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THE STABILITY FIELD OF AMPHIBOLE FROM THE SØR RONDANE MOUNTAINS, EAST ANTARCTICA: IMPLICATION FOR THE EMPLACEMENT DEPTH OF SYENITE MAGMA

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Abstract: By using the stability field of amphibole in the melting experiments, we attempt to estimate the emplacement depth of amphibole-bearing syenites from the Sør Rondane Mountains. The melting relationships of four syenites and one granite were determined in the temperature range of 650-900°C under water pressure of 0.1-0.3 GPa and oxygen fugacities of the FMQ buffer. In two syenites and a granite, the maximum pressure stability limit of amphiboles in subliquidus is lower pressure than 0.35 GPa. The emplacement depth of the syenites from the Sør Rondane Mountains is similar to that of syenites from the Yamato Mountains.

1. Introduction

In the present study, we aim to estimate the emplacement depth of syenites and a granite from the Sør Rondane Mountains, East Antarctica. We already estimated the emplacement depth of the amphibole-bearing syenites from the Yamato Mountains, 300 km east of the Sør Rondane Mountains, in terms of melting experiments (OBA and SHIRAISHI, 1993, 1994). OBA and SHIRAISHI (1994) reported that the stability field of amphiboles in granite and syenite with low K_2O/Na_2O ratio is wider than that of syenite with higher K_2O/Na_2O ratio. Therefore, we supposed that the amphibole stability field in syenitic and granitic rocks with a higher K_2O/Na_2O ratios from the Sør Rondane Mountains could be determined under the present experimental conditions.

2. Petrography and Mineralogy of the Syenitic Rocks

The Sør Rondane Mountains are underlain by various kinds of upper amphibolite to granulite facies metamorphic rocks and plutonic rocks dating from the Neoproterozoic to early Paleozoic (SHIRAISHI *et al*., 1991; SAKIYAMA *et al*., 1988; SHIRAISHI and KAGAMI, 1992; TAINOSHO *et al*., 1992; OSANAI *et al*, 1992). Succeeding the pioneer work by Belgian researchers (PICCIOTTO *et al*., 1963; PASTEELS and MICHOT, 1968; VAN AUTENBOER, 1969), two age groups of the plutonism have been elucidated; 950 Ma and 450-602 Ma (TAKAHASHI *et al*., 1990; ARAKAWA *et al*., 1994). The younger intrusive rocks comprise various sizes of granitic masses, stocks and dikes, and a syenitic complex in the central part of the mountains (KOJIMA and SHIRAISHI, 1986; SAKIYAMA *et al*., 1988). Samples for the present study were collected from a syenite mass, a few kilometers in size, and a neighboring granite mass at Lunckeryggen (Fig. 1A, modified from SAKIYAMA *et al.*, 1988).

Three stages of syenite intrusions were observed. The schematic field relationship of these syenites is illustrated in Fig. 1B. The oldest and largest body of layered syenite has a heterogeneous appearance on a mesoscopic scale. Characteristic dark mafic layers (SR-103B: field number is 85012103B) and the felsic layers (SR-103C: 85012103C), a few tens of centimeters to several meters wide, show rhythmic layering. Constituent minerals are bluish green Na-actinolite, bluish green clinopyroxene, biotite, K-feldspar, quartz and plagioclase. In the felsic layer, albite occurs along grain boundaries of K-feldspar, whereas it occurs as very thin films around K-feldspar in the mafic layer. K-feldspar shows reddish schillerization owing to the thin flakes of hematite inclusions.

The younger leucocratic fine-grained quartz syenite (SR-101A: 85012101A) intruded in the layered syenite. It consists of common minerals with the layered syenite. Biotite is not found. In the youngest syenite (SR-103D: 85012103D) which characteristically contains green microcline (amazonite), no amphibole is observed, and green clinopyroxene occurs as subhedral prisms. The fine-grained quartz syenite (SR-2001C: 85012001C) intruded into the layered syenite at the southern part of the layered syenite body. As compared to SR-101A quartz syenite, SR-2001C is slightly richer in felsic minerals. It includes also the same mineral assemblage as the layered syenite. The coarse-grained granite (SR-2002A: 85012002A) is exposed at the southern part of the syenite. SAKIYAMA *et al.* (1988) reported that the granite intrudes into quartz syenite and tonalite of the older intrusives and it has angular xenoliths of these rocks. The constituent minerals are quartz, K-feldspar (microcline), plagioclase, biotite, green hornblende and clinopyroxene.

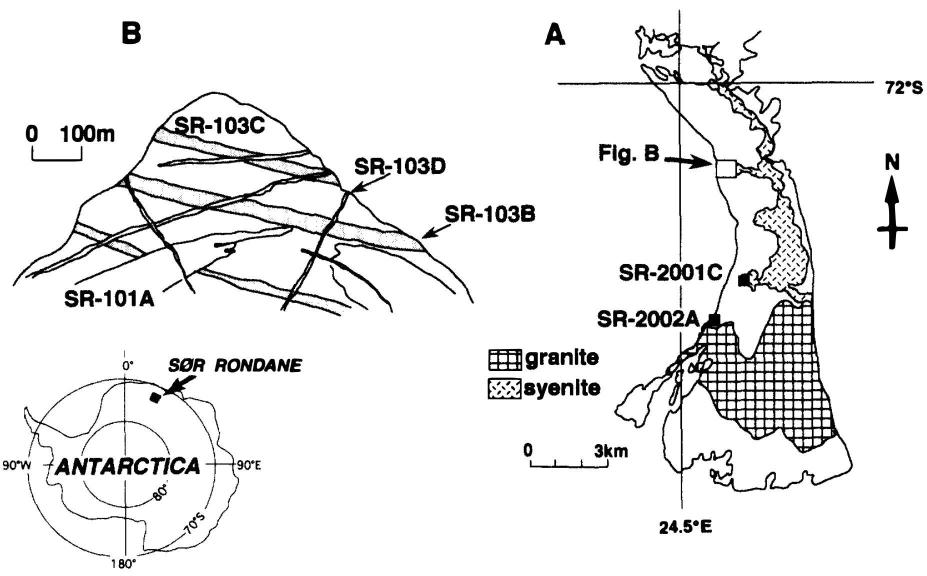


Fig. 1. A. Map showing the distribution of syenitic rocks and simplified cross section, modified from SAKIYAMA *et al. (1988).*
B. Schematic sketch of site B in Fig. A, showing a cliff of a hill. SR-101A: Quartz syenite, SR-103B: A mafic layer of the layered syenite, SR-103C: A felsic layer of the layered syenite, SR-103D: The youngest green microcline (amazonite)-bearing syenite.

Clinopyroxene occurs as euhedral crystal or relict inclusion in amphibole.

The bulk compositions and CIPW norms of four syenites and a granite for the melting experiments are given in Table 1. The analyses use an X-ray fluorescence spectrometer at the Joetsu University of Education. Three syenites are no quartz normative, except for SR-2001C syenite and SR-2002A granite. The K_2O/Na_2O ratios of four syenites and a granite are higher than 1. SAKIYAMA *et al.* (1988) noted that syenitic rocks in the Sør Rondane Mountains have extremely high K_2O/Na_2O as compared with the Yamato and Belgica Mountains.

Chemical compositions of amphibole and K-feldspar were determined with a JEOL 733 Superprobe, using standard procedure at the National Institute of Polar Research. Figure 2 shows the variety of chemical compositions of Ca-amphibole. Bluish green richteritic tremolite and large K-feldspar phenocrysts appear in both the leucocratic and

Table 1. Analyses and CIPW norms of the syenitic rocks and granite from the Sør Rondane Mountains.

Sample		SR-103A quartz syenite	SR-103B syenite	SR-103C syenite	SR-2001C quartz syenite	SR-2002A granite
SiO_2		57.43	46.13	59.78	69.42	70.04
TiO_2		1.42	2.00	0.65	0.43	0.60
Al_2O_3		15.36	6.87	16.25	14.75	13.81
FeO*		4.27	8.95	2.77	2.26	2.62
MnO		0.06	0.17	0.03	0.05	0.06
MgO		2.01	10.02	1.78	0.42	1.02
CaO		4.86	13.42	2.15	1.12	2.07
Na_2O		3.41	1.02	1.72	3.50	3.62
K_2O		7.84	4.57	11.84	7.61	5.55
P_2O_5		0.93	3.39	0.62	0.15	0.32
Total		97.59	96.54	97.59	99.71	99.71
				CIPW norms		
Qz		0	0	0	16.3	21.6
Or		47.0	27.4	71.0	45.1	32.9
Ab		25.2	1.7	14.0	29.7	30.7
An		3.5	0.7	1.7	2.1	5.1
Ne		2.2	3.8	0.5	0	0
Di	Wo	6.2	18.5	2.1	1.1	1.3
	En	2.5	10.5	1.0	0.3	0.5
	Fs	3.7	7.3	1.1	0.9	0.8
Hy	En	0	0	0	0.8	2.0
	Fs	0	0	0	2.7	3.1
Ol	Fo	1.8	10.4	2.5	0	0
	Fa	3.0	8.0	3.3	0	0
Il		2.7	3.8	1.3	0.8	1.1
Ap		2.2	8.0	1.5	0.3	0.7
Total		100.0	100.1	100.0	100.1	99.8
Qz		0	0	0	17.9	25.4
Or		65.1	94.2	83.5	49.5	38.6
Ab		34.9	5.8	16.5	32.6	36.0
K_2O/Na_2O		2.3	4.5	6.9	2.2	1.5

FeO*: total irons as FeO.

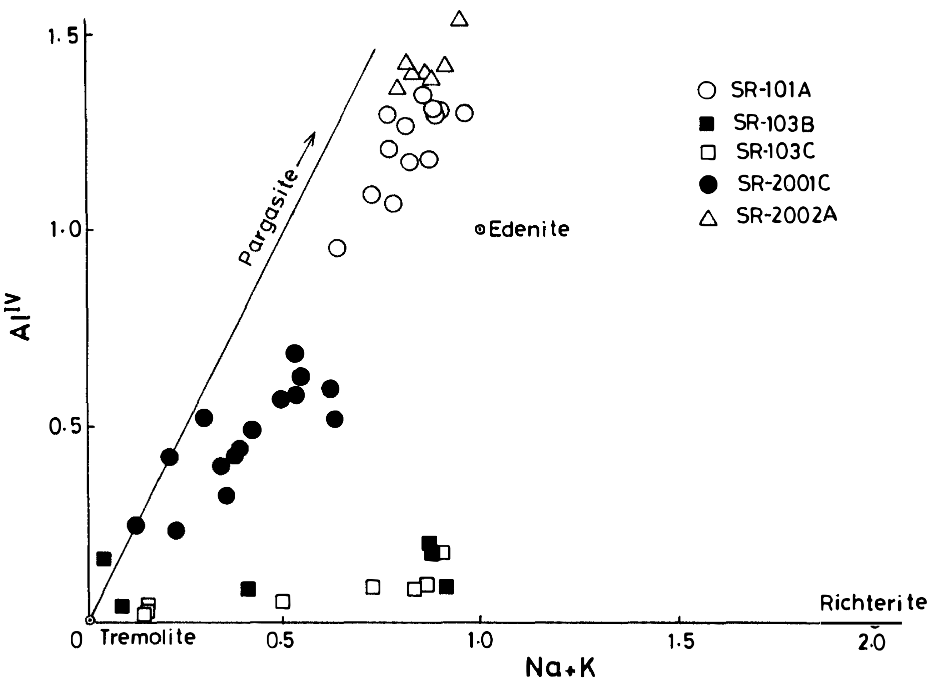


Fig. 2. The chemical variation of the amphiboles from the Sør Rondane Mountains expressed as the numbers of (Na+K) and Al^{IV} atoms per formula unit.

mafic layered syenites. In the two syenites SR-101A and SR-2001C, and one granite SR-2002A, Ca-amphiboles are plotted between lines representing tremolite-pargasite and tremolite-edenite. According to the classification by DEER *et al.* (1963), Ca-amphiboles in SR-101A and SR-2002A are pargasitic hornblende; on the other hand, Ca-amphibole in SR-2001C is common hornblende. Mg/(Mg+Fe) ratios of amphiboles in SR-103B, SR-103C and SR-2001C are about 0.6, while those of amphiboles in SR-101A and SR-2002A are about 0.45 and 0.4, respectively. Mg/(Mg+Fe) ratios of pargasitic hornblende are lower than those of Na-actinolite and common hornblende. K-feldspar shows various shapes of perthitic textures.

3. Experimental Results

The experimental methods in the present study were the same method reported by OBA and SHIRAISHI (1993). H_2O was always in excess (6-10 wt%). The phases were identified with X-ray powder diffraction patterns and an optical microscope.

The experimental results are illustrated in Figs. 3 to 7. We could not determine the high pressure stability limit of amphibole in SR-101A (Fig. 3). The present experimental results suggest that the extended line of the high pressure stability limit of amphibole intersects the extension of the solidus line at lower than 0.4 GPa. With the increasing temperature, quartz disappears first, then plagioclase disappears.

The solidus curve of SR-103B is 700°C at 0.1 GPa and 710°C at 0.25 GPa (Fig. 4). The curve for the disappearance of quartz is a few tens of degrees above the solidus. With increasing temperature below 0.25 GPa, plagioclase disappeared after quartz in a lower temperature range than K-feldspar, amphibole, biotite and clinopyroxene.

SR-103C begins to melt at 690°C and 0.1 GPa, and at 640°C and 0.3 GPa (Fig. 5). Plagioclase (albite) disappears at a higher temperature than quartz. The high temperature stability limit of amphibole intersects with the solidus at 630°C and about 0.26 GPa. Richteritic actinolite in two layered syenites (SR-103B and SR-103C) becomes unstable at 150°C above the solidus at 0.1 GPa.

The water saturated solidus temperatures of SR-2001C are about 720°C/0.1 GPa and 660°C/0.3 GPa (Fig. 6). *P-T* curves for the disappearance of quartz and plagioclase are sub-parallel to the solidus above a few tens of degrees. Clinopyroxene, biotite and K-feldspar are still stable at 900°C under the water pressure of 0.1 GPa.

Figure 7 shows the granite SR-2002A has the narrow stability field of amphibole. The intersecting point of the upper pressure stability limit of amphibole with the solidus is about 700°C and 0.24 GPa. The curve for the disappearance of quartz is a hundred degrees above and parallel to the solidus. K-feldspar disappears after quartz with increasing temperature. Plagioclase is still stable at 850°C and 0.15 GPa.

The stability limits of amphibole and solidi are summarized in Fig. 8. The solidi of the syenites and a granite used in this study vary considerably. In syenites, K-feldspar, biotite and clinopyroxene are stable at higher temperature than the stability field of amphibole. In SR-103C, SR-2001C and SR-2002A, the upper pressure stability limits of amphibole intersect the solidi at lower pressure than 0.35 GPa. Especially in syenite of SR-103C, the solidus of syenite and the stability limit line of amphibole intersect at a

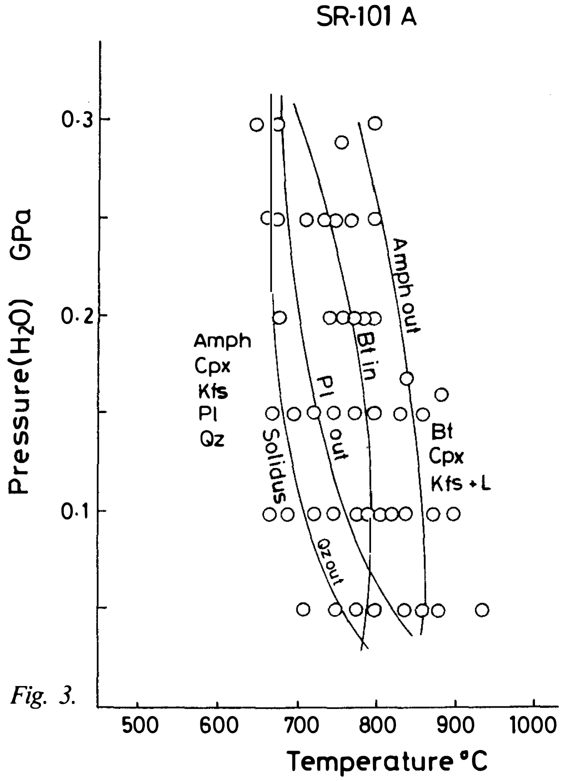


Fig. 3.

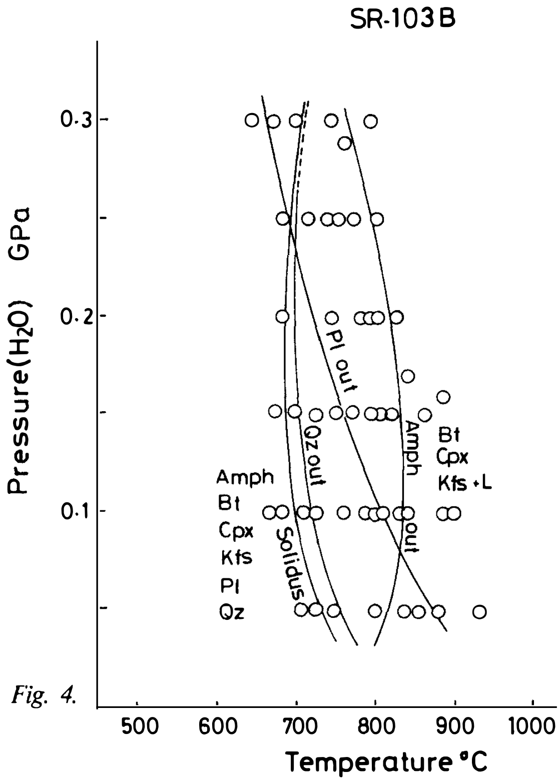


Fig. 4.

Fig. 3. Phase diagram of the SR-101A. Abbreviations: Amph: amphibole, Bt: biotite, Cpx: clinopyroxene, Kfs: K-feldspar, Pl: plagioclase, Qz: quartz, L: liquid

Fig. 4. Phase diagram of the SR-103B. Abbreviations as for Fig. 3.

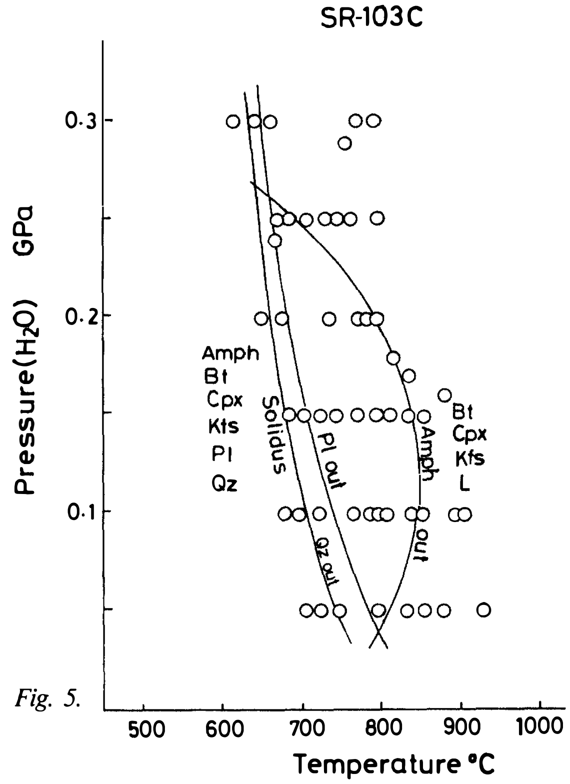
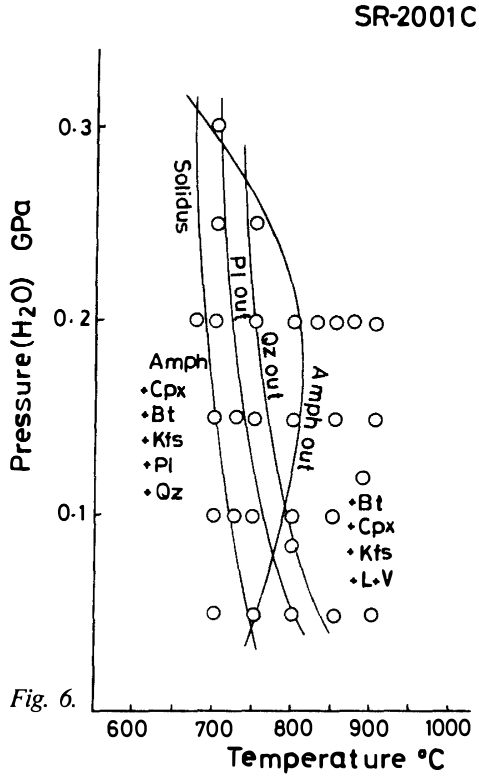


Fig. 5.



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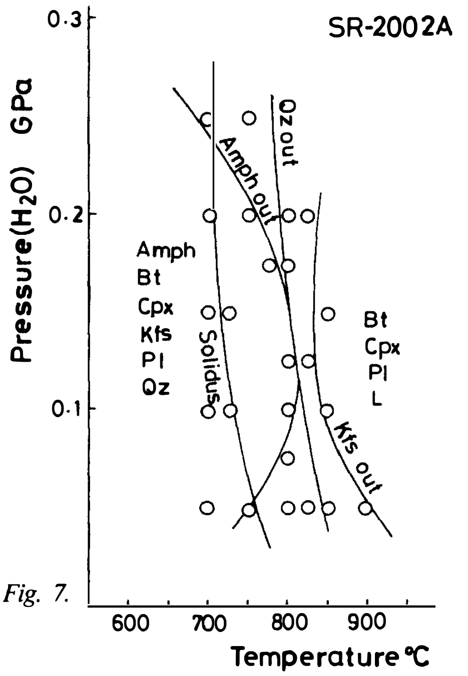

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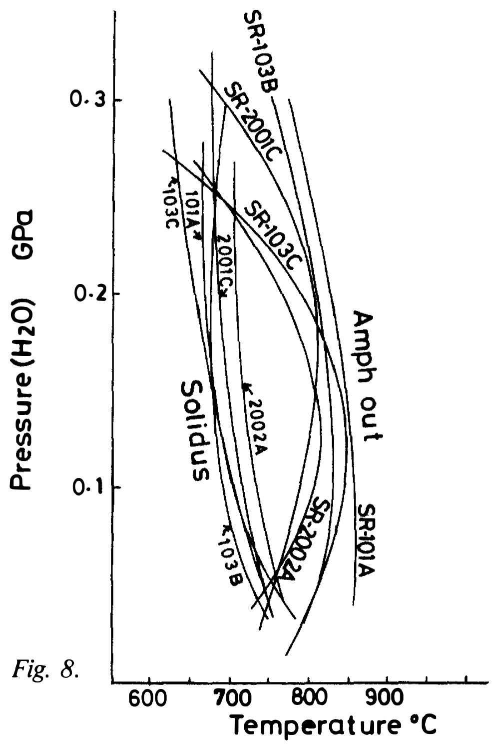

Fig. 8.

Fig. 5. *Phase diagram of the SR-103C. Abbreviations as for Fig. 3.*
Fig. 6. *Phase diagram of the SR-2001C. Abbreviations as for Fig. 3.*
Fig. 7. *Phase diagram of the SR-2002A. Abbreviations as for Fig. 3.*
Fig. 8. *P-T diagram showing the stability fields of amphiboles in four syenites and one granite from the Sør Rondane Mountains.*

pressure lower than 0.3 GPa. SR-103C and SR-103B formed the layered syenite, and then the leucocratic syenite (SR-101A) intruded into the layered syenites (SR-103B and SR-103C).

4. Discussion

In the present experiment, K-feldspar is a stable phase at high temperature. The concentration of K_2O content in the syenites depends on the amount of K-feldspar. Figure 9 shows the compositional variation of coexisting feldspars with plagioclase at 0.1 and 0.2 GPa with increasing temperature. Albite contents in K-feldspars from experiments on sample SR-101A slightly increase with increasing temperature below the solidus. The compositions of K-feldspar coexisting with liquid above the solidus are nearly constant, around $Ab_{35}Or_{65}$. On the other hand, albite contents in K-feldspars during experiments on samples SR-103B and SR-103C are nearly constant and about $Ab_{15}Or_{85}$ with increasing temperature. High Or content in K-feldspar from the Sør Rondane Mountains depends on the high K_2O/Na_2O ratios of the bulk compositions of syenites, as suggested by the experimental results in the Yamato Mountains (OBA and SHIRAISHI, 1994).

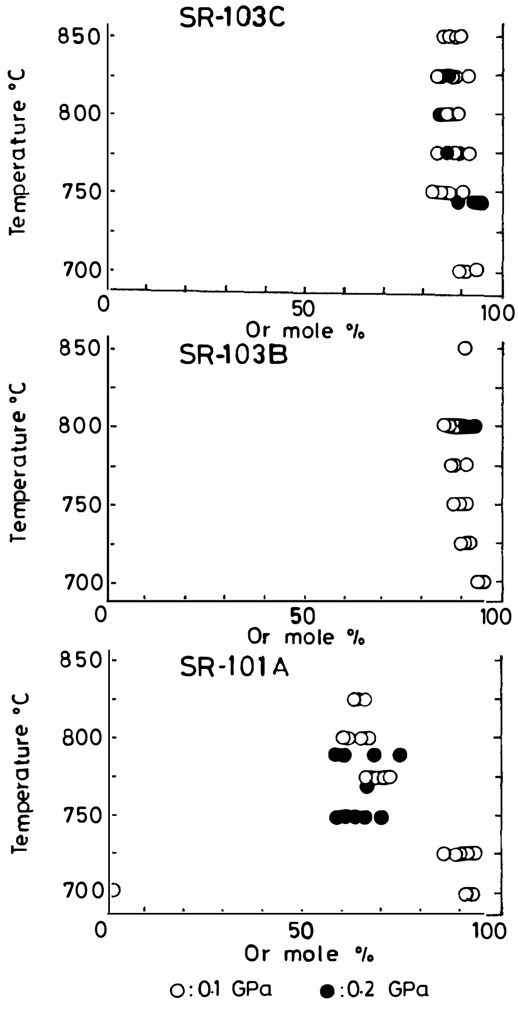

Fig. 9. Compositions of the synthetic feldspars on SR-101A, SR-103B and SR-103C. Open and solid circles indicate feldspars formed at 0.1 and 0.2 GPa, respectively.

It is assumed that the concentration of K-feldspar in syenite magma by floating may result in K_2O enrichment with high K_2O/Na_2O ratio in a part of the syenite during crystallization. The variations of K_2O against Na_2O content in the layered syenites correspond to the amounts of K-feldspar (SAKIYAMA *et al*., 1988). However, the high K_2O/Na_2O ratio of the mafic layered syenite suggests that the original magma already has a high K_2O/Na_2O ratio when the syenitic magma intruded into the present place. The present experimental results support the hypothesis that the amphibole-bearing syenites crystallized in a shallow crustal magma chamber (probably less than 10 km in depth). OBA and SHIRAISHI (1993, 1994) reported that in the syenites Y34A, Y556, Y557 and Y904 from the Yamato Mountains the solidus and the stability limit line of amphibole intersect at a lower pressure than 0.3 GPa. The emplacement depth of the syenites from the Sør Rondane Mountains is similar to that of the syenites from the Yamato Mountains.

BOWEN and TUTTLE (1950) noted that the stability limit of K-feldspar with $Or_{90}Ab_{10}$ is about 940°C at $P_{H_2O}=0.2$ GPa. YODER *et al*. (1957) reported that K-feldspar is unstable above 876°C and $P_{H_2O}=0.5$ GPa. At high pressure such as $P_{H_2O}=1.0$ GPa, the solidus of syenite intersects with the high temperature stability limit of K-feldspar. This fact supports a shallow emplacement depth of the syenites. It is noteworthy in the present study that the high K_2O magma intruded in a shallow crust.

SHIRAISHI *et al*. (1987) and HIROI *et al*. (1991) considered that the syenites in the Yamato Mountains were formed within the hinterland of a Cambrian continent-continent collision zone. The evolution model of syenite magma in the Yamato Mountains by ZHAO *et al*. (1995) does not contradict the above tectonic model. In the Sør Rondane Mountains, the relationship between the tectonics and the magma genesis needs to be clarified in the future.

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