotope values. Their parental mafic magma was possibly derived from the upper mantle or mafic lower crust. The difference of magma chemistries and processes of magma formation between two granite types were caused by the change of tectonic situation during early Paleozoic (500–530 Ma). Distinctively high Sr initial ratios (>0.730) for the within plate type granites may indicate the existence of older crustal rocks, probably of early to middle Proterozoic.

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