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THE EMPLACEMENT PRESSURE OF SYENITE ESTIMATED FROM THE STABILITY FIELD OF AMPHIBOLE FROM THE YAMATO MOUNTAINS, EAST ANTARCTICA

Takanobu OBA[1] and Kazuyuki SHIRAISHI[2]

[1]*Department of Geoscience, Joetsu University of Education, Joetsu 943*
[2]*National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: T. OBA and K. SHIRAISHI (Proc. NIPR Symp. Antarct. Geosci., 6, 72, 1993) attempted to estimate the pressure of amphibole-bearing syenites based on the stability field of amphibole in melting experiments. The present study shows improvement over our previous paper. Four hornblende clinopyroxene quartz syenites, a hornblende clinopyroxene mela-syenite and a hornblende two-pyroxene syenite from the Yamato Mountains were determined under 0.05-0.3 GPa P_{H_2O} in the temperature range 650-900°C, and at the oxygen fugacity of the FMQ buffer. The stability limit curves of amphibole from four syenites (Y556, Y557, Y904 and Y34A) intersect with their solidi at lower pressure than 0.3 GPa. In all syenites except for a mela-syenite (Y405), quartz disappears first, then plagioclase and amphibole in that order with increasing temperature at 0.1 GPa. K-feldspar, in experiments on sample Y405, disappears at lower temperature than amphibole. In experiments on Y405, Y556 and Y904, albite contents in the synthesized K-feldspar slightly increase with increasing temperature below the solidus temperature, whereas the chemical compositions of K-feldspar are constant and around $Ab_{45}Or_{55}$ above the solidus temperature. The chemical compositions of liquids formed by partial melting of syenites are quartz and corundum normative and show the granite minimum composition at 0.1 GPa. They are similar to the chemical compositions of aplitic granites from the southern Yamato Mountains, suggesting that the aplitic granites are low pressure derivatives from the syenites.

1. Introduction

The syenitic rocks in the Yamato Mountains occur as isolated masses and nunataks scattered over a distance of 50 km (Fig. 1). Petrography and petrochemistry were described in SHIRAISHI (1977) and SHIRAISHI *et al.* (1983b). Syenites in the Yamato Mountains have been classified into three types in terms of the mode of occurrence and petrography: two pyroxene syenites, clinopyroxene syenite and clinopyroxene quartz monzo-syenite (SHIRAISHI *et al.*, 1983b). Emplacements of the former two types are thought to have taken place during or in the waning stage of the latest Proterozoic to early Cambrian granulite facies metamorphism, whereas the last type is a younger intrusive into the former ones. ASAMI and SHIRAISHI (1985) estimated that the peak granulite facies metamorphism at Massif A in the southern Yamato Mountains took place at about 750°C and below 0.6 GPa. However, the emplacement pressure of syenite and the pressure of

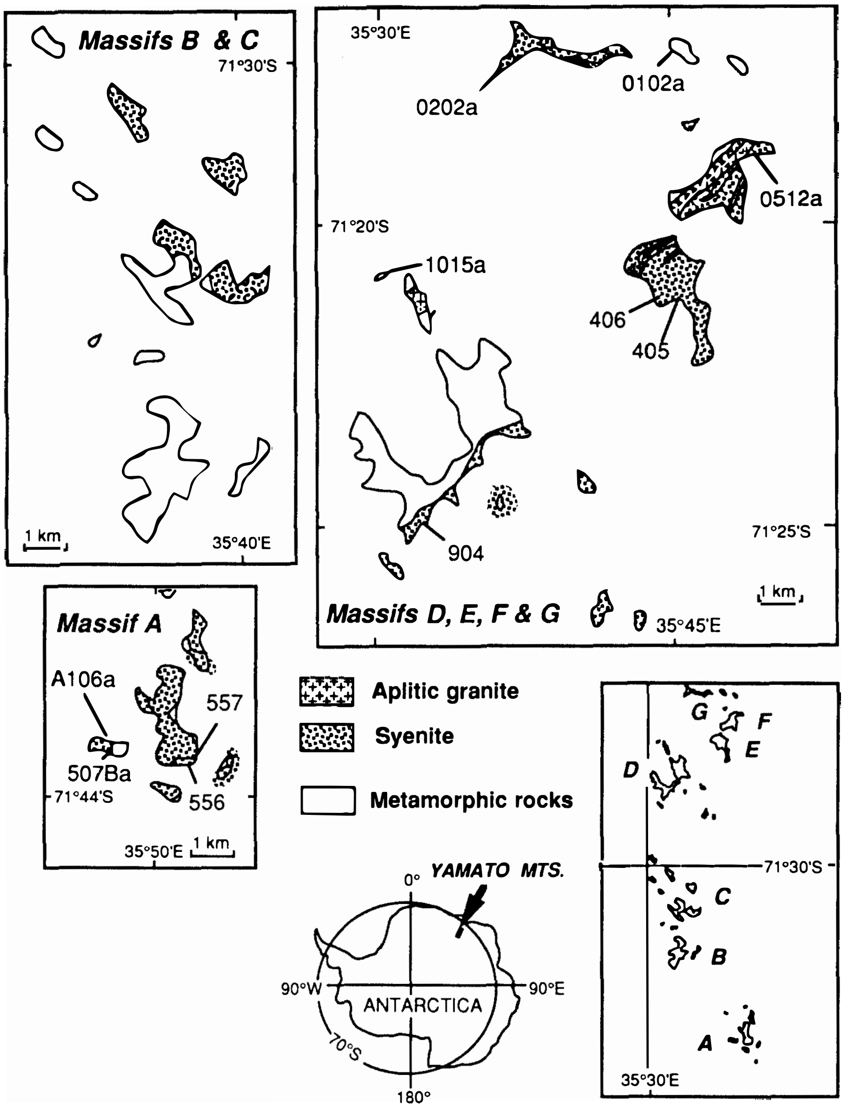

Fig. 1. Map showing the distribution of syenitic rocks and localities of samples, modified from S*hiraishi et al. (1983b).*

metamorphic rocks have not been clarified. Therefore, Oba and Shiraishi (1993) attempted to estimate the crystallization pressure of the amphibole-bearing syenites based on the stability field of amphibole in the melting experiments, by using three clinopyroxene syenites (Y405, Y406, Y904) from the northern part of the Yamato Mountains and a two-pyroxene syenite (Y556, Note : Sample number Y557 in the previous paper should be read as Y556) from the southern part. The experimental result suggested that amphibole from Y556 and Y904 syenites could have crystallized at pressures less than 0.3 GPa (depth ~10 km). The present study shows improvement over our previous paper. In this study, we performed a melting experiment on two combined syenites (Y557 and Y34A) from the southern Yamato Mountains to verify the emplacement pressure of syenite. In addition, the chemical variations of the run products of K-feldspar and liquids in the experiments on Y405, Y556 and Y904 synthesized at 0.1 and 0.2 GPa are discussed in order to clarify the syenite crystallization.

2. Petrography and Mineralogy of the Syenitic Rocks

The two samples Y34A (Y80A34A) and Y557 (Y80A557) on which we performed our melting experiment in the present work belong to the two-pyroxene syenite type, the same as Y556, and clinopyroxene quartz monzo-syenite, respectively. According to Streckeisen's nomenclature (STRECKEISEN, 1976), Y557 and Y34A are classified as fine grained K-feldspar porphyritic hornblende biotite clinopyroxene quartz syenite and two pyroxene biotite mela-syenite. All syenites including those described in OBA and SHIRAISHI (1993) are composed of porphyritic K-feldspar, plagioclase, quartz, biotite, Ca-amphibole, clinopyroxene with or without orthopyroxene, sphene and ilmenite. Most amphiboles are isolated euhedral or subhedral crystals. Some amphiboles show glomeropophyritic texture with biotite and clinopyroxene. Clinopyroxene and/or orthopyroxene in Y556 and

Table 1. Analyses and CIPW norms of the syenitic rocks from the Yamato Mountains.

Sample	Y904	Y405	Y406	Y556	Y557	Y34A
SiO_2	65.31	50.70	61.64	62.70	61.30	55.81
TiO2	0.82	1.68	0.77	1.01	1.58	1.46
Al_2O_3	15.50	7.68	14.72	14.85	14.48	12.95
FeO*	3.46	10.25	5.28	4.53	5.27	6.92
MnO	0.03	0.25	0.03	0.07	0.09	0.12
MgO	0.94	9.35	1.99	2.40	2,63	6.02
CaO	1.41	9.36	2.81	3.09	3.80	6.10
Na_2O	4.48	3.19	4.36	3.17	3.62	2.49
K_2O	7.51	3.50	7.04	6.80	5.83	6.62
P_2O_5	0.21	3.54	0.35	0.38	0.82	0.90
Total	99.73	99.50	98.99	99.00	99.42	99.39
	CIPW norms					
Oz	5.5	—	0.2	7.5	6.5	—
Or	44.5	20.8	42.0	40.6	34.7	39.4
Ab	38.0	20.1	36.9	27.1	30.8	21.2
An	tr.	—	—	6.3	6.1	4.6
Ns	—	1.6	0.1	—	—	—
Di Wo	2.5	9.8	4.9	2.8	3.1	8.3
En	0.8	5.5	1.8	1.3	1.5	4.9
Fs	1.7	3.9	3.2	1.5	1.6	3.4
Hy En	1.5	9.7	3.2	4.7	5.1	1.4
Fs	3.3	6.9	5.4	5.4	5.7	1.0
Ol Fo	—	5.7	—	—	—	6.2
Fa	—	4.5	—	—	—	4.8
Il	1.6	3.2	1.5	1.9	3.0	2.8
Ap	0.5	8.2	0.8	0.9	1.9	2.1
Total	99.9	99.9	100.0	100.0	100.0	100.0
Qz	6.3	0	0.3	10.0	9.0	0
Or	50.6	50.9	53.1	54.0	48.2	65.0
Ab	43.2	49.1	46.6	36.0	42.8	35.0

* Total Fe expressed as FeO.

Table 2. Analyses and CIPW norms of the aplitic granites from the Yamato Mountains.

Sample	Y0102a	Y0202a	Y0512a	Y1015a	YA106a	Y507Ba
SiO_2	69.62	73.65	75.22	76.08	75.09	77.11
TiO_2	0.76	0.05	0.16	0.11	0.12	0.07
Al_2O_3	14.63	14.95	13.48	13.92	13.62	12.53
FeO*	1.69	0.08	1.33	0.58	0.50	0.29
MnO	0.02	0.01	0.01	0.04	0.01	0
MgO	0.55	0.09	0.12	0.32	0.24	0.17
CaO	0.87	1.24	0.65	1.31	1.44	0.90
Na_2O	3.86	4.25	4.25	2.86	2.78	2.75
K_2O	5.77	4.99	4.98	5.63	5.40	5.03
P_2O_5	0.15	0.04	0.03	0.03	0.02	0.01
Total	98.22	99.35	100.23	100.88	99.22	98.86
	CIPW norms					
Qz	22.4	27.3	28.9	34.0	34.8	40.0
C	1.1	0.4	—	0.8	0.6	1.0
Or	34.7	29.7	39.3	33.0	32.2	30.1
Ab	33.3	36.2	35.9	24.0	23.7	23.5
An	3.4	5.9	3.0	6.2	7.1	4.5
Hy En	1.4	0.2	0.3	0.8	0.6	0.4
Fs	1.9	0.1	2.2	0.9	0.7	0.4
Il	1.5	0.1	0.3	0.2	0.2	0.1
Ap	0.4	0.1	0.1	0.1	0.1	tr.
Total	100.1	100.0	100.0	100.0	100.0	100.0
Qz	24.8	29.3	30.7	37.3	38.4	42.7
Or	38.4	31.9	31.2	36.3	35.5	32.1
Ab	36.8	38.8	38.1	26.4	26.1	25.2

* Total Fe expressed as FeO.

Y557 syenites are partly replaced by green hornblende with actinolitic hornblende at the rim. Ca-amphiboles in Y904 and Y405 syenites are edenitic hornblende with high Na-tremolite content. In Y406, Y34A, Y556 and Y557 syenites, Ca-amphiboles are hornblende plotted between lines representing tremolite-pargasite and tremolite-edenite. The felsic constituents are K-feldspar and sodic plagioclase with quartz. K-feldspar shows various shapes of perthitic textures.

The chemical analysis data and CIPW norms of the six syenites from the melting experiments, and the three aplitic granites and three aplitic syenites, are given in Tables 1 and 2 (analyses with Rigaku S3030 model X-ray fluorescence spectrometer at Joetsu University of Education). Y406, Y556 and Y557 syenites have similar chemical compositions and normative quartz. Y405 and Y34A syenites are not quartz normative. All syenites are diopside normative and no corundum normative. On the other hand, all aplitic granites except for Y0512a in Table 2 are quartz and corundum normative but not diopside normative.

3. Experimental Results

The experimental methods used in this work were described in a previous paper (OBA and SHIRAISHI, 1993). The phases were identified with X-ray powder diffraction patterns and an optical microscope.

The stability limits of amphibole in five syenites, except for Y405 syenite, and the curves for the beginning of melting of each syenite are shown in Fig. 2. The solidi of the syenites used in this study vary considerably. Y557 syenite begins to melt at 730°C and 0.1 GPa. The stability field of amphibole is similar to that of Y904 syenite. Amphibole is stable at 750°C and 0.25 GPa, while amphibole disappears at 775°C and 0.25 GPa, and 700°C and 0.3 GPa. The stable mineral assemblage in the experiments of Y557 is clinopyroxene, biotite, plagioclase, K-feldspar and liquid at 775°C and 0.25 GPa, and 700°C and 0.3 GPa. The high temperature stability limit of amphibole intersects with the solidus at 700°C and about 0.28 GPa. Y34A begins to melt at 775°C and 0.1 GPa and at 710°C and 0.2 GPa. Amphibole is unstable at 700°C and 0.25 GPa. The intersecting point is about 0.23 GPa.

Compositions of liquids formed by partial melting and K-feldspars in the experiments on the sample Y904 and Y405 are determined by microprobe analysis of quenched liquid (a JEOL 733 Superprobe, using standard procedure at the National Institute of Polar Research). The data given in Table 3 show that those liquids are silica-and alumina-rich comparing to the bulk compositions of Y904 and Y405 syenites in Table 1. The liquids melted at 0.1 and 0.2 GPa are plotted near the boundary of feldspar and quartz (cotectic line) at 0.1 GPa in the Qz-Ab-Or diagram (Fig. 3). Figure 4 shows the compositional

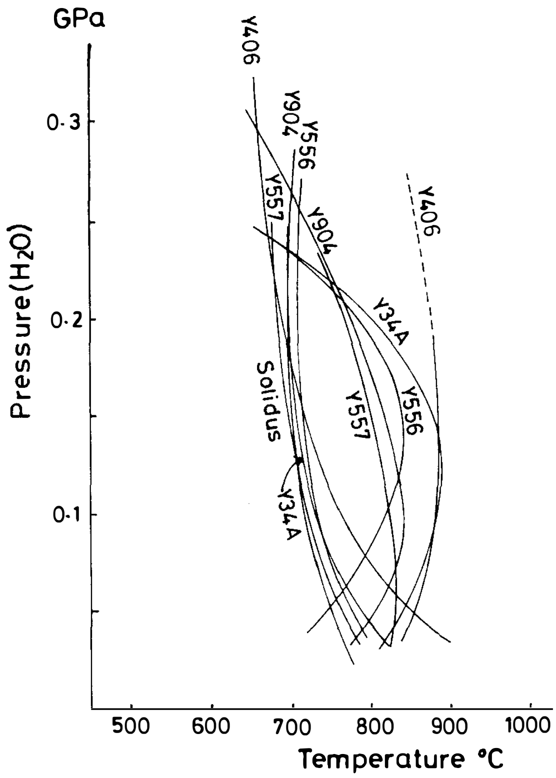

Fig. 2. P-T diagram showing the stability fields of amphiboles in five syenites from the Yamato Mountains. Data added to OBA and SRIRAISHI (1993). Note : sample number Y557 in OBA and SHIRAISHI (1993) should be read as Y556.

Table 3. Chemical compositions of liquids formed at 0.1 and 0.2 GPa.

Sp. No.	Y904						Y405		
Press. (GPa)	0.1		0.2				0.1		0.2
Temp. (°C)	750	800	700	725	775	800	800	825	740
SiO_2	70.27	65.46	65.71	67.94	67.87	67.69	63.28	62.17	67.23
TiO_2	0	0.10	0.08	0.14	0.50	0.35	0.25	0.50	0.26
Al_2O_3	16.34	12.79	12.78	13.54	15.41	15.10	12.07	12.63	13.09
FeO*	0.34	0.93	1.00	1.33	0.19	0.29	0.93	2.69	1.24
MnO	0.02	0.09	0.04	0.03	0.01	0.03	0.04	0.08	0
MgO	0.02	2.16	0.04	0.10	0.30	0.14	0.11	2.43	0.09
CaO	0.05	5.21	0.42	0.40	0.39	0.39	0.28	1.99	0.26
Na_2O	3.31	3.75	2.25	2.71	2.30	2.34	2.60	2.27	3.30
K_2O	5.43	4.79	4.68	5.05	5.56	5.12	4.66	2.96	3.59
Total	95.79	98.28	87.00	91.24	92.53	91.45	84.22	87.72	89.06
		CIPW norm							
Qz	31.1	12.6	37.9	33.8	34.5	36.6	34.4	31.7	36.8
C	5.1		3.7	3.2	5.3	5.5	2.7	2.4	3.7
Or	33.5	28.8	31.8	32.7	35.5	33.1	32.7	19.9	23.8
Ab	29.2	32.3	21.9	25.1	21.0	21.7	26.1	21.9	31.4
An	0.3		2.4	2.2	2.1	2.1	1.6	11.3	1.4
Di Wo		9.3							
En		4.0							
Fs		5.3							
Hy En	0.1	1.5	0.1	0.3	0.8	0.4	0.3	6.9	0.3
Fs	0.7	2.0	2.0	2.5	0	0	1.6	4.9	2.1
Il		0.2	0.2	0.3	0.5	0.7	0.6	1.1	0.6
Ru					0.3				
Total	100.0	100.0	100.0	100.1	100.0	100.1	100.0	100.1	100.1
D.I.	93.8	73.7	91.5	91.6	91.1	91.3	93.2	73.5	92.0
Qz	36.9	17.1	41.4	36.9	37.9	40.0	36.9	43.1	40.0
Or	35.1	39.1	34.7	35.7	39.0	36.2	35.1	27.1	25.9
Ab	28.0	43.8	23.9	27.4	23.1	23.7	28.0	29.8	34.1

* Total Fe expressed as FeO.

variation of coexisting feldspars at 0.1 and 0.2 GPa with increasing temperature. Albite contents in K-feldspars from experiments on samples Y405, Y556 and Y904 slightly increase with increasing temperature below the solidus. The compositions of K-feldspar coexisting with liquid above the solidi are nearly constant and around $Ab_{45}Or_{55}$. The chemical variation of K-feldspar in the present experiment is similar to that of the run product reported by McDowell and Wyllie (1971).

4. Discussion

Oba and Shiraishi (1993) reported that the curves for the upper stability limit of amphibole obtained from the experiments on Y904 and Y556 intersect with the solidus below 0.3 GPa. In the present work, the intersecting pressure of Y34A and Y557 from the southern Yamato Mountains is below 0.3 GPa. The experimental results strongly suggest

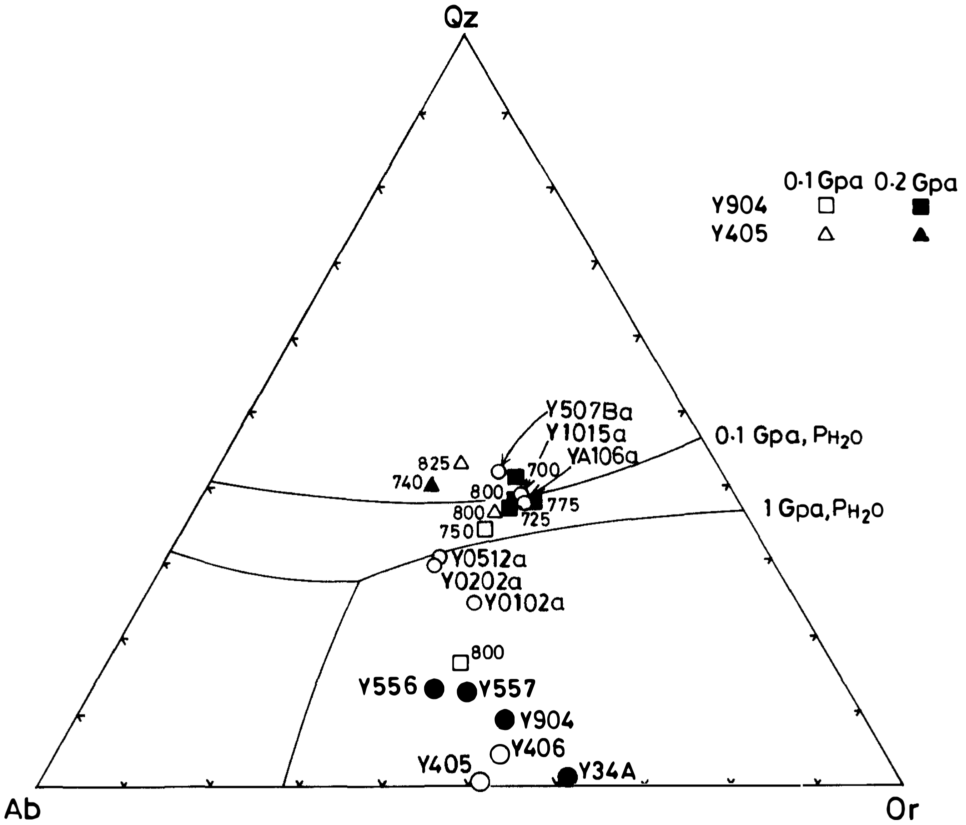

Fig. 3. Compositions of syenites and liquids produced in the melting experiments on the Qz-Ab-Or diagram, showing the projection of isobaric cotectic lines and eutectic at 0.1 (TUTTLE and BOWEN, 1958) and 1 GPa (P_{H_2O}) (LUTH et al., 1964). Liquids formed at 0.1 and 0.2 GPa and compositions of the six syenites and six aplitic granites are also plotted. Large circles indicate six syenites used in this study. Solid large circles are syenites with intersecting pressure below 0.3 GPa, between the solidus and the upper stability limit of amphibole. Open large circles indicate syenites with intersecting pressure above 0.3 GPa. The six small circles are aplitic granites. The experimental results on Y904 are shown by squares : open squares for 0.1 GPa and solid squares for 0.2 GPa. Two open triangles and a solid triangle are liquids formed at 0.1 and 0.2 GPa in Y405, respectively.

that the emplacement of the syenite from the southern Yamato Mountains occurred at a relatively shallower crustal level than 9 km.

The liquid formed by partial melt from Y405 and Y904 at different temperatures are plotted near the granite minimum under the Qz-Ab-Or diagram (Fig. 3). This suggests that the granitic compositions of the liquids are caused by the residual liquid formed by fractional crystallization of the syenites under low pressure condition. SHIRAISHI *et al.* (1983a) reported that the aplitic granites occur widely as dykes and sills in the Yamato Mountains. The compositions of aplitic granites from the Yamato Mountains are plotted in Fig. 3. Two of them are plotted at the granite minimum at 0.1 GPa, suggesting that the aplitic granites might be derived from syenite at low pressure. This is consistent with the emplacement pressure of syenite estimated from the stability field of amphibole. On the other hand, three aplitic granites between the granite minimum at 0.1 GPa and the bulk

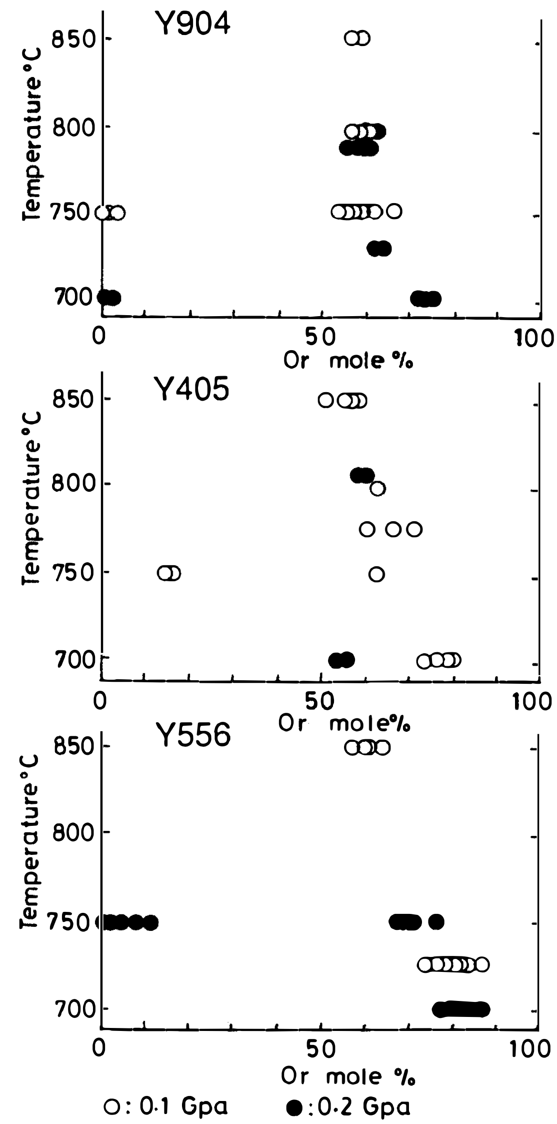

Fig. 4. Compositions of the feldspars in the run on Y904, Y405 and Y556. Open and solid circles indicate feldspars formed at 0.1 and 0.2 GPa.

compositions of host syenites are not clear as to whether the residual liquid is formed at higher temperature than the granite minimum or at the granite minimum temperature at $\sim$1 GPa.

The stability field of amphibole depends on the physical conditions and bulk composition of the host rock. The present experiments were carried out under the same physical conditions; therefore, the bulk composition remains an important factor. The Y34A, Y556, Y557 and Y904 syenites with the intersecting point below 0.3 GPa between the solidus and the upper stability limit of amphibole were plotted on the Qz-Or rich side of Y405 and Y406 with the intersecting point beyond 0.3 GPa. In granite and syenite with low K_2O/Na_2O ratio, the stability field of amphibole in other experiments (PIWINSKII, 1968; PIWINSKII and WYLLIE, 1968; McDOWELL and WYLLIE, 1971) is wider than that of the present experiment in syenite with high K_2O/Na_2O ratio. This supports the fact that K_2O content in host rock is probabily important for the high pressure stability limit of amphibole. In the experiment on the sample Y405, K-feldspar appears at 775°C, and disappears at 810°C and 0.25 GPa. K-feldspar except for the experiment on the sample Y405 is stable under all *P-T* conditions in the present experiments. The experimental result suggests that the syenite magma derived from the lower crust has K-rich composition. Therefore, a narrow stability field of amphibole might depend on K-rich bulk composition.

In conclusion, the additional experimental results support the conclusion that the syenites in the southern Yamato Mountains crystallized at pressures lower than 0.3 GPa.

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