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AGE AND PALEOMAGNETIC STUDIES FOR INTRUSIVE AND METAMORPHIC ROCKS FROM THE SØR RONDANE MOUNTAINS, ANTARCTICA

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Abstract: Two ^{40}Ar-^{39}Ar and five K-Ar ages and the virtual geomagnetic pole (VGP) were obtained for metadolerite dikes and gneiss at three sites, 1550 Nunatak, Brattnipane and Austkampane of the Sør Rondane Mountains, Antarctica. The radiometric age of 1550 Nunatak was determined to be 440–450 Ma, which is the youngest one so far reported in this area. The obtained VGP is similar to those estimated from rocks of the other area in Antarctica in Cambrian-Ordovician age, but is different from that reported by J. D. A. ZIJDERVELD (J. Geophys. Res., **73**, 3773, 1968).

1. Introduction

Paleomagnetic studies for Cambrian-Ordovician samples from Antarctica have been performed by many investigators (*e.g.*, NAGATA and YAMA-AI, 1961: ZIJDERVELD, 1968), and were summarized by FUNAKI (1984). The positions of virtual geomagnetic pole (VGP) in Cambrian-Ordovician age were centered on the African continent except for the VGP from the Sør Rondane Mountains (ZIJDERVELD, 1968).

In order to reveal the reason for such a difference, we examined the radiometric age and the natural remanent magnetization (NRM) of gneiss and metadolerites from 1550 Nunatak, Brattnipane and Austkampane situated in the Sør Rondane Mountains.

2. Geology and Samples

The Sør Rondane Mountains are situated in East Antarctica and their geology was examined in detail by recent workers (*e.g.*, KOJIMA and SHIRAISHI, 1986). The lithology of this area is composed of various metamorphic rocks represented by gneiss, granitic rocks and the associated dikes. The results of radiometric dating by the Rb-Sr, U-Pb and K-Ar methods have indicated that the metamorphism of gneiss had occurred at about 550 Ma and the younger intrusive activities took place during the period between 460 and 510 Ma. (PICCIOTTO *et al.*, 1964, 1966).

^{40}Ar-^{39}Ar analyses were performed on two samples from 1550 Nunatak (Fig. 1).

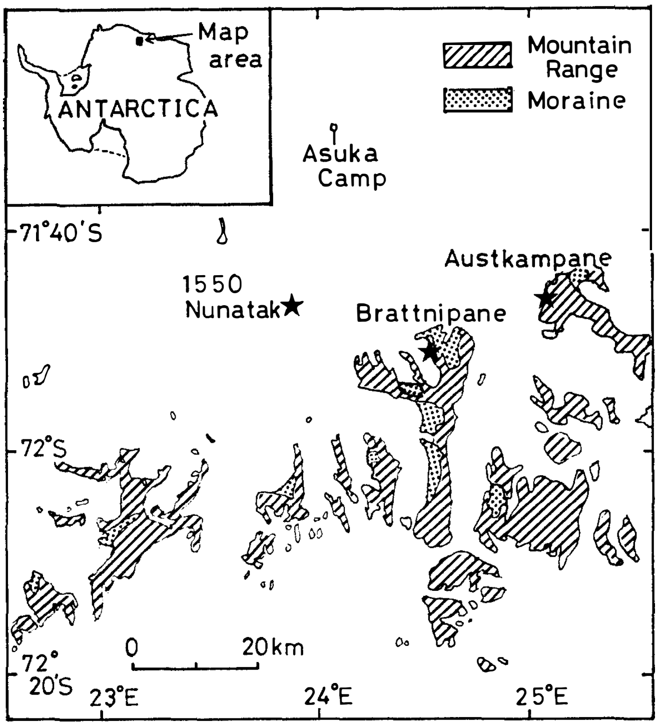

Fig. 1. Sampling sites in the Sør Rondane Mountains. Closed stars indicate sampling sites. (Modified after KOJIMA and SHIRAISHI, 1986 and ZIJDERVELD, 1968).

One is gneiss (sample 1120) and the other is metadolerite dike (sample 1123) with a width of about 50 cm intruding the gneiss.

K-Ar ages were obtained for two metadolerite samples (samples 1123 and 1125) and one gneiss sample (sample 1122) from 1550 Nunatak and two gneiss samples from Austkampane (sample 1098) and Brattnipane (sample 1117) (Fig. 1).

For paleomagnetic studies, 6, 39 and 9 samples were used from 1550 Nunatak, Austkampane and Brattnipane, respectively.

Descriptions of these samples studied are given in more detail in Appendix.

3. Experimental Procedures

3.1. ^{40}Ar-^{39}Ar method

Block samples (about 1.5 g) were stacked in a vacuum sealed quartz tube together with the standard samples of JG-1 biotites (K_2O; 7.64 wt%, 90.8±1.7 Ma) (0.05 g), CaF_2 (0.15 g) and K_2SO_4 (0.12 g). They were irradiated with the total neutron flux of about 7×10^{18} fast neutrons/cm^2 in the Japan Material Testing Reactor of Tohoku University. The irradiated samples put in a Mo crucible were heated stepwise for 45 min at each temperature with an induction heater at the Radio Isotope Center of University of Tokyo for the Ar gas extraction. The temperature was controlled by the output power of the induction heater calibrated with an optical pyrometer. The extracted Ar gas was purified by conventional procedures and analyzed with a quadrupole mass spectrometer (TAKIGAMI *et al.*, 1984). To correct for interfering Ar isotopes produced from Ca and K by the neutron irradiation, the following values were used, $(^{40}Ar/^{39}Ar)_K=0.18$, $(^{39}Ar/^{37}Ar)_{Ca}=0.00125$ and $(^{36}Ar/^{37}Ar)_{Ca}=0.00044$. Data reductions were made after conventional procedures (*e.g.*, DALRYMPLE and LANPHERE, 1971).

3.2. *K-Ar Method*

Ar gases were extracted and analyzed by the same procedure as the ^{40}Ar-^{39}Ar method. The amount of radiogenic ^{40}Ar was determined by the isotope dilution method with the use of ^{38}Ar spike. The K content was analyzed with a flame photometer.

3.3. *NRM*

The NRM was measured with a spinner magnetometer. AF demagnetization was performed by the AF demagnetizer consisting of a two-axes tumbler and a triple-layer mumetal shield to cancel the effect of the earth's magnetic field. Details about the NRM measurement were reported in FUNAKI (1984).

4. Results and Discussions

4.1. *Ages*

The results of ^{40}Ar-^{39}Ar ages and K-Ar ages are shown in Tables 1 and 2, and Figs. 2a and 2b. The apparent old age at 700°C fraction of the ^{40}Ar-^{39}Ar analysis of sample 1120 would be owing to an artifact, such as redistribution of radiogenic ^{40}Ar or recoil effect during the neutron irradiation. The Ar content for sample 1117 was obtained by calibrating the sensitivity of the quadrupole mass spectrometer, which was determined from the ^{38}Ar spike contents in the other samples. For this sample, a larger uncertainty is included in the calculation age. The relatively large error of sample 1122 reflects mostly that of the K measurements.

For sample 1123 (metadolerite dike) from 1550 Nunatak, five fractions from 900 to 1500°C give a ^{40}Ar-^{39}Ar plateau age of 439±13 Ma which constitutes 99% of the total released ^{39}Ar (Fig. 2b). This plateau age agrees with the K-Ar age (451±12 Ma) within their experimental uncertainties. The 1500°C temperature fraction of sample 1120 (gneiss) from 1550 Nunatak shows a similar ^{40}Ar-^{39}Ar age (431±13 Ma) to the plateau age (439±13 Ma) of sample 1123.

Sample 1120 has a stair-case age spectrum in which ages increase with increasing temperature except for the 700°C temperature fraction (Fig. 2a). The stair-case pattern in this type of age spectrum might be caused by Ar loss due to the secondary effects such as weathering or weak metamorphism, though we have not found a definite evidence to identify the cause. A slightly younger K-Ar age (419±57 Ma) for sample 1122 (gneiss) from 1550 Nunatak might also have been caused due to Ar loss by the same effect, because this age agrees with the ^{40}Ar-^{39}Ar total fusion age (412±13 Ma) of sample 1120.

Accordingly, except for the relatively old age of sample 1125 (488±18 Ma), it is suggested that the age of 440–450 Ma represents a thermal event affecting the gneiss and the associated metadolerite dike at 1550 Nunatak. In the metadolerite, amphibole

Table 1. Analytical data of ^{40}Ar-^{39}Ar ages.

Sample 1120, gneiss of 1550 Nunatak 1.35 g $J^{(1)}=0.05933\pm0.0020$

Temperature (°C)	$^{40}Ar^{(3)}$ ($\times10^{-6}$ cm^3 STP/g)	$^{36}Ar/^{40}Ar$ ($\times10^{-4}$)	$^{37}Ar/^{40}Ar$ ($\times10^{-3}$)	$^{39}Ar/^{40}Ar$ ($\times10^{-2}$)	$^{40}Ar_{rad}{}^{(5)}/^{40}Ar$ ($\times10^{-1}$)	^{39}Ar (%)	Age (Ma)
700	2.25 $\pm$0.003	12.2 $\pm$0.2	12.5 $\pm$2.5	6.40 $\pm$0.03	6.28 $\pm$0.06	1.0	827 $\pm$ 24
800	1.47 $\pm$0.003	9.02 $\pm$0.13	2.95 $\pm$0.03	19.2 $\pm$0.1	6.99 $\pm$0.04	2.0	354 $\pm$ 11
900	3.60 $\pm$0.004	2.13 $\pm$0.02	1.21 $\pm$0.50	24.4 $\pm$0.1	8.93 $\pm$0.01	6.3	355 $\pm$ 11
1000	5.51 $\pm$0.01	1.01 $\pm$0.02	8.21 $\pm$0.48	24.3 $\pm$0.1	9.27 $\pm$0.01	9.6	368 $\pm$ 12
1100	7.58 $\pm$0.01	1.07 $\pm$0.02	17.5 $\pm$0.5	23.4 $\pm$0.1	9.26 $\pm$0.01	12.7	381 $\pm$ 12
1200	8.91 $\pm$0.01	1.39 $\pm$0.02	33.0 $\pm$0.8	22.3 $\pm$0.1	9.19 $\pm$0.01	14.2	394 $\pm$ 12
1500	36.1 $\pm$0.04	1.02 $\pm$0.02	29.9 $\pm$3.8	20.5 $\pm$0.1	9.33 $\pm$0.01	54.2	431 $\pm$ 13
Total	66.1	1.69	24.3	21.1	9.13	100.0	412 $\pm$ 13

Sample 1123, metadolerite of 1550 Nunatak 1.82 g $J=0.05933\pm0.0020$

Temperature (°C)	^{40}Ar ($\times10^{-6}$ cm^3 STP/g)	$^{36}Ar/^{40}Ar$ ($\times10^{-4}$)	$^{37}Ar/^{40}Ar$ ($\times10^{-2}$)	$^{39}Ar/^{40}Ar$ ($\times10^{-2}$)	$^{40}Ar_{rad}/^{40}Ar$ ($\times10^{-2}$)	^{39}Ar (%)	Age (Ma)
600	1.96 $\pm$0.003	33.3 $\pm$0.6	0.30 $\pm$0.03	0.53 $\pm$0.003	1.54 $\pm$1.69	0.1	288 $\pm$296
700	1.11 $\pm$0.003	32.8 $\pm$0.5	3.11 $\pm$0.16	1.42 $\pm$0.01	2.70 $\pm$1.54	0.2	194 $\pm$105
800	1.16 $\pm$0.001	30.6 $\pm$0.6	3.46 $\pm$0.04	2.74 $\pm$0.02	9.13 $\pm$1.16	0.4	326 $\pm$ 55
900	1.51 $\pm$0.003	22.5 $\pm$0.3	4.63 $\pm$0.25	7.34 $\pm$0.04	32.1 $\pm$1.0	1.4	417 $\pm$ 17
1000	3.91 $\pm$0.01	7.29 $\pm$0.09	8.67 $\pm$0.14	16.2 $\pm$0.1	75.6 $\pm$0.3	7.8	442 $\pm$ 14
1100	11.0 $\pm$0.02	2.88 $\pm$0.05	6.13 $\pm$0.12	18.8 $\pm$0.1	88.1 $\pm$0.1	25.3	443 $\pm$ 14
1200	13.7 $\pm$0.03	2.95 $\pm$0.05	16.0 $\pm$0.2	19.9 $\pm$0.1	87.7 $\pm$0.2	23.9	418 $\pm$ 13
1500	17.8 $\pm$0.04	2.50 $\pm$0.07	41.4 $\pm$0.5	18.8 $\pm$0.1	89.2 $\pm$0.2	40.9	449 $\pm$ 14
Total	52.2	5.50	19.3	15.6	72.3	100.0	438 $\pm$ 13
Plateau age (900°C−1500°C)							439 $\pm$ 13

(1) $J=(\exp(\lambda t_s)-1)/(^{40}Ar/^{39}Ar)_s$; t_s: age of a standard sample; subscript "s" refers to a standard sample; $\lambda=5.543\times10^{-10}$/y.

(2) All values were corrected for K-derived ^{40}Ar and Ca-derived ^{39}Ar and ^{36}Ar.

(3) The amounts of ^{40}Ar were estimated from the sensitivity of the mass spectrometer deduced from the amount of radiogenic ^{40}Ar in the standard sample. About 30% uncertainty is assigned to the amount of ^{40}Ar on the basis of reproducibility.

(4) $\pm$ in values are errors of one standard deviation.

(5) $^{40}Ar_{rad}$ means radiogenic ^{40}Ar.

Table 2. Summary of K-Ar and ^{40}Ar-^{39}Ar ages.

Sample No.	Site (Rock type)	K (wt%)	$^{40}Ar_{rad}$ ($\times 10^{-5}$ cm^3 STP/g)	$f^{(1)}$ (%)	K-Ar[(2)] age (Ma)	^{40}Ar-^{39}Ar age (Ma)	^{40}Ar-^{39}Ar total fusion age (Ma)
1098	Austkampane (gneiss)	1.07 ±0.04	2.17 ±0.03	1.8	468 ± 21	—	—
1117	Brattnipane (gneiss)	0.88 ±0.03	2.15 ±0.22	5.4	551 ± 56	—	—
1120	1550 Nunatak (gneiss)	—	—	—	—	1500°C 431 ± 13	412 ± 13
1122	1550 Nunatak (gneiss)	2.73 ±0.37	4.88 ±0.06	5.4	419 ± 57	—	—
1123	1550 Nunatak (metadolerite)	1.62 ±0.04	3.15 ±0.05	14.2	451 ± 12	plateau 439 ± 13	438 ± 13
1125	1550 Nunatak (metadolerite)	1.58 ±0.06	3.36 ±0.01	5.9	488 ± 18	—	—

± indicates one standard deviation.

(1) $f=(^{40}Ar)_{air}/(^{40}Ar)_{total}$.

(2) K-Ar ages were calculated with the following values (Steiger and Jäger, 1977). $\lambda_e=0.581\times10^{-10}$/y, $\lambda_\beta=4.962\times10^{-10}$/y, $^{40}K/K=1.167\times10^{-4}$ moles/mole.

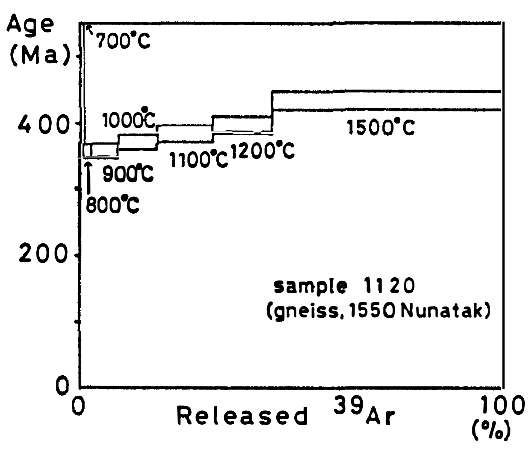

Fig. 2a. The ^{40}Ar-^{39}Ar age spectrum for sample 1120, gneiss from 1550 Nunatak. Vertical and horizontal axes indicate the age and the released fraction of ^{39}Ar in %. The bands in the age indicate errors of one standard deviation.

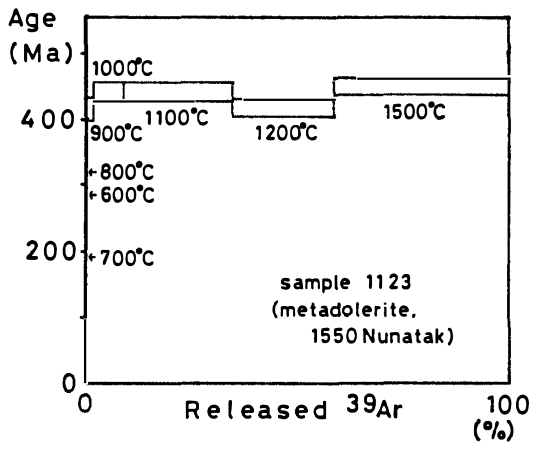

Fig. 2b. The ^{40}Ar-^{39}Ar age spectrum for sample 1123, metadolerite at 1550 Nunatak.

and ilmenite may have been derived from clinopyroxene suggesting that the dike had been metamorphosed under the condition of the amphibolite facies above 400°C (Ishizuka, personal communication). The release pattern of Ar suggests no weathering effect for sample 1123. Hence, the obtained age of 440–450 Ma at the site of 1550 Nunatak would probably represent a thermal event after the dike intrusion into the gneiss. At present, however, we cannot characterize the thermal source such as granitic intrusions affecting the dolerite at 440–450 Ma near 1550 Nunatak.

This thermal event at 440–450 Ma is the youngest one in the Sør Rondane Mountains as far as the published data are concerned (PICCIOTTO *et al.*, 1964, 1966; KOJIMA and SHIRAISHI, 1986). Generally, young K-Ar ages obtained in this area have been attributed to Ar loss (*e.g.* PICCIOTTO *et al.*, 1964, 1966). However, our data suggest the existence of a younger thermal event in this area. Hence, the data would be worth reexamining in order to check the possibility.

The older K-Ar age (488±18 Ma) of sample 1125 might correspond to the time of the metadolerite dike intrusion before 440–450 Ma. However, we cannot deny a possibility of the occurrence of inherited Ar in this sample.

K-Ar ages of Austkampane (gneiss; 468±21 Ma) and Brattnipane (gneiss; 551±56 Ma) are consistent with the previous results (460–550 Ma) in the Sør Rondane Mountains (PICCIOTTO *et al.*, 1964, 1966; KOJIMA and SHIRAISHI, 1986). As secondary minerals such as epidote are recognized from the microscopic examination, however, there is a possibility of Ar-loss during the contact metamorphism caused by the intrusion of igneous complex, or by the weathering in these samples.

4.2. NRM

The results are shown in Fig. 3. The intensity of the NRM for these samples is relatively small (1550 Nunatak; 3.3×10^{-7} Am^2/kg, Austkampane; 6.8×10^{-6} Am^2/kg and Brattnipane; 5.4×10^{-5} Am^2/kg). Therefore, the direction of the NRM was obtained only for the 100 Oe demagnetized samples of Brattnipane that have a relatively large intensity of the NRM among these samples. 5 samples examined at this site have the mean inclination (50.8°) and declination (19.6°) of the NRM. The precision (K) is estimated to be 16. The semi-angle of the cone of confidence of 95% probability (α_{95}) is 19.5. The position of the VGP is calculated to be 14.4°S and 41.2°E.

The position of the VGP in this study agrees with those obtained from the other Antarctic samples in a range of α_{95} value (Fig. 4), but disagrees with the position of the VGP for the Sør Rondane Mountains estimated by ZIJDERVELD (1968). As the result of this study has a large α_{95} value (19.5), more accurate experiments may be required to settle the problem for the Sør Rondane Mountains.

Moreover, if the VGP was obtained for the younger rocks such as those of 1550 Nunatak, a more precise polar wander path for Antarctica might be obtained.

5. Summary

Based on ^{40}Ar-^{39}Ar and K-Ar ages in this study together with the previous age results, the history of the Sør Rondane Mountains area could be summarized as follows:

(1) Precambrian; sedimentation (MICHOT and KLERKX, 1966)

(2) ~550 Ma; metamorphism of gneiss (PICCIOTTO *et al.*, 1964, 1966)

(3) 440–510 Ma; intrusion of igneous masses and contact metamorphism (PICCIOTTO *et al.*, 1964, 1966; KOJIMA and SHIRAISHI, 1986; this study).

The position of the VGP for the Sør Rondane Mountains estimated in this study is different from that reported by ZIJDERVELD (1968). As our data include large uncertainties, more accurate data should be required in further works.

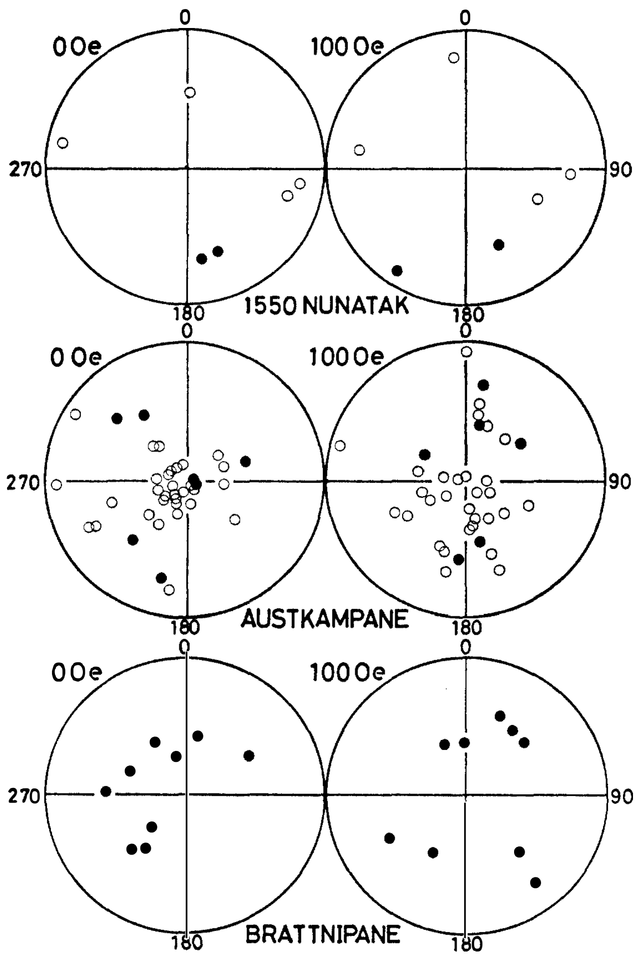

Fig. 3. The NRM directions before and after 100 Oe AF demagnetization for samples from 1550 Nunatak, Austkampane and Brattnipane. Open circle; normal polarity, solid circle; reversed polarity.

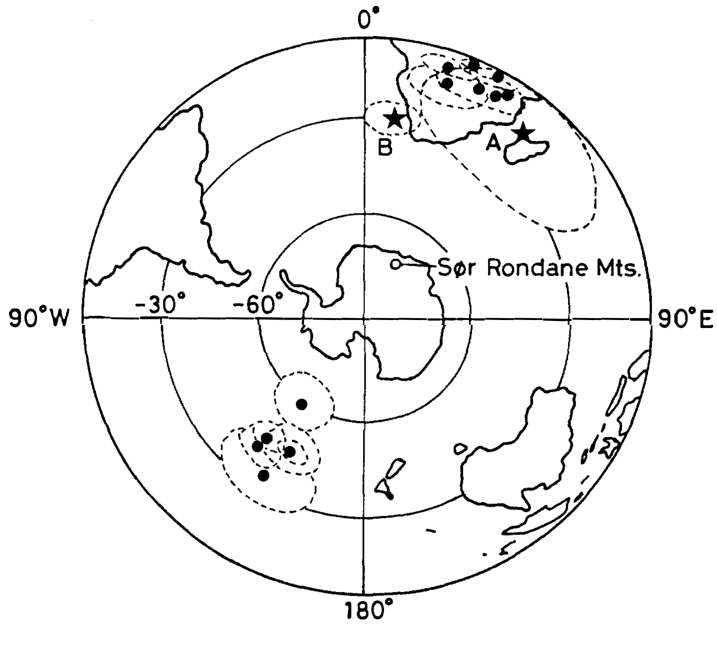

Fig. 4. Positions of the VGP from Antarctic samples in Cambrian-Ordovician time. Equal-area projection. Solid star A: Brattnipane, Sør Rondane Mountains (this study), solid star B: Sør Rondane Mountains (ZIJDERVELD, 1968), closed circle: others. Broken lines indicate the range of α_{95}. (Modified after FUNAKI, 1984).

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Appendix

Rock types and constituent minerals for each sample are described as follows (by H. ISHIZUKA).

Sample No.

1098 Biotite-hornblende gneiss.
Hornblende, biotite, plagioclase, quartz, apatite, sphene, opaque minerals.

1117 Hornblende-biotite gneiss.
Biotite, hornblende, epidote, plagioclase, quartz, apatite, opaque minerals.

1120 Garnet-biotite gneiss.
Biotite, garnet, plagioclase, K-feldspar, quartz, apatite, muscovite.

1123 Metadolerite.
Plagioclase, amphibole, ilmenite, biotite, apatite.

No descriptions were made for 1122 and 1125.