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1. Introduction

The Sør Rondane Mountains locate from 71°30′S to 72°40′S and 21°30′E to 28°E in western Dronning Maud Land, East Antarctica. The mountains were found from the air in 1937 by a Norwegian expedition, and then a U.S. Navy Antarctic Expedition (operation "Highjump") made a topographical map of 1:250,000 scale during 1946–1947 that was published by the Norwegian Polar Institute in 1957. Pioneer work for geological, glaciological and geomorphological studies was carried out by Belgian geological reconnaissance parties during 1958 to 1960 using "Base Roi Baudouin (70°26′S, 24°19′E)" (MICHOT, 1961, 1962; VAN AUTENBOER, 1964; PICCIOTTO *et al.*, 1964). Based on the results of these investigations a geological map was published in 1:500,000 scale by VAN AUTENBOER (1969).

The 25th Japanese Antarctic Research Expedition (JARE-25) started a geological survey in the central part of the Sør Rondane Mountains in 1984 (MEMBER OF THE SØR RONDANE RECONNAISSANCE PARTY, 1985) followed by 7 more research expeditions covering the whole region of the mountains using "Asuka Station" (71°25′S, 24°10′E). JARE-26 (1984–1985), -29 (1987–1989), -30 (1988–1989) and -31 (1989–1991) performed various surveys in the west-central to western region of the mountains (Walnumfjellet, Widerøefjellet and Nilslarsenfjellet) (KOJIMA and SHIRAISHI, 1986; MORIWAKI *et al.*, 1986, 1989; SHIRAISHI *et al.*, 1992a). JARE-29 and

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-31 also performed a geological survey in the eastern region (mainly eastern side of the Byrdbreen) (ASAMI *et al.*, 1989; MAKIMOTO *et al.*, 1990; OSANAI *et al.*, 1990a). Moreover the central part of the mountains was covered by all JARE parties especially in JARE-27 (1985–1986), -28 (1986–87), -31 and -32 (1990–1991) (ISHIZUKA and KOJIMA, 1987; HIRAKAWA *et al.*, 1987; SAKIYAMA *et al.*, 1988; OSANAI *et al.*, 1990a; OWADA *et al.*, 1992). Among them the JARE-31 team surveyed the whole region of the Sør Rondane Mountains including the southern highland continuing to the Nansen Ice field and many isolated nunataks by helicopter (OSANAI *et al.*, 1990a). All of the results of these field investigations except the central region have already been published as the Antarctic Geological Map Series of Balchenfjella (Sheet 31: ASAMI *et al.*, 1991), Widerøefjellet (Sheet 32: SHIRAISHI *et al.*, 1992a) and Bergersenfjella (Sheet 33: ISHIZUKA *et al.*, 1993).

The present issue, Sheet 34 "Brattnipene" of the Antarctic Geological Map Series (1:100,000 in scale) covers the central part of the Sør Rondane Mountains (71°30′S–72°20′S and 24°00′E–25°30′E) including large mountain masses of Brattnipene, Lunckeryggen, Walnumfjellet, Austkampane, Menipa, Mefjell, and Dufekfjellet. This sheet is compiled mainly based on the results of the geological and geomorphological surveys by JARE-26, -27, -28, -31 and -32.

2. General Geology

2.1. *Quaternary geology and geomorphology*

The Sør Rondane Mountains form a barrier damming the northward flow from the inland ice, then the elevation of the ice surface abruptly descends toward the north from 2200 m to 1200 m in and around the mountains (Plate 1). The mountains are divided by outlet glaciers into several mountain blocks. The highest peak (2996 m) of the mountains located in Widerøefjellet, the western part of the Sør Rondane. In the mapped area, the highest point is a glaciated round-topped peak (2879 m) at Dufekfjellet.

A large part of the mountains was once covered by an ice sheet (VAN AUTENBOER, 1964; HIRAKAWA and MORIWAKI, 1990; MORIWAKI *et al.*, 1992). Several outlet glaciers through the mountains form steep glacial valley walls along them, and some of them have a subglacial deep bottom below sea-level (*e.g.* Jenningsbreen and Gjelbreen: PATTYN and DECLEIR, 1995).

Flat-topped mountains (*e.g.* Brattnipene) scattered throughout the mountains may be explained by assuming that the Sør Rondane was gently sloped mountains in the pre-glacial age. In many places, the mountains are covered with tills showing various degrees of weathering. Tills form moraine fields on the top and foot of mountains and on ice, and lateral moraines on mountain flanks. Moraines and bedrock at higher level are strongly weathered (MORIWAKI *et al.*, 1991; MATSUOKA, 1995). These moraines attain several tens of meters in thickness (*e.g.* at the northernmost part of Mefjell: HIRAKAWA *et al.*, 1988). On the other hand, tills covering the lower part of mountain flanks and formerly glaciated valley walls are thin and less weathered, and tills of supraglacial moraine fields around mountains are very thin and fresh (MORIWAKI *et al.*, 1991).

Table 1. Weathering stage or exposure age of landforms and their height above the present ice surface.

Period	Landform (Weathering stage)	Height above ice surface	Cosmogenic exposure age (sample ID)	Locality
Quaternary	Glaciated bedrock	3 m	0.036 ± 0.01 Ma (TAC-9)	Bergersenfjella *
	Thin moraine field (1a)	5 m		
	Thin moraine field (1b)	30 m		
	Glaciated bedrock	40 m	0.15 ± 0.02 Ma (TAC-8)	Berkmanskampen
	Glaciated bedrock	110 m	0.88 ± 0.08 Ma (TAC-11)	Vetrehø
	Small lateral moraine (2)	140 m		
	Glaciated bedrock	180 m	1.77 ± 0.17 Ma (TAC-10)	Sørhaugen *
Tertiary	Glaciated bedrock	350 m	3.00 ± 0.41 Ma (TAC-12)	Mefjell
	Glaciated bedrock	>400 m	2.90 ± 0.80 Ma (TAC-13)	Mefjell
	Thick moraine field (3-4)	400-600 m		
	Glaciated bedrock	600 m	>4 Ma (TAC-14)	Mefjell

* out of the map

NISHIIZUMI *et al.* (1991) derived cosmogenic exposure ages back to 4 Ma for seven samples from the Sør Rondane Mountains (Table 1). MORIWAKI *et al.* (1992) reconstructed the glacial history of the mountains on the basis of glacial landforms, degree of weathering of tills and the cosmogenic exposure ages. The early? gentle-sloped Sør Rondane Mountains with the exception of several high peaks were covered by a temperate ice sheet which produced a large quantity of tills prior to Early Pliocene age. Deglaciation took place until late Pliocene time. The lower ice surface caused temperate outlet glaciers which deeply eroded the valley systems dividing the mountains into separate blocks. The ice sheet re-advanced up to 100–140 m higher than the present ice surface at the beginning of Pleistocene age, and it poorly glaciated the mountains forming a small quantity of tills. Since then, the ice sheet has been a cold polar type and the level of the ice sheet has been descending with minor fluctuations until the present.

We have no evidence showing the rate of the uplift of the Sør Rondane Mountains during Cenozoic period. Therefore, it is uncertain whether the ice sheet prior to Pliocene was larger than that of Pleistocene or not. IWATA (1993) suggested that the isostatic uplift of the mountains has been caused by glacial denudation since Miocene.

2.2. *Basement geology*

The Sør Rondane Mountains consists mainly of Proterozoic high- and medium-grade metamorphic rocks and various plutonic rocks which intruded into the metamorphic basement rocks (KOJIMA and SHIRAISHI, 1986; ISHIZUKA and KOJIMA, 1987; SAKIYAMA *et al.*, 1988; SHIRAISHI *et al.*, 1991; ASAMI *et al.*, 1992; TAINOSHO *et al.*, 1992a, b). The metamorphic rocks show evidence of 1000–1100 Ma granulite-facies metamorphism (SHIRAISHI and KAGAMI, 1989, 1992; GREW *et al.*, 1992) in the northern and eastern parts and were intruded by 950 Ma and *ca.* 500 Ma plutonic rocks

(TAKAHASHI *et al.*, 1990). During the late Proterozoic to early Cambrian orogeny, strong deformation and thrust-up movement resulted in a typical mylonite formation. Five distinct mylonite zones form tectonic boundaries in the central Sør Rondane Mountains, in which the Sør Rondane Suture (SRS: OSANAI *et al.*, 1992a) and the Main Shear Zone (MSZ: KOJIMA and SHIRAISHI, 1986) are especially important to divide the terranes (SHIRAISHI *et al.*, 1992a).

VAN AUTENBOER (1969) and VAN AUTENBOER and LOY (1972) subdivided the gneisses into two groups: the Teltet-Vengen group in the north and the Nils Larsenfjellet group in the south. The boundary between them is close to the MSZ, but the definitions of both group are not clear. Therefore we consider that the most important tectonic boundary is the SRS which passes through the central part of the mapped region from northwest to southeast (OSANAI *et al.*, 1992a).

2.2.1. Metamorphic rocks

The Brattnipene region (this sheet) is underlain by various kinds of metamorphic and plutonic rocks with minor mafic and acidic dike rocks.

The metamorphic rocks in the central part of the Sør Rondane Mountains, including the eastern part of the Widerøefjellet region (Sheet 32), the western part of the Bergersenfjella region (Sheet 33) and the Brattnipene region can be classified into following eight rock types; (1) biotite-hornblende gneisses and hornblende gneisses, (2) garnet-biotite gneisses and biotite gneisses, (3) garnet-sillimanite-biotite gneisses, (4) amphibolites, (5) marble and calc-silicate rocks, (6) amphibole schists (7) metatonalite and (8) ultramafic rocks and mafic granulites. Rare ultramafic rocks and mafic granulites are observed as thin intercalations or small xenolithic blocks in the intrusive rocks only in the northern part. Orthopyroxene is found in hornblende-biotite gneisses, garnet-biotite gneisses and amphibolites in the northeastern to eastern part of the region. A cordierite-garnet-K-feldspar paragenesis is also found in garnet-biotite gneisses in the northeastern part of the region and is probably more magnesian than most garnet-biotite gneiss. On the other hand, in the southwestern part of the region where metatonalite and amphibole schists are dominant, orthopyroxene and related granulite-facies mineral assemblages have not been found, but amphibolite- to greenschist-facies mineral assemblages are widespread. Thus the region can be divided into two terranes on the basis of the metamorphic conditions: granulite-facies north to northeastern terrane (NE-terrane): Austkampane, Brattnipene, Menipa, eastern Mefjell, Komsa, and Salen, and amphibolite- to greenschist-facies southwestern terrane (SW-terrane): Walnumfjellet, Lunckeryggen, western Mefjell, Dufekfjellet, Alden, Tovihögda and southernmore nunataks. The boundary between the two terranes is a large shear zone, which we call the Sør Rondane Suture (SRS). Moreover, the southwestern terrane is cut by the Main Shear Zone (MSZ).

The metamorphic *P-T* conditions of the granulite-facies rocks have been estimated by using various geothermobarometers. *P-T* conditions determined on pelitic and basic rocks are 750° to 850°C and 700 to 800 MPa for non-mylonitized gneisses, and 530° to 630°C and 500 to 550 MPa for mylonitized gneisses (SHIRAISHI and KOJIMA, 1987; ASAMI and SHIRAISHI, 1987; OSANAI *et al.*, 1988; ASAMI *et al.*, 1992).

Bulk chemical analyses of the 131 metamorphic rocks were performed. Major

Table 2. Representative chemical analyses of metamorphic rocks from the Brattnipene region.

Sample No.	M1	M3	M5	M19	M20	M21	M22	M28	M38	M40
Major element(%)										
SiO2	72.12	49.33	48.01	54.15	52.38	65.91	57.76	41.94	47.91	51.22
TiO2	0.31	1.52	3.09	1	1.33	0.7	1.01	0.57	3.88	0.37
Al2O3	13.9	15.34	13.23	13.36	15.23	15.52	19.71	19.18	17.02	10.21
Fe2O3	1.39	4.54	4.09	1.3	2.93	2.87	1.86	4.36	1.96	7.64
FeO	1.87	7.93	11.3	9.68	4.36	4.13	6.68	6.61	7.48	2.11
MnO	0.06	0.61	0.26	0.21	0.12	0.1	0.09	0.14	0.14	2.56
MgO	0.72	3.33	4.93	3.81	7.62	2.01	2.69	18.24	5.42	0.92
CaO	3.51	6.34	8.29	6.02	6.76	3.44	1.09	1	6.46	22.64
Na2O	1.08	1.96	0.4	1.22	2.95	0.94	4.88	2.27	2.04	0.11
K2O	4.15	3.67	2.77	5.89	3.87	3.17	1.43	1.15	4.06	0.1
P2O5	0.09	0.85	0.24	0.31	0.32	0.12	0.14	0.07	0.65	0.09
CO2		0.32	<0.20	0.18	<0.20	0.25	<0.20	<0.20	0.51	<0.20
LOI	0.28	0.66	0.53	0.76	0.1	0.45	1.33	1.31	0.75	0.21
Total	99.20	95.42	96.61	96.95	97.87	98.91	97.34	95.53	97.02	97.97
Trace element(ppm)										
Ba		780	140	180	1600	120	560	60	640	60
Cr		8	40	12	300	60	80	128	50	12
F		830	210	430	720	230	350	1400	980	180
Hf	2	2	2	<2	6	8	6	<1	10	3
Nb	<5	7	<5	6	6	7	15	<5	75	5
Ni		3	17	5	140	21	32	152	36	1
Pb										
Rb		19	7	14	80	30	200	110	62	2
Sr		500	116	180	730	140	28	122	750	6
Th		<1.0	<1.0	<1.0	7	1	21			
U		<1.0	<1.0	<1.0	1	<1.0	2			
V		200	680	240	160	110	140	160	160	70
Y	14	40	47	21	35	57	105	52	46	40
Zn		444	133	155	95	73	97	300	146	303
Zr	100	110	130	75	240	295	200	38	270	130
La		28	8	12	50	3	54	3		
Ce		60	18	32	128	8	146	6		
Nd		25	15	10	40	<5	45	<5		
Sm		9.8	6.1	4.3	9.1	5.2	12.2	1.4		
Eu		3	1.5	1	1.5	<0.50	1.5	<0.50		
Tb		1.7	0.7	0.4	1.5	<0.10	1.6	0.7		
Dy		6	5	3	3	8	8	3		
Yb		3.2	5.5	2.6	1.6	1.9	6.9	1.8		
Lu		0.4	0.7	0.3	0.3	0.3	1.1	0.3		

M1 85011503D Garnet-orthopyroxene-biotite-hornblende gneiss (Brattnipene)
M3 85011760A Calc-silicate rock (Walnumfjellet)
M5 85011802B Epidote amphibolite (Walnumfjellet)
M19 A86011803D Clinopyroxene amphibolite (Menipa)
M20 A86012205A Hornblend-biotite gneiss (Mefjell)
M21 AB86010602F Granite-biotite gneiss (Austkanpane, North)
M22 AB86010705C Andalusite-sillimanite-garnet-biotite gneiss (Austkanpane, West)
M28 AB86010903C Sapphirine-biotite-anthophyllite gneiss (Austkanpane, East)
M38 O87011508A Orthopyroxene amphibolite (Brattnipene)
M40 O87011613A Garnet skarn (Brattnipene)

and trace elements were analyzed by X-ray fluorescence spectrometry (XRF) of Chemex Laboratories Ltd., Canada, Kochi University and Fukuoka University of Education, and Inductively Coupled Plasma Spectrometry (ICP) at Chemex Labs. Ltd., in combination with ordinary wet chemical analyses for FeO and Fe_2O_3 ($KMnO_4$ titration) and loss on ignition (LOI). Rare earth element analyses were obtained by using instrumental neutron activation analyses (NAA) at Chemex Labs. Ltd. Selected chemical data of the metamorphic rocks are shown in Table 2. Detailed discussions of the geochemistry of the metamorphic rocks has been given by OSANAI *et al.* (1992a, b).

2.2.2. Intrusive rocks

SAKIYAMA *et al.* (1988) surveyed the intrusive rocks at Lunckeryggen in detail, and clarified field occurrences and petrographical features of the granitic rocks and syenitic rocks. TAINOSHO *et al.* (1992a,b, 1993) pointed out that the granitic rocks in the district are regarded as A-type granite in terms of the chemical data. ARAKAWA *et al.* (1994) discussed the petrogenesis of the granitic rocks from Nd and Sr isotope data.

VAN AUTENBOER and LOY (1972) divided the granitic rocks into two groups: younger (520 Ma, *e.g.*, Romnaesfjellet granite) and older ones (600 Ma, *e.g.*, Lunckeryggen granite) from U-Pb zircon dating by PICCIOTTO *et al.* (1964) and PASTEELS and MICHOT (1970). TAKAHASHI *et al.* (1990) and TAINOSHO *et al.* (1992a) showed Rb-Sr isochron ages of some granitic stocks in the mountains. TAKIGAMI and FUNAKI (1991) have determined Ar-Ar and K-Ar ages for the intrusive rocks and the metamorphic rocks from the mountains. All these results suggest that the granitic magma intruded in early Paleozoic age.

In the mapped area, the intrusive rocks are divided into five groups: Mefjell plutonic complex, Lunckeryggen granite, Lunckeryggen syenites, Dufek granite and small intrusive rocks.

The Mefjell plutonic complex occurs as stocks with concordant boundaries to the gneisses. The complex consists of granite, quartz monzonite and olivine monzonite. The Lunckeryggen syenite occurs as a stock of which the margin shows mylonitic structure. This stock is composed of layered syenite, melanocratic syenite, quartz syenite and granite. The Lunckeryggen granite occurs as a stock which intrudes discordantly into the gneisses of the SW-terrane and the syenite stock. It is composed mostly of medium- to coarse-grained biotite granite (with minor hornblende in places). The Dufek granite stock intrudes discordantly into the metamorphic rocks. It is composed mainly of medium- to coarse-grained biotite granite. The radiometric ages show that these stocks intruded in early Paleozoic.

Besides these stocks, the granitic rocks occur as small bodies and dikes throughout the mapped area. In addition, diorite, dolerite, lamprophyre, and ultramafic rocks are exposed locally in the present area.

Chemical analyses of the intrusive rocks have been performed by means of XRF, ICP and NAA by Chemex Labs Ltd. in Canada. Chemical data of the intrusive rocks are shown in Table 3 (see details in TAINOSHO *et al.*, 1992b). Many of the granitic rocks in the area belong to the A-type granite. Mefjell granite is characterized by high alkalis and somewhat enriched Al_2O_3. Moreover, this granite is lower in CaO, Rb

Table 3. Representative chemical analyses of plutonic and intrusive rocks from the Brattnipene region.

Sample No.	P2	P4	P19	P26	P39	P106	P135	A	B	C
Major element(%)										
SiO2	43.12	60.33	74.49	72.33	50.56	74.35	66.48	60	60.68	49.75
TiO2	2.09	1.05	0.18	0.05	1.22	0.02	0.38	0.69	1.33	3.13
Al2O3	6.47	16.1	13.48	14.79	16.03	15.59	16.53	18.57	13.24	13.51
Fe2O3	4.8	1.82	0.75	0.32	1.41	0.02	1.5	2.16	5.06*	11.51*
FeO	6.97	2.15	0.68	0.31	6.62	0.07	2.28	3.12		
MnO	0.22	0.05	0.01	0	0.16	<0.01	0.06	0.11	0.1	0.17
MgO	8.56	1.05	0.25	0.11	5.6	<0.01	0.2	2.9	3.62	5.42
CaO	12.49	3.84	1.01	1.46	8.98	1.56	1.53	6.63	3.28	7.41
Na2O	4.94	6.57	4.65	5.16	1.67	4.56	5.78	1.5	1.73	3.35
K2O	1.62	4.04	4.02	4.04	3.72	4.21	4.68	4.68	7.13	2.51
P2O5	2.31	0.22	0.04	0.03	0.21	0.07	0.01	0.18	1.07	1.09
CO2	<0.20	<0.20	<0.20	0.89	<0.20					
LOI	0.46	0.64	0.55	0.64	0.39	0.78	1.64	0.78	0.64	0.84
Total	93.59	97.22	99.56	98.60	96.18	100.45	99.43	100.54	97.88	98.69
Trace element(ppm)										
Ba	5500	6300	360	1400	300	1770	320		2888	1857
Cr	140	12	6	4	54	1	5		343	263
F	5950	1500	760	120	2150	80	120			
Ga						16	22		Co 16.6	Co 37.7
Hf						<2	16		19.2	5.8
Nb	5	21	15	8	7	8	24		21	26
Ni	108	2	1	1	23	2	1		118	348
Pb						52	12		19	7
Rb	150	140	150	150	92	130	60		415	44
Sr	6300	2350	140	140	230	373	64		1127	1388
Th	6	9	29	4	1				13.9	2.3
U									7.4	0.7
V	280	50	10	10	250	<1	<1		68	125
Y	88	60	41	50	56	14	21		21	34
Zn	179	85	36	21	118	8	72		128	137
Zr	740	860	145	66	130	32	570		724	275
La	8	7	62	9	15				37.7	56.3
Ce	301	213	119	14	32				78	131
Nd	151	104	56	10	18				43	72
Sm	25.4	13.8	7.1	1.3	5.4				7.59	13.5
Eu	6.8	3.3	0.9	0.5	1.1				2.01	4.04
Tb	2.1	1.2	0.4	0.3	1.1				0.7	1.4
Yb	3.2	2.8	2.2	2.2	3				1.32	2.21
Lu	0.5	0.4	0.2	0.4	0.5				0.22	0.31

P2	85011453B	Melasyenite (Lunckeryggen)
P4	85012009A	Syenite (Lunckeryggen)
P19	O87020101E	Medium-grained bioteite granite (Dufekfjellet)
P26	S870120-2	Fine-medium-grained biotite granite (Lunckeryggen)
P39	S870128-2A	Biotite-hornblende quartz diorite (Austkanpane)
P106	B90011205B	Gneissose biotite granite (Austkanpane)
P135	B90012402A	Gneissose hornblend-biotite granodiorite Mefjell
A	B90011901B	Gneissose hornblend-biotite tonalite (Lunckeryggen)
B	9031505	Lamprophyre (Mefjell)
C	85011307	Metamorphosed dolerite (Brattnipene)

and F, and higher in Ba than those of the other granitic rocks. The Lunckeryggen granite is high in alkalies and F. The Dufek granite is high in alkalies and Sr, and relatively lower in K_2O/Na_2O. Austkampane granite has higher K_2O/Na_2O ratio, F and Rb, and lower MgO and Ba compare with the other granitic rocks. Rogerstoppane granite is relatively low in K_2O/Na_2O.

Most of the Lunckeryggen syenites is extremely rich in K_2O, Ba and F, and has high K_2O/Na_2O ratio. The layered syenite belongs to the ultrapotassic rocks which are defined by high K_2O content (K_2O>3 wt%), MgO content (MgO>3 wt%) and K_2O/Na_2O ratio (K_2O/Na_2O>2%) (FOLEY *et al.*, 1987). They have low to intermediate silica content (SiO_2=43–59 wt%). The melanocratic syenites have low silica content (SiO_2=45–52 wt %) and show similar composition to the dark-colored layers in the layered syenite. The quartz syenites have intermediate silica content (SiO_2 =55–62 wt%) and show many similar characteristics to the layered syenite, but have lower K_2O/Na_2O ratio than the layered syenite.

3. Metamorphic Rocks

Metamorphic rocks are classified into the following rock types for mapping units, based on the mode of occurrence and lithologic facies;
(1) biotite-hornblende gneisses and hornblende gneisses (Gbh),
(2) garnet-biotite gneisses and biotite gneisses (Gb),
(3) garnet-sillimanite-biotite gneiss (Ggb)
(4) amphibolites (Amp and Amb),
(5) marble and calc-silicate rocks (M),
(6) amphibole schist (Sch),
(7) metatonalite (To),
(8) ultramafic rocks and mafic granulites (U),

Rock types (6) and (7) are not exposed in the NE-terrane, while in the SW-terrane there are types (1) to (7) excepting (3).

3.1. Biotite-hornblende gneisses and hornblende gneisses

Biotite-hornblende gneisses form the greatest proportion of the metamorphic rocks in this area. The biotite-hornblende gneisses generally show a banded structure composed of leucocratic (quartzofeldspathic) and melanocratic (biotite- and/or hornblende-rich) parallel bands of mm to cm size in thickness (Plate 2A). These gneisses are also found as unmappable-scale thin layers within the biotite gneisses throughout the mapped areas. Alternating bands of the biotite gneiss and the hornblende gneiss (0.1 to 1.0 m wide) are common as well. The gneisses are coarse- to medium-grained rocks with a granoblastic texture, and basic to intermediate in bulk chemical composition.

Typical mineral assemblages in the NE-terrane (Plate 3A) are:
(1) hornblende+biotite+plagioclase+quartz,
(2) garnet+hornblende+biotite+plagioclase+quartz,
(3) garnet+orthopyroxene+hornblende+biotite+plagioclase+quartz,
(4) orthopyroxene+clinopyroxene±garnet+biotite+hornblende+plagioclase+

quartz,
(5) orthopyroxene+hornblende+biotite+plagioclase+quartz,
(6) clinopyroxene+cummingtonite±garnet+hornblende+biotite+plagioclase+ quartz.

K-feldspar is present in some cases. Charnockitic gneisses which have mineral assemblages similar to assemblage (3) occur as thin layers, especially in northern Brattnipene and central Austkampane.

In contrast, mineral assemblages in the SW-terrane are characterized by orthopyroxene- and clinopyroxene-free and sphene-rich associations (Plate 3B) as follows:
(7) hornblende+biotite±epidote+plagioclase±K-feldspar+quartz,
(8) garnet+hornblende+biotite+plagioclase±K-feldspar+quartz,
(9) biotite+cummigtonite+plagioclase+quartz.

Secondary epidote and chlorite are observed in places.

Rb-Sr and Sm-Nd whole rock isochron ages were determined for charnockitic gneisses in northern Brattnipene. A well-defined Rb-Sr isochron gives an age of 978±52 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70426±0.00017. A Sm-Nd isochron also gives a similar age of 961±101 Ma with an initial $^{143}Nd/^{144}Nd$ ratio of 0.51163± 0.00010 (see more details in SHIRAISHI and KAGAMI, 1992).

3.2. *Garnet-biotite gneisses and biotite gneisses*

Garnet-biotite gneisses and biotite gneisses are typical pelitic to semi-pelitic rocks and have occasionally psammitic composition. These gneisses are widely distributed in northern Brattnipene, northern Austkampane and Menipa in the NE-terrane (Plate 2B), and locally occur as thin layers and xenolithic blocks in the SW-terrane (Walnumfjellet, Mefjell, Dufek and southern nunataks). These gneisses forms a banded structure of melanoclatic biotite-rich gneisses and leucocratic quartzofeldspathic gneisses (layered type migmatite); each band ranges from several mm to cm in thickness. In the mylonite zones in the NE terrane, garnet-biotite and biotite gneisses are highly deformed with protomylonite to ultramylonite structures (Plate 2C). Typical mineral assemblages (Plate 3C) in the NE-terrane are:
(1) biotite+plagioclase+K-feldspar+quartz,
(2) biotite+sillimanite+plagioclase±K-feldspar+quartz,
(3) garnet+biotite+plagioclase+K-feldspar+quartz,
(4) garnet+cordierite+biotite+plagioclase+K-feldspar+quartz,
(5) orthopyroxene+garnet+biotite+plagioclase+K-feldspar+quartz.
(6) orthopyroxene+clinopyroxene±garnet+biotite+plagioclase+K-feldspar+ quartz.

A cordierite+garnet+K-feldspar paragenesis in the garnet-biotite gneisses probably has more magnesian affinity than most of the garnet-biotite gneiss. Spotted cordierite-bearing fine-grained biotite gneiss (biotite+cordierite+plagioclase+K-feldspar+ quartz) can also be found at the highest peak of Komsa.

Rare thin intercalation of orthopyroxene-plagioclase gneiss (restitic orthopyroxene granulite) occurs only in Austkampane. In part of assemblage (6) goldmanite (vanadian garnet)-bearing graphite-rich association (Plates 3D–3F) is found in

Menipa (see detail in OSANAI *et al.*, 1990b). Kyanite porphyroblasts which would have formed during the retrograde stage (ASAMI *et al.*, 1992) occur in assemblages (2) and (3) along the mylonite bands in southern Brattnipene. Andalusite occurs in several garnet-biotite gneisses from the northern and western areas of Austkampane. It occurs as granular or prismatic crystal associated with prismatic sillimanite, both of which replace biotite or plagioclase, and as poikiloblastic crystal that includes fine-grained quartz, plagioclase, sillimanite and biotite. These andalusites and associated sillimanite are considered to be retrograded products in response to the plutonic intrusion (YOSHIKURA *et al.*, 1992). Corundum is also found in the garnet-biotite gneiss as a rare case (sample No. B86012509C). This corundum-bearing gneiss is strongly retrograded; in it garnet and biotite are partially replaced by chlorite and muscovite, respectively, and plagioclase by epidote or prehnite, and corundum is restricted to inclusions within muscovites.

On the other hand, mineral assemblages of those gneisses in the SW-terrane are characterized by primary muscovite occurrence and stable staurolite+quartz association (Plate 4B) as follows:

(7) biotite±muscovite+plagioclase±K-feldspar+quartz,
(8) biotite±muscovite +sillimanite+plagioclase±K-feldspar+quartz,
(9) garnet+biotite±muscovite+plagioclase±K-feldspar+quartz,
(10) garnet+biotite+staurolite+plagioclase±K-feldspar+quartz.

Such a difference of metamorphic mineral assemblages between NE- and SW-terranes implies a contrast of *P-T* conditions.

3.3. *Garnet-sillimanite-biotite gneiss*

Garnet-sillimanite-biotite gneisses occur as thin intercalations (several cm to several m in thickness) of the biotite gneiss and the garnet-biotite gneiss in the NE-terrane. Typical exposures in this mapped area are northern Brattnipene, northern Austkampane and central Menipa. The following mineral assemblages are observed in the gneisses:

(1) garnet+sillimanite±spinel+biotite+plagioclase+K-feldspar+quartz,
(2) garnet+cordierite+sillimanite±spinel+biotite+plagioclase+K-feldspar+quartz,
(3) garnet+cordierite+orthopyroxene+gedrite+plagioclase+quartz.

Assemblage (3), characterized by biotite-free and minor-plagioclase, occurs only as thin layers or lenses in the gneiss-containing assemblage (2).

Garnet in assemblage (1) is usually corroded and rimmed by sillimanite+biotite symplectite that indicates a retrograde metamorphic reaction. Symplectic intergrowth containing hercynitic green spinel+sillimanite+corundum occurs as inclusions in garnet in assemblage (1), and green spinel+fibrolite symplectite occurs as inclusions in cordierite in assemblage (2) in Brattnipene and Austkampane (Plate 4A).

3.4. *Amphibolites*

Amphibolites widely occur throughout the mapped areas, as dark-colored thin layers or bands of 0.1 to *ca.* 10 m in thickness interbedded within the various kinds of gneisses (Plate 2D), or as various-sized xenoliths included in the granites. Typical mineral assemblages of the amphibolites (brown to greenish brown hornblende-

bearing) in the NE-terrane are:
(1) hornblende+plagioclase+quartz,
(2) hornblende+garnet+plagioclase+quartz,
(3) orthopyroxene+clinopyroxene+hornblende+plagioclase+quartz,
(4) orthopyroxene±clinopyroxene +cummingtonite+hornblende+plagioclase+ quartz,
(5) orthopyroxene+clinopyroxene+garnet+hornblende+plagioclase+quartz.
Minor biotite, epidote, and chlorite are commonly found as secondary retrograde minerals (Plate 4C).

In contrast, those in the SW-terrane are characterized by occurrence of green to bluish green hornblende and biotite, and lack of orthopyroxene as follows (Plate 4D):
(6) hornblende±biotite±clinopyroxene+plagioclase+quartz,
(7) garnet+hornblende±biotite+plagioclase+quartz,
(8) hornblende+biotite+epidote+plagioclase+quartz.

A rare orthopyroxene-clinopyroxene-hornblende-plagioclase rock also occurs as lensoid block in amphibolite at southern nunatak (Arden) in the SW-terrane. It has a characteristic cumulate texture.

3.5. Marble and calc-silicate rocks

Marble and calc-silicate rocks are widespread in the mapped area, occurring as intercalations (a few tens to hundred of meters wide) or small lenses within gneisses and amphibolites (Plate 2E). Constituent minerals of marble and calc-silicate rocks in the NE-terrane are as follows:
(1) wollastonite+calcite+quartz,
(2) wollastonite+phlogopite+pargasite+vesvianite+calcite±plagioclase+quartz,
(3) wollastonite+phlogopite+scapolite+calcite+quartz,
(4) clinopyroxene+pargasite+scapolite±wollastonite+calcite+quartz,
(5) clinopyroxene+garnet±scapolite±pargasite+plagioclase+quartz,
(6) olivine+phlogopite±spinel±humite±pargasite+calcite+dolomite+plagioclase.
Those in the SW-terrane are:
(7) clinopyroxene+garnet+scapolite+hornblende±epidote+plagioclase+quartz,
(8) clinopyroxene+epidote+zoisite±sphene+plagioclase+quartz.
Wollastonite-bearing rocks (assemblage (1) to (3)) are predominant in Menipa, and olivine-bearing rock (assemblage (6)) occurs in Brattnipene and Menipa (Plate 4E). Assemblage (7) shows thin alternation of clinopyroxene-rich bands and scapolite-rich bands at southern nunatak (Arden).

3.6. Metatonalite and amphibole schist

These rocks are the main constituents of the SW-terrane in the eastern part of the mapped area (Walnumfjellet) (Plate 2F). The metatonalite is a medium- to coarse grained gneissose rock containing thin layers (up to 10 m wide) and lensoid blocks of dark-green amphibole schist (epidote-chlorite and/or chlorite-epidote-biotite schist) (Plate 4F). Typical gneissose metatonalite is composed of bluish green hornblende, biotite, epidote, plagioclase and quartz with or without garnet and K-feldspar. Accessory minerals are sphene, apatite, zircon, ilmenite, and rare magnetite.

Piedmontite veins also occur in the gneissose tonalite. See more detail in SHIRAISHI *et al.* (1992a).

3.7. Ultramafic rocks and other mafic granulites

The ultramafic rock occurs in the northern area of Austkampane, forming a lense (about 10 m diameter) within the garnet-biotite gneiss. It is a coarse-grained and massive rock, and consists mainly of spinel, olivine, orthopyroxene and hornblende with minor magnetite, apatite, pyrite, chalcopyrite and pentlandite (Plates 5C and 5D). Of these minerals, hornblende and orthopyroxene commonly include tiny crystals or lamellae of ilmenite. Bulk rock (Table 2) and mineral chemistries indicate that the rock was originally a kind of cumulate crystallized from basaltic magma (ISHIZUKA *et al.*, 1996).

The characteristic mafic granulite containing sapphirine is found as a medium- to coarse-grained and massive rock (sample No. AB86010903C) in the northeastern area of Austkampane, in which other constituent minerals include phlogopite, hydrous cordierite, plagioclase, gedrite, orthopyroxene, spinel, corundum, rutile and ilmenite (Plates 5A and 5B). Bulk rock analyses (Table 2) show basaltic compositions in a broad sense, but they are enriched in Al_2O_3, MgO, Cr and Ni, suggesting a precursor with troctolitic composition. Under a microscope, sapphirine is never in direct contact with orthopyroxene, and between the two phases the hydrous cordierite-spinel symplectite occurs. This indicates that the reaction sapphirine+orthopyroxene+H_2O=hydrous cordierite+spinel have occurred (ISHIZUKA *et al.*, 1995). Corundum in the sapphirine-bearing rock occurs, coexisting with sapphirine, orthopyroxene and spinel as well.

4. Intrusive Rocks

The intrusive rocks are divided into granitic rocks (Gr), syenites (Sy), diorite (Di), and dolerite and lamprophyre (Dy). Dolerite and lamprophyre are discussed as dike rocks in the next section. The granitic rocks are subdivided into Mefjell plutonic complex, Lunckeryggen granite, Dufek granite and other small granitic bodies. The syenite complex is named the Lunckeryggen syenite complex in below description. Modal data of the granitic and syenitic rocks are shown in Table 4.

4.1. Mefjell complex

The Mefjell plutonic complex is exposed in an area of 7×10 km in the eastern part of Mefjell. The complex consists of granodiorite, granite (Plate 6A), quartz monzonite and olivine monzonite. It varies from granite composition in the northeast to an alkaline composition in the southwest. It has mostly intermediate magnetic values (20 to 100×10^{-4} SIU). The Mefjell complex intrudes into the gneiss parallel to its gneissosity with a clear boundary, and is sometimes intruded by fine-grained biotite granite and locally by tonalite to diorite stocks. It is foliated by mafic mineral orientation and rarely has mafic layering. The foliation strikes generally N-S to NW-SE and dips steeply (70°–90°).

A medium- to coarse-grained granodiorite is light gray in color and consists of

Table 4. Selected modal analyses of plutonic rocks from the Brattnipene region (vol%).

	Mefjell plutonic complex		Syenite complex		Lunckeryggen granite		Dufek granite	
(vol.%)	1	2	3	4	5	6	7	8
Plagioclase	26.1	45.0	1.9	27.0	26.9	27.5	39.7	58.7
K-feldspar	35.8	17.3	83.5	47.6	36.9	45.3	27.5	16.3
Quartz	27.9	7.7	0.2	10.0	29.5	21.2	26.4	16.3
Biotite	7.7	10.8	5.5	-	3.6	1.5	4.6	6.5
Chlorite	-	-	-	-	0.1	0.2	-	-
Amphibole	2.4	15.0	1.7	11.3	-	1.9	-	-
Clinopyroxene	-	1.0	5.3	-	-	-	-	-
Opaque minerals	-	1.7	0.3	0.1	0.5	0.8	0.4	0.9
Muscovite	0.2	-	-	-	1.7	-	0.2	0.4
Sphene	-	0.5	0.7	3.0	0.5	-	1.3	2.2
Allanite	-	-	-	-	-	0.8	-	-
Apatite	-	1.0	1.1	0.3	-	0.2	-	-
Epidote	-	-	-	0.7	-	0.3	-	-
Calcite	-	-	-	-	0.5	0.1	-	-
Zircon	-	-	-	-	-	0.1	-	-

1: B900124O2A 2: T870202O4B 3: T870119O1A 4: S850120O9A
5: S850120O7A 6: T870131O4A 7: B900123O5B 8: B900123O4B

plagioclase, quartz, biotite, hornblende and K-feldspar with a trace of apatite, zircon and iron oxide. Medium-grained granite consists of biotite, plagioclase, K-feldspar and quartz with minor zircon, apatite and opaque minerals (Plate 7D). Quartz monzonite is a medium-grained light gray color rock and contains much hornblende (7–15% in modal composition). Other constituents are K-feldspar, plagioclase, quartz, biotite and clinopyroxene with trace amounts of apatite, zircon and iron oxide. Olivine monzonite is coarse-grained and is characterized by dark greenish gray to dark brownish gray color. The rock is characterized by large idiomorphic crystals of mesoperthite, and consists of clinopyroxene, olivine, orthopyroxene and antiperthitic plagioclase with zircon, apatite and iron oxide. Both biotite and hornblende occur as fine-grained flakes surrounding orthopyroxene and clinopyroxene, respectively. Sometimes it is bleached along a later pegmatite and aplite with several cm to several m wide. The bleached part has large amounts of secondary biotite and hornblende instead of olivine, orthopyroxene and clinopyroxene.

The whole rock isochron age was determined in the Mefjell complex. Four samples give an age of 506±43 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70563±0.00055 (TAINOSHO *et al.*, 1992a).

4.2. Lunckeryggen syenite complex

There is a syenite-quartz syenite complex in the central part of Lunckeryggen (Plate 6B). It is composed of layered syenite, melanocratic syenite, quartz syenite and granite. The layered syenite shows conspicuous rhythmic layering ranging from a few cm to a few m in thickness. Euhedral K-feldspar and mafic minerals in the syenite show preferred orientation showing a basin structure of the mass. Marginal part of the mass partly shows remarkable mylonitic structure which is parallel to the contact plane of the mass. Small dikes of fine-grained melanocratic syenite discordantly intrude into the layered syenite.

Medium- to fine-grained quartz syenite occurs as dikes, sheets or lenticular veins intruding the layered syenite and the melanocratic syenite. It has a brecciated appearance due to abundant angular xenoliths of precedent rocks. Miarolitic cavities are common throughout the rock. Small dikes of fine- to medium-grained granite characterized by the presence of light bluish-colored K-feldspar (amazonite) are intruded into the layered syenite. Magnetic susceptibility of the complex is mostly intermediate to high (50 to 500×10^{-4} SIU).

The layered syenite is composed mainly of K-feldspar, biotite, amphibole (actinolite to richiterite) and clinopyroxene (aegirine-augite) with accessory sphene, apatite, zircon, and magnetite. K-feldspar often shows strong schillerization owing to inclusions of minute flakes of hematite. These mineral assemblages and modal compositions vary with layers. Light-colored layers are rich in K-feldspar and poor or absence in clinopyroxene. On the other hand, dark-colored layers are rich in clinopyroxene and poor in K-feldspar and amphibole. The melanocratic syenites have minerals of the same assemblage as the layered syenite, but they are fine-grained and very rich in mafic minerals. The quartz syenite contains K-feldspar, plagioclase, quartz and amphibole (edenite to actinolitic hornblende) with or without biotite and clinopyroxene (aegirine-augite). Accessory constituents are sphene, apatite, zircon, allanite and magnetite. Interstitial fluorite is rarely present. Granite dikes are composed mainly of quartz, K-feldspar (miclocline), plagioclase and clinopyroxene (aegirine-augite) with accessory garnet (hydrogrossular), sphene and magnetite. K-feldspar is microline perthite and often occurs as phenocryst attaining 5 cm (Plate 7F).

^{40}Ar-^{39}Ar plateau ages of 499.7±9.0 and 495.7±8.9 Ma are obtained for biotites of this complex (TAKIGAMI and FUNAKI, 1991).

4.3. Lunckeryggen granite

The Lunckeryggen granite is exposed in an area of 6×6 km^2 in center of Lunckeryggen. It is composed of a stock of coarse-grained granite and many dikes of fine-grained granite. The granite intrudes into metatonalite of the SW-terrane (Plate 6C) and quartz syenite of the syenite complex and has angular xenoliths of these rocks. The coarse-grained granite is generally homogeneous and massive, but it has foliation in places, which may be a primary flow structure. Dark inclusions about 20 cm in diameter are sometimes present. The fine-grained granite dike intrudes into the coarse-grained granite and contains abundant xenoliths of coarse-grained granite and tonalitic rocks of the SW-terrane. Magnetic susceptibility is high (100 to 200×10^{-4} SIU) in the coarse-grained granite and intermediate to high (25 to 400×10^{-4} SIU) in the fine-grained granite.

Principal constituents of the coarse-grained granite are quartz, K-feldspar, plagioclase and biotite with or without hornblende. Most of biotite occurs interstitially. Accessory constituents are sphene, apatite, zircon and magnetite with or without fluorite. The fine-grained granite shows similar mineral assemblage to the coarse-grained granite, but hornblende is absent. Interstitial fluorite always occurs.

The Rb-Sr whole rock isochron age of the Lunckeryggen granite gives 525±32 Ma with an initial ratio of 0.7050 (TAKAHASHI *et al.*, 1990), whereas K-Ar whole rock ages of the Lunckeryggen granite are 406 and 415 Ma. Biotites from the Lunckeryggen syenite complex show Ar-Ar plateau ages of about 500 Ma, which are similar to the Rb-Sr age (TAKIGAMI and FUNAKI, 1991).

4.4. Dufek granite

The Dufek granite is named after Dufekfjellet. The granite is exposed in an area of approximately 10×10 km^2 in and around the Dufekfjellet (Plates 7A and 7B). The granite includes many xenoliths of the tonalite in the north and huge blocks of the gneisses especially in the south. This suggests that the Dufek granite discordantly intrudes into the host gneisses of the SW-terrane though the intrusive relation between the granite and the country rocks is not clear at the outcrops. The doleritic dikes intrude into the Dufek granite at the northern margin of the Dufekfjellet. The Dufek granite has intermediate to high magnetic values (60 to 200×10^{-4} SIU).

The Dufek granite is unfoliated and composed mainly of medium-grained biotite granite with fine-grained biotite granite and medium-grained hornblende biotite granodiorite. The medium-grained granite is composed of plagioclase, K-feldspar, quartz and biotite with accessory sphene, apatite, zircon, muscovite and opaque minerals (Plate 7E). The fine-grained biotite granite has a similar mineral assemblage with medium-grained granite. The medium-grained hornblende biotite granodiorite occurs as enclaves in the main facies.

Six samples of the Dufek granite define an isochron with an age of 528±31 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70372±0.00029 (TAINOSHO *et al.*, 1992a).

4.5. Small intrusive bodies

Austkampane granite

At the eastern side of Austkampane, a granitic body is exposed in an area 1×3 km^2. It intrudes into the gneiss with a concordant boundary. Mafic minerals of the granite show a parallel arrangement defining a foliation. Petrographically it has a coarse-grained granodiorite to granite composition, and is accompanied by fine- to medium-grained quartz diorite. The main constituents of the granodiorite to granite are quartz, plagioclase, K-feldspar, hornblende and biotite. Accessories are zircon, apatite, sphene and ilmenite. The quartz diorite is composed mainly of plagioclase, quartz, biotite, hornblende and clinopyroxene with accessories of zircon, apatite, sphene and ilmenite.

In addition to this body, many small granitic dikes and sheets of unmappable sizes intrude into the metamorphic rocks in Austkampane. They are mostly fine- to medium-grained muscovite bearing biotite granite, containing garnet in places.

Rogerstoppane granite

A medium-grained hornblende biotite granite crops out at Rogerstoppane at the southern end of the mapped area. Field occurrence of the granite is uncertain due to ice cover. This granite consists mainly of plagioclase, quartz, K-feldspar, biotite and hornblende with accessory allanite, epidote, zircon, apatite and opaque minerals.

Other granitic rocks

Small granitic rocks are locally exposed in some places: medium- to coarse-grained biotite granite in the northern margin of Menipa, medium-grained biotite granite in Komsa and the fine-grained (hornblende) biotite granite in Salen.

At Nordtoppen and Sorhaugen, medium- to coarse-grained dark-grayish dioritic rocks crop out. The main constituent minerals are orthopyroxene, clinopyroxene, hornblende, biotite, plagioclase and quartz.

5. Dike Rocks

Mafic dike rocks (high potassium rock, "lamprophyre", and dolerite) which have been metamorphosed up to amphibolite facies grade intrude into the Proterozoic metamorphic rocks, but are cut in places by younger veins of Paleozoic granite and pegmatite. Similar mafic dikes with various ages and compositions have been reported from eastern Queen Maud Land including the Lützow-Holm Complex, Yamato-Belgica Complex and Schirmacher Hills (SHIRAISHI *et al.*, 1988; ARIMA and SHIRAISHI, 1993). The radiogenic ages (K-Ar and Ar-Ar methods) of the youngest mafic dike rocks from the Sør Rondane Mountains indicate 434–536 Ma (KOJIMA and SHIRAISHI, 1986; TAKIGAMI *et al.*, 1987; TAKIGAMI and FUNAKI, 1991). Major and trace element abundances of the mafic dike rocks are given in Table 3.

5.1. Lamprophyre

High potassium lamprophyric rocks exhibit a well-recrystallized grano-lepidoblastic texture and distinct igneous texture is not preserved. Dikes of lamprophyre occur in several areas including the southwestern area of Austkampane and the western side of Mefjell. Because of poor exposure, the contact relation with the host rock is not clear. The rocks consist dominantly of greenish brown biotite and alkali-feldspar which commonly shows microcline texture with or without bluish green amphibole, epidote, muscovite, and quartz. Accessory minerals are apatite, sphene, orthite, hematite, and opaque minerals.

The lamprophyre are characterized by extremely high K_2O, P_2O_5, Rb, Ba, Sr, Zr, and light rare earth elements which have minette or lamproite affinity. These geochemical characteristics of the lamprophyre are similar to those of the high potassium dike rocks in the Yamato Mountains *ca.* 300 km east of the present area (ARIMA and SHIRAISHI, 1993). In the incompatible-element concentrations diagrams which are normalized to the estimated primitive mantle abundance, the lamprophyre shows pronounced negative anomalies of Nb-Ta and Ti (IKEDA *et al.*, 1995). Such features are commonly observed in subduction related rocks, lamproite and calc-alkaline lamprophyre (MITCHELL and BERGMAN, 1991; ROCK, 1991).

5.2. Dolerites

A slightly metamorphosed dolerite is found throughout the mapped area, occurring as a dike within the gneisses. The contact between the dike and host gneisses is clear, along which the distinct chilled margin develops. On the northern margin of Dufekfjellet, dolerite dikes also intrude into the Dufek Granite, as mentioned in Section 4.4 (Plate 7C).

Dolerites are re-crystallized in various grades. They generally show a sub-ophitic dolerite texture and are composed of igneous pyroxene and plagioclase, and of metamorphic biotite with or without greenish to bluish green hornblende. Ilmenite, apatite, sphene, orthite, and pyrite are common as accessory minerals. Some dolerites are well-recrystallized and corroded plagioclase laths are not well preserved. Hornblende-biotite schist without pyroxenes is completely recrystallized.

Dolerites are characterized by relatively high contents of K_2O (2.0–3.0 wt%), TiO_2 (2.5–3.6 wt%), P_2O_5 (0.9–1.6 wt%), Ba (1206–2354 ppm), Sr (883–1434 ppm) and Zr (273–772 ppm). On the standard discrimination diagrams of MULLEN (1983), MESCHEDE (1986) and IKEDA (1990), most of the samples plot within the field of alkaline rocks in within-plate. However, the mantle-normalized trace element patterns of the dolerites show Nb-Ta depression which is common to the island-arc rocks (IKEDA *et al.*, 1995).

Assuming 480 Ma (average K-Ar age) for the age of mafic dike rocks, calculation of the initial Sr and Nd isotopic compositions reveals that both lamprophyre and dolerite have similar initial Nd and Sr isotopic compositions, and the enriched isotopic compositions compare to mid-oceanic ridge basalt (MORB) and ocean island basalt (OIB). These isotopic features are generally interpreted to mean that their source regions have long histories with higher Rb/Sr and Sm/Nd ratios than those of bulk Earth and are derived from metasomatized mantle sources (IKEDA *et al.*, 1995).

5.3. *Tectonic significances of the mafic dike rock*

High potassium rocks such as lamproite suites occur in a wide variety of tectonic settings, including continental rift zone, oceanic island, island arcs, active continental margin and continental collision zones (ROCK, 1987; FOLEY *et al.*, 1987). The geological and geochemical data described above suggest that the mafic dike rock magmas formed in a continental within-plate tectonic setting by mixing of subduction-related materials and a metasomatically enriched mantle source (IKEDA *et al.*, 1995). A similar model is also apply to the origin of the *ca.* 500 Ma post-tectonic syenite in the Yamato Mountains (ZHAO *et al.*, 1995).

The mafic dike rocks from eastern Queen Maud Land were emplaced about a few tens of million years after the *ca.* 500 Ma Pan-African orogeny (SHIRAISHI *et al.*, 1992b, 1994). ARIMA and SHIRAISHI (1993) argued that the mafic dike rocks in eastern Queen Maud Land are best interpreted as a manifestation of post orogenic igneous activity linked to the Pan-African orogeny. SHIRAISHI *et al.* (1992b, 1994) interpreted that the orogeny was associated with overthickening of the lithosphere by collision of east and west Gondwana.

The Nd and Sr isotopic data suggest that the mafic dike rocks, lamprophyre and dolerite, from the Sør Rondane Mountains, were derived from similar metasomatically enriched mantle sources (IKEDA *et al.*, 1995). In the magma process identification diagram (ALLEGRE and MINSTER, 1978), the lamprophyre and dolerite follow a partial melting trend with relatively steep slope. The geochemical features suggest that these rocks are derived from a common enriched mantle source with almost the same degree of partial melting. Following the partial melting, fractional crystallization with horizontal trend probably occurred. The advanced fractional crystallization process may concentrated incompatible elements such as P, Rb, Ba, Ce, La, Zr, Sr, and Zr. These geochemical characteristics suggest that both the lamprophyre and dolerite from the Sør Rondane Mountains originated from similar mantle segments (IKEDA *et al.*, 1995).

6. Structural Geology

Structural evolution of the central part of the Sør Rondane Mountains is divided into seven stages, from D_1 to D_7, based on their characteristics of deformation, metamorphism and igneous activity (TOYOSHIMA *et al.*, 1995) (Table 5). The deformations of three early stages (D_2 to D_4) are of penetrative type (Fig. 1), and those of three later stages (D_5 to D_7) are not of penetrative type. Because each stage of deformation is associated with metamorphism and in some cases with magmatic intrusion, the deformation history is intimately related to the metamorphic and

Table 5. Deformation history of the Brattnipene region after TOYOSHIMA *et al. (1995).*

Deformation event	Structure	Magmatism	Metamorphism	Movement picture	Age (Ma)
D_1	banding-parallel foliation (S_1) with boudins, tight to isoclinal fold (B_1')		peak of prograde metamorphism ? granulite to amphibolite facies ?		1000*
D_2	fracture filled with tonalite and gabbro intrusives, mylonitic foliation (S_2) and tight fold (B_2)	tonalitic and gabbroic	amphibolite facies	top-to the SW to S displacement formation of the MSZ	950**
D_3	mylonitic foliation (S_3), minor tight fold (B_3) and major recumbent fold (B_3)	pegmatite I and granitic	retrograde metamorphism	top-to the SE displacement formation of the SRS	
D_4	WNW-ESE trending open to tight fold (B_4), minor shear zone and fracture filled with intruded granitic rock	pegmatite II	greenschist facies	N-S trending compression and northward thrusting ?	
D_5	N-S trending open to gentle fold (B_5)			E-W trending compression	
D_6	NE-SW trending gentle fold (B_6)			NW-SE trending compression	
D_7	fracture filled with intruded syenitic and granitic rocks	syenitic and granitic			500**

*SHIRAISHI and KAGAMI (1989), **TAKAHASHI *et al.* (1990).
MSZ: Main Shear Zone (KOJIMA and SHIRAISHI, 1986).
SRS: Sør Rondane Suture (OSANAI *et al.*, 1992).

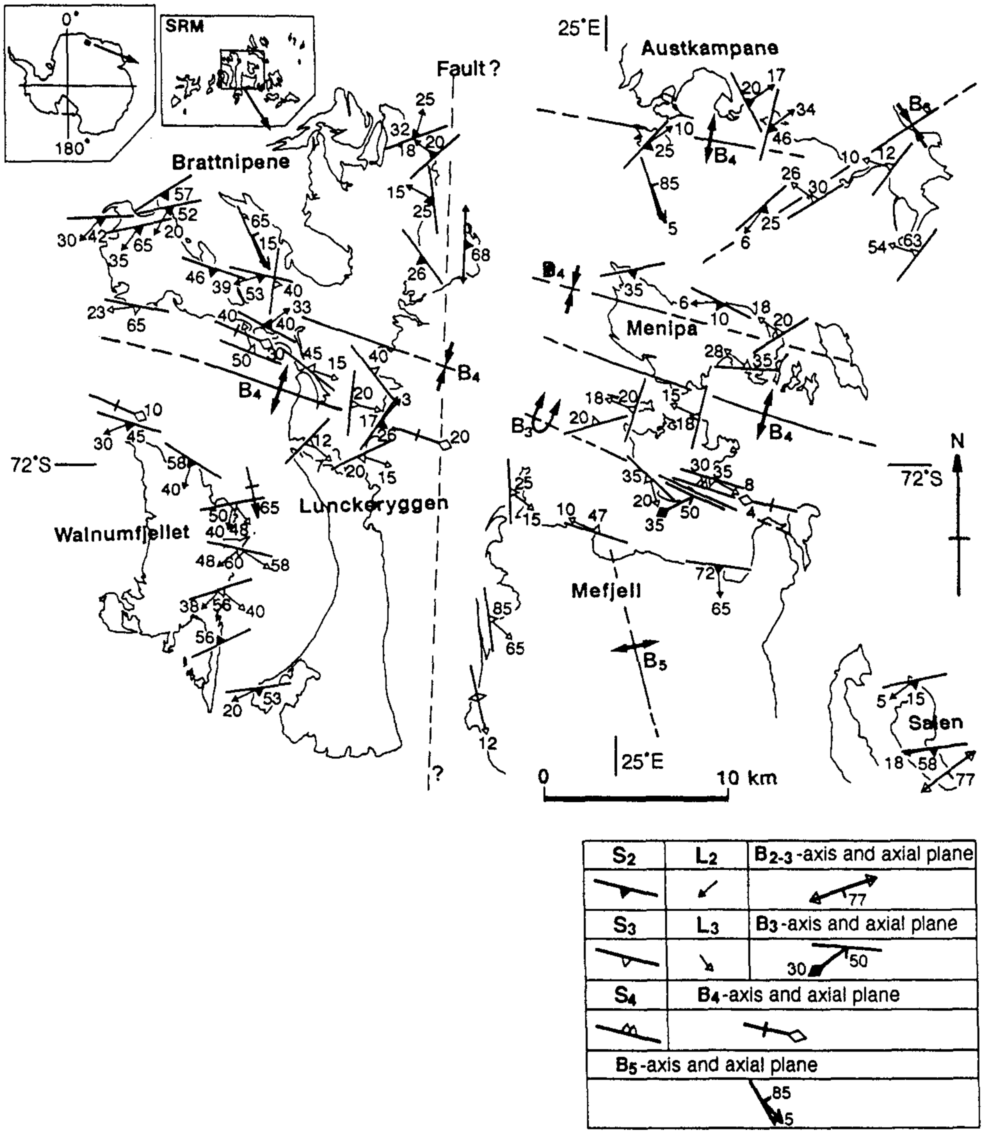
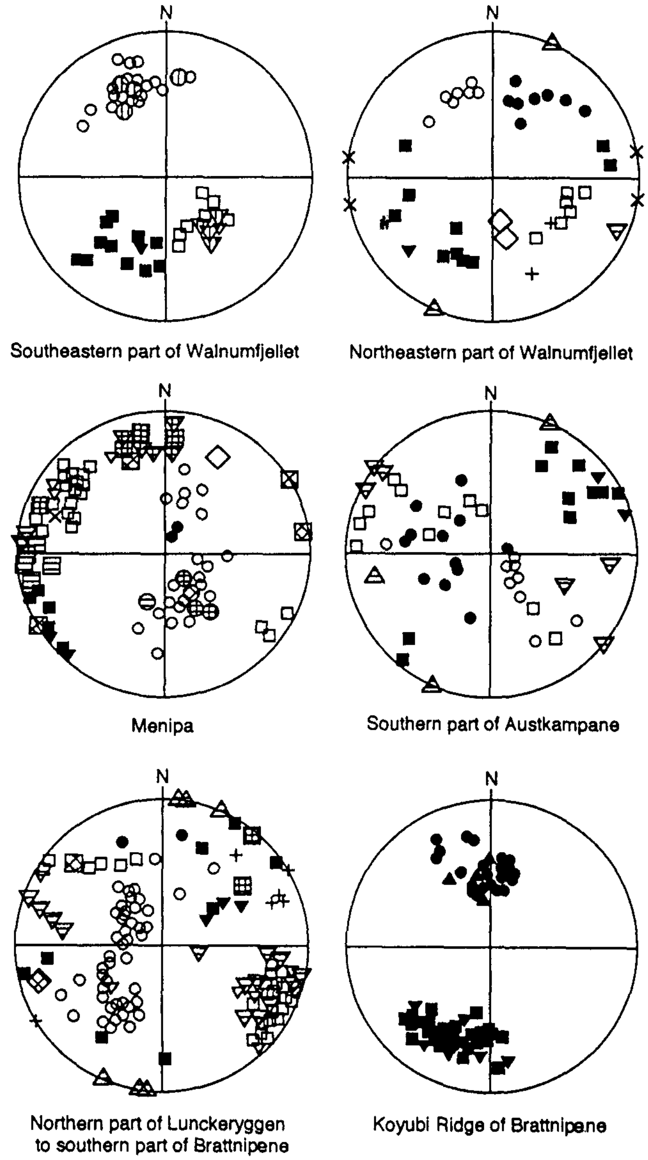


Fig. 1. Structural map of the Brattnipene region after Toyoshima *et al. (1995).* B_5*-antiform in Mefjell can be viewed from Menipa.*

magmatic history. The metamorphic-deformation history is divided into three stages, prograde metamorphic peak stage (D_1) related to flattening type deformation, retrograde metamorphic stage (D_2 to D_6) related to its exhumation and mylonitization, and contact metamorphic stage (D_7). The metamorphism of the former two stages has occurred not only associated with ductile deformation but also with various kinds of magmatic intrusions.

Foliation of metamorphic rocks trends variously in the central part of the Sør



Stage	D1	D1-3	D2	D3	D4	D5	D6
Pole of foliation	⊗	⊕	●	○	⊖	◈	
Mineral lineation	⊠	⊞	■	□	⊟		
Fold axis		⩔	▼	▽	⩢	◇	+
Pole of axial plane of fold			▲		⩡	×	
Pole of shear plane of minor shear zone					⦶		
Mineral lineation in shear zone					⩛		

Fig. 2. Lower hemisphere equal area projections of foliations (S), mineral lineations (L) and fold axes (B) within the Brattnipene region (TOYOSHIMA et al., 1995).

Rondane Mountains (Figs. 1 and 2) as well as the eastern part where NE-SW and NW-SE trending folds develop (ISHIZUKA *et al.*, 1993). On the other hand E-W to NE-SW trending and southward dipping foliation is the most prominent structure in the western part of the Sør Rondane Mountains (SHIRAISHI *et al.*, 1992a). Multiphase folding (D_4 to D_6) has given rise to variations in orientation of foliation in the central part of the Sør Rondane Mountains (TOYOSHIMA *et al.*, 1995) (Figs. 1 and 2). Discontinuity of fold axes of WNW-ESE trending antiform and synform implies a N-S trending fault in the Gjelbreen (shown by a broken line in Fig. 1), as shown by SHIRAISHI *et al.* (1991).

The earliest deformation structure in the mapped area is a lithological-banding-parallel foliation (S_1) with boudins and axial foliation (S_1') of tight to isoclinal folds, defining the D_1 stage (TOYOSHIMA *et al.*, 1995). The S_1-boudin have a pancake shape, flattened parallel to the S_1-foliation. No rotated boudin of the D_1 stage are observed in the metamorphic rocks which were only slightly deformed in ductile fashion after tonalite intrusion. Most of the D_1-structures appear to have strongly lost their initial structural characteristics owing to overprinting of subsequent deformation such as mylonitization and folding. The D_1 stage before the tonalite intrusion is considered to correspond to the prograde metamorphic peak stage, on the basis of relationships between deformation and metamorphic histories (TOYOSHIMA *et al.*, 1995). Rb-Sr and Sm-Nd whole rock isochron ages of *ca.* 1000 Ma have been regarded as the age of the granulite-facies regional metamorphic peak in the Sør Rondane Mountains (SHIRAISHI and KAGAMI, 1992).

Mylonitization and exhumation of the lower crustal rocks in the central part of the Sør Rondane Mountains began at the D_2 stage, closely related to the tonalite intrusion (partly gabbro and granite), folding (B_2) of pre-D_2-foliations, and retrograde metamorphism under amphibolite facies conditions (TOYOSHIMA *et al.*, 1995). Structures of the D_2 stage are prominent in the central part of the Sør Rondane Mountains. Mylonitic foliation (S_2) trends E-W to ENE-WSW and dip southward with NE-SW to N-S trending mineral lineation (L_2) (Figs. 1 and 2).

The E-W trending large-scale sheets of D_2-tonalites which are strongly mylonitized after their intrusion occupy most of the SW terrane, and the northern edge of the tonalite zone roughly corresponds to the Main Shear Zone (KOJIMA and SHIRAISHI, 1986; SHIRAISHI *et al.*, 1991, 1992a). The tonalite sheets are parallel to the S_2-mylonitic foliation. Many D_2-tonalite veins are injected along shear fractures. Thus these features imply that the tonalite intruded into a regional fracture zone at first, and then the zone functioned as a mylonite zone. The tonalite intrusion may have occurred in the same series of movements as the mylonitization.

Almost all of the D_2-intrusive rocks have S_2-mylonitic foliation and L_2-mineral lineation, showing that they, together with surrounding metamorphic rocks and contained metamorphic inclusions, were deformed immediately after the intrusion. The S_2-mylonitic foliation produced immediately after the tonalite intrusion was formed parallel to the planes along which the tonalite magma was emplaced. This imples that the initial stage of the exhumation tectonics of the Sør Rondane Mountains rocks resulted from the rise and intrusion of the tonalite magma, and that the D_2-shearing during the exhumation controlled and enhanced the tonalite

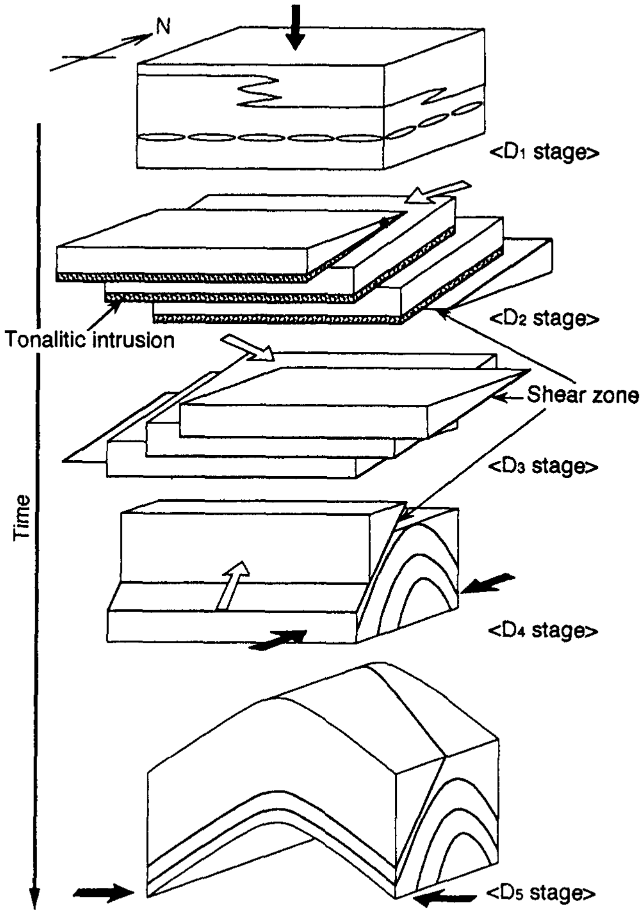


Fig. 3. Schematic diagram illustrating the structural evolution of metamorphic and plutonic rocks from the Brattnipene region (TOYOSHIMA et al., 1995). Solid arrows show compressional stresses. Open arrows indicate shear directions (displacement vectors) lying within the shear planes.

intrusion along the shear planes (Fig. 3).

Metamorphic mineral assemblages defining the S_2-foliation show that during the D_2 stage, retrograde amphibolite facies mylonitization occurred in the granulite facies NE terrane. On the other hand, the amphibolite facies SW terrane during the D_2 stage appears to have mylonitized under the same amphibolite facies conditions as its metamorphic peak. Asymmetry of the D_2-structures shows that the D_2-mylonitization and tonalite intrusion were caused by the top-to the SW to S displacement along the planes dipping to the S. These imply that the structurally-overlaid NE terrane was exhumed to nearly the same level in the crust as the structurally-underlaid SW terrane in an extensional tectonic regime (Fig. 3). Therefore, the D_2-deformation and exhumation may have been related to rifting accompanying large-volume intrusion of tonalite magma (TOYOSHIMA *et al.*, 1995) (Fig. 3).

Subsequently, the D_3-deformation was caused by the top-to the SE displacement of the Sør Rondane Mountains rocks in another extensional tectonic regime under amphibolite facies conditions (TOYOSHIMA *et al.*, 1995) (Fig. 3). The D_3-deformation is characterized by another retrograde mylonitization developed S_2-parallel mylonitic foliation (S_3) with NW-SE trending mineral lineation (L_3), by refolding (B_3) of B_2-folds and by intrusion of diorite, granodiorite, leucocratic granite, and pegmatite (pegmatite I after OWADA *et al.*, 1991, 1992). Structures of the D_3 stage are prominent in the central part of the Sør Rondane Mountains.

The D_3 stage corresponds in movement picture and metamorphic conditions to the mylonite-forming event after OSANAI *et al.* (1988). Therefore, the Sør Rondane Suture (OSANAI *et al.*, 1991, 1992a) was formed during the D_3 stage. ASAMI and SHIRAISHI (1987), OSANAI *et al.* (1988) and ASAMI *et al.* (1992) suggest that the metamorphic conditions of the D_2 to D_3 stages were 530° to 580°C and 550 to 450 MPa in the central part of the Sør Rondane Mountains. A retrograde kyanite-forming reaction (ASAMI and SHIRAISHI, 1987; ASAMI *et al.*, 1992) involving the breakdown of garnet in pelitic gneisses occurred in this retrograde metamorphic stage.

After these mylonite-forming tectonics, multi-stage folding occurred in some compressional tectonic regimes (TOYOSHIMA *et al.*, 1995). The NNE-SSW compressional stress acted after the D_3 stage, resulting in the WNW-ESE trending folds and minor thrusts with top-to the N sense. The central Sør Rondane Mountains rocks

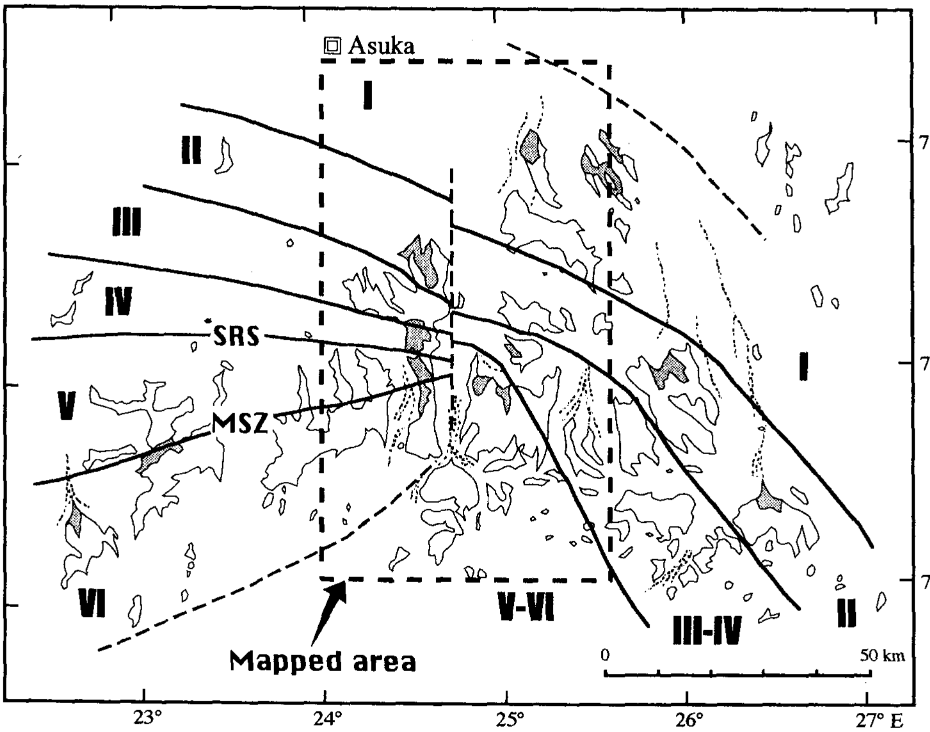


Fig. 4. Tectonic division of lithologic units in the central Sør Rondane Mountains (OSANAI et al., 1992). Roman numerals of I to VI show unit numbers. SRS: Sør Rondane Suture, MSZ: Main Shear Zone. Broken lines indicate inferred shear zones.

were emplaced under the greenschist-facies condition during this stage before the contact metamorphism with the D_7-granites. Subsequently, the E-W compressional stress worked during the D_5 stage, and then NW-SE compression resulted in D_6-folding. The non-foliated 500 Ma granite and syenite intruded in the last stage (D_7-stage) of the structural evolution of the central part of the Sør Rondane Mountains. Strain-free quartz ribbon and random-oriented kyanites and biotites have been produced by contact metamorphism with the granites, and the metamorphic grade increased from greenschist-facies to amphibolite facies (TOYOSHIMA *et al.*, 1995).

7. Tectonic Evolution

According to OSANAI *et al.* (1992a, b), the differences in the chemistry between the basic and intermediate metamorphic rocks of six units (unit I to VI: Fig. 4) suggest that the protoliths of the various units developed in different tectonic settings. Unit I comprises basic, pelitic, psammitic and calc-silicate (including marbles) metamorphic rocks with rare ultramafic rocks. The geochemical characteristics of the basic metamorphic rocks show mid-oceanic ridge basalt (MORB)-like affinities. Units II, III, IV and V consist of basic, intermediate, acidic, pelitic, psammitic and calc-silicate metamorphic rocks. The basic metamorphic rocks of unit II have island arc basalt (IAB)-type geochemical characteristics, while those of units III, IV and V have both of MORB- and IAB-type characteristics. The intercalated intermediate metamorphic rocks are slightly different in chemical compositions between unit II and units III-V. The intermediate rocks of unit II are characterized by island arc andesite (IAA)-type affinities, while those of units III to V show the continental margin andesite (CMA)-type with rare IAA-type chemical compositions. TAKAHASHI *et al.* (1991) also showed that intermediate metamorphic rocks (metatonalites) in unit V were derived from a primitive island arc due to their low initial Sr isotopic ratios. The unit VI mainly consists of basic and intermediate metamorphic rocks with subordinate meta-sedimentary rocks. The chemical characteristics of basic and intermediate meta-morphic rocks of unit VI show IAB-type and CMA-type, respectively.

Thus the rock assemblages in the central Sør Rondane Mountains can be classified into the following types with a zonal arrangement from north to south: oceanic type (unit I), island-arc type (unit II), mixture of oceanic, island-arc and continental-margin island-arc types (accretional complex?: units III, IV, V) and continental-margin island-arc type (unit VI).

Based upon major and trace element compositions, especially ocean ridge granite normalized patterns, the granitic rocks are genetically divided into two groups. One is volcanic arc type granite which includes the Mefjell plutonic complex, the Lunckeryggen granite and the Dufek granite (unit IV to VI). This group is characterized by relatively high alkalis, Ba, Sr, and low Y and Nb contents. The other type is within-plate type granite which involves Austkampane granite (unit I), having Sr, Cr, and high Y and Nb, in comparison with the above group. Mineral compositions of the granitic rocks are also related to the above-mentioned two types. Mg/(Mg+Fe) ratios of ferromagnetian minerals of the within-plate type granites are very low, while those of the volcanic arc type granites have intermediate

Mg/(Mg+Fe) ratios except for the Mefjell plutonic complex. Anorthite contents of plagioclase in the within-plate granites are low, while those of the volcanic arc type granites have slightly high anorthite content.

It is concluded that the central Sør Rondane Mountains consists of oceanic, island-arc, accretional complex and continental-margin island arc types protoliths in analogy to the modern plate tectonic systems. These complicated original rock constitutions were formed during a collision event prior to the main regional metamorphism and deformation at *ca.* 1000 Ma (SHIRAISHI and KAGAMI, 1989, 1992; GREW *et al.*, 1992) and experienced poly-stage deformation with folding and thrust-up movement before *ca.* 500 Ma granite activity (TAKAHASHI *et al.*, 1991; TOYOSHIMA *et al.*, 1995); subsequently, A-type igneous activities (syenite: SAKIYAMA *et al.*, 1988) took place in the tectonic environments of the active plate margin. These features suggest that there was internal fracturing of Gondwanaland during an early stage of rift development before eventual break-up (SHIRAISHI *et al.*, 1988) in the central Sør Rondane Mountains. These late Proterozoic metamorphic and deformation events which were followed by the latest Proterozoic to early Paleozoic deformation with or without thrusting have also been reported from the other Antarctic Proterozoic terranes of Rayner Complex, Northern Prince Charles Mountains and MacRobertson Land (GREW, 1978; TINGEY, 1982; BLACK *et al.*, 1987; SHERATON *et al.*, 1987; HARLEY and HENSEN, 1990).

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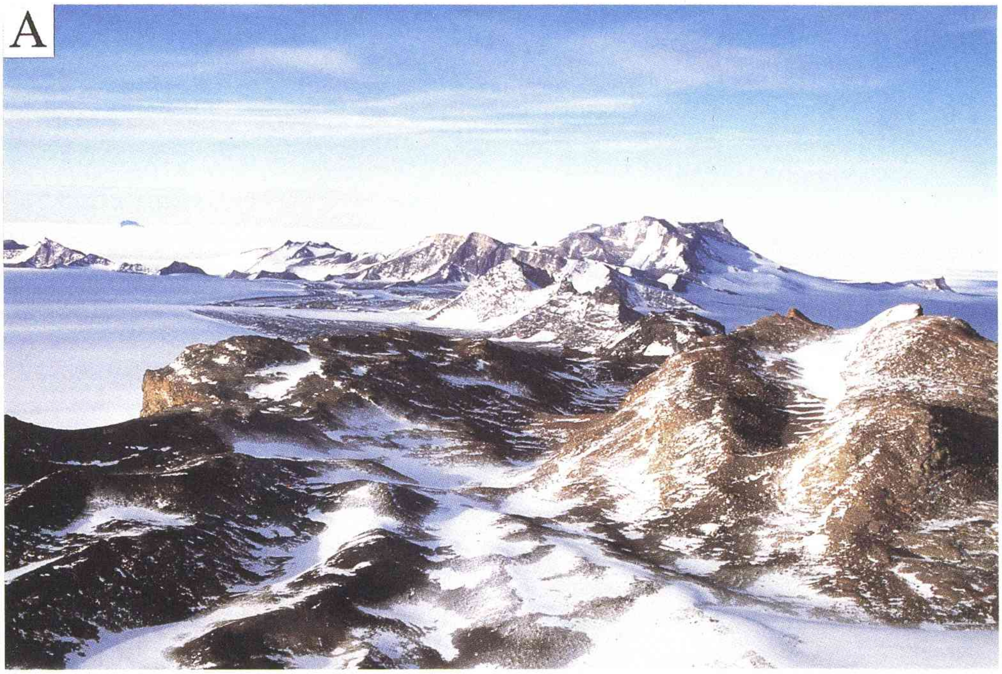
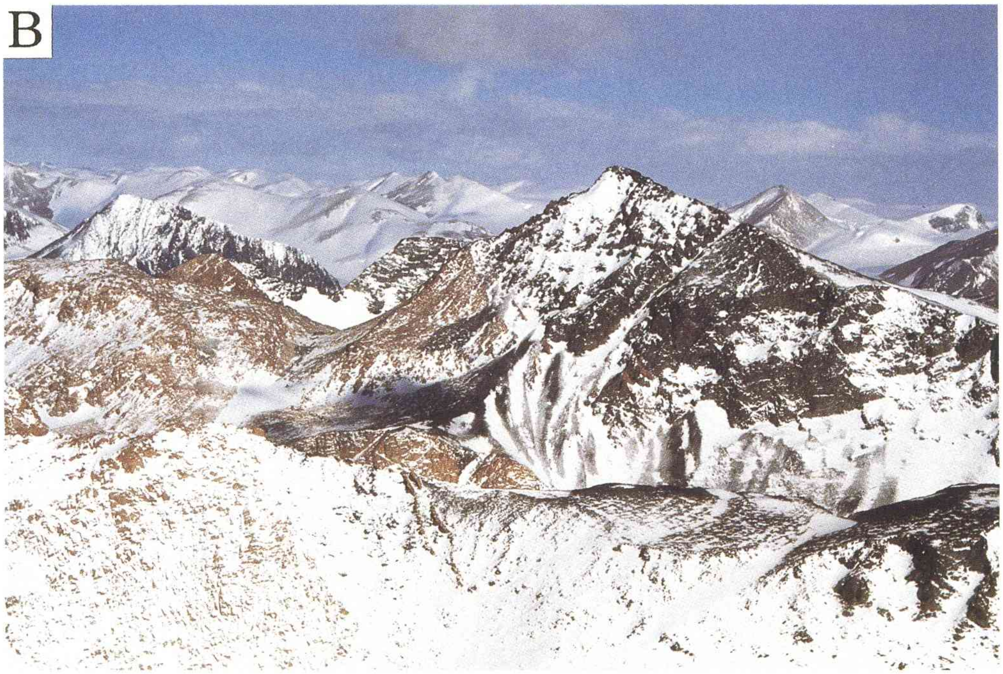
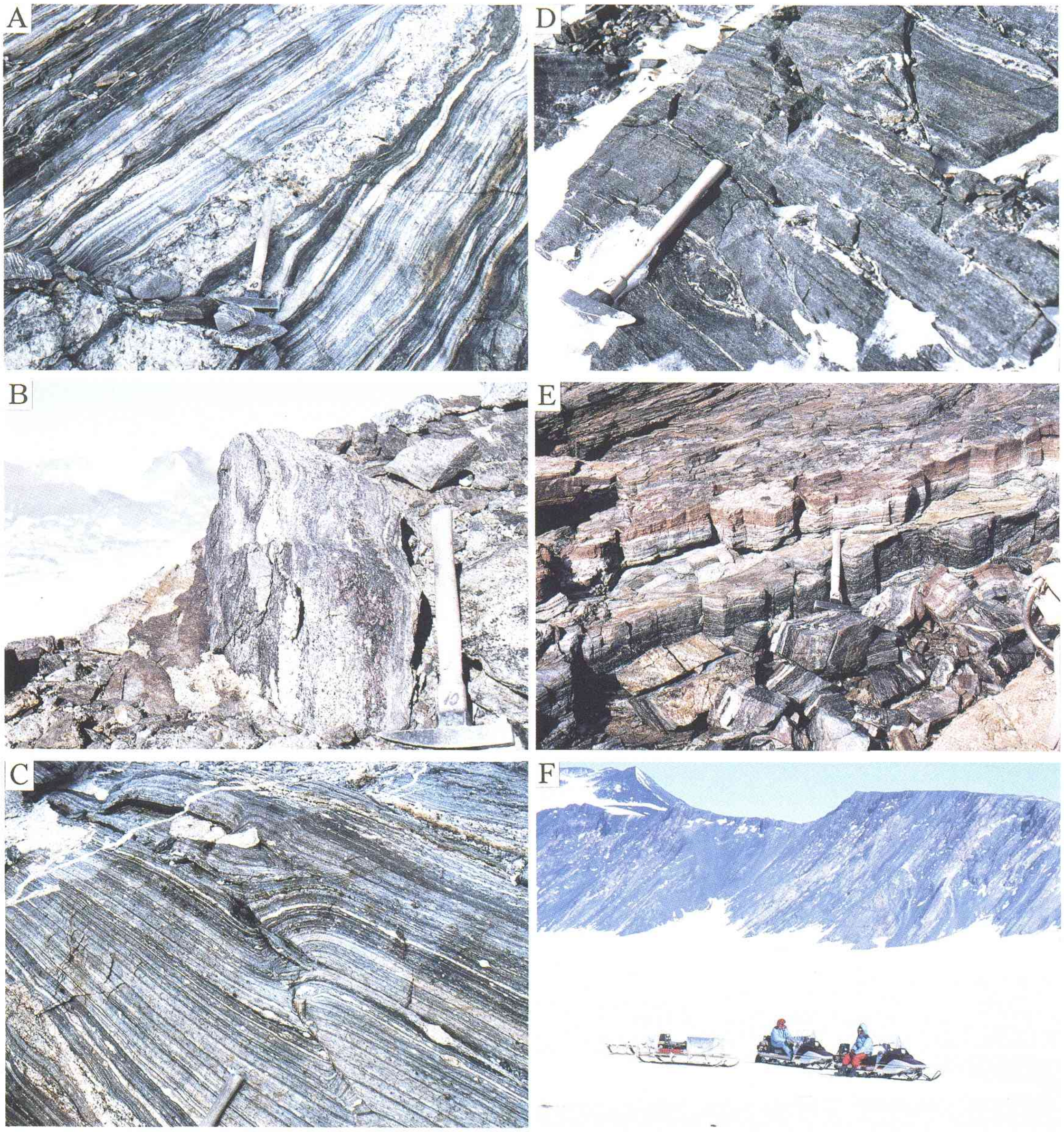




A. *The northern Lunckeryggen and Brattnipene, viewed from the south through helicopter window (photograph taken on January 17, 1990). The small nunatak (far left back) is Romnaesfjellet close to Asuka.*

B. *The Mefjell (backside snowy mountains) and summit of Lunckeryggen in the south-central part of the mapped region, viewed from the NW through helicopter window (photograph taken on January 24, 1990).*

Plate 2



A. Banded sequence of biotite-hornblende gneiss at Brattnipene. Note the layer-parallel granitic intrusion.

B. Thin intercalation of garnet-biotite gneiss in banded biotite-hornblende gneiss at Menipa.

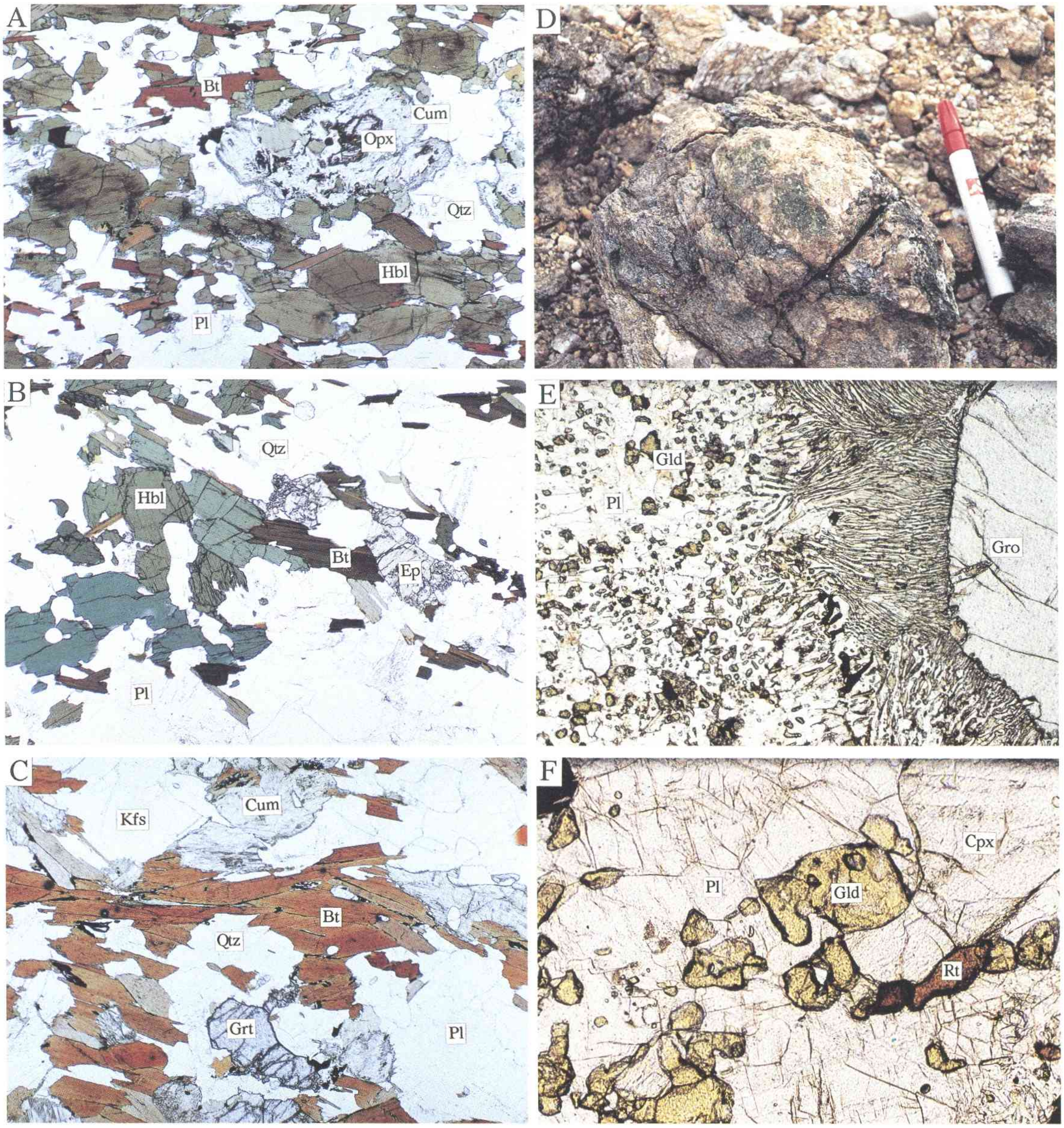
C. Close up of mylonite band in the biotite-hornblende gneiss in Austkampane. Note the plagioclase porphyroclast with asymmetrical pressure shadow of right-lateral strike slip sense.

D. Banded orthopyroxene-bearing amphibolite in Brattnipene.

E. Calc-silicate rock layer in Amphibolite in Menipa. Note that the reddish part is rich in garnet.

F. Metatonalite associated with dark green amphibole schist in Walnumfjellet, viewed from the eastern side of Jenningsbreen. Partly thin intercalation of biotite schist also occurs.

Plate 3



A. *Photomicrograph of orthopyroxene-bearing biotite-hornblende gneiss (O87012201D) from the NE terrane at Brattnipene. Note that orthopyroxene is replaced by cummingtonite. Opx: orthopyroxene, Hbl: hornblende, Bt: biotite, Pl: plagioclase, Qtz: quartz, Cum: cummingtonite. Open nicol. Width of field of view is 3.2 mm. Mineral abbreviations are common in all photographs.*

B. *Photomicrograph of epidote-bearing biotite-hornblende gneiss (A90012407A) from the SW terrane at the southern small nunatak of Mefjell. Ep: epidote. Open nicol. Width of field of view is 3.2 mm.*

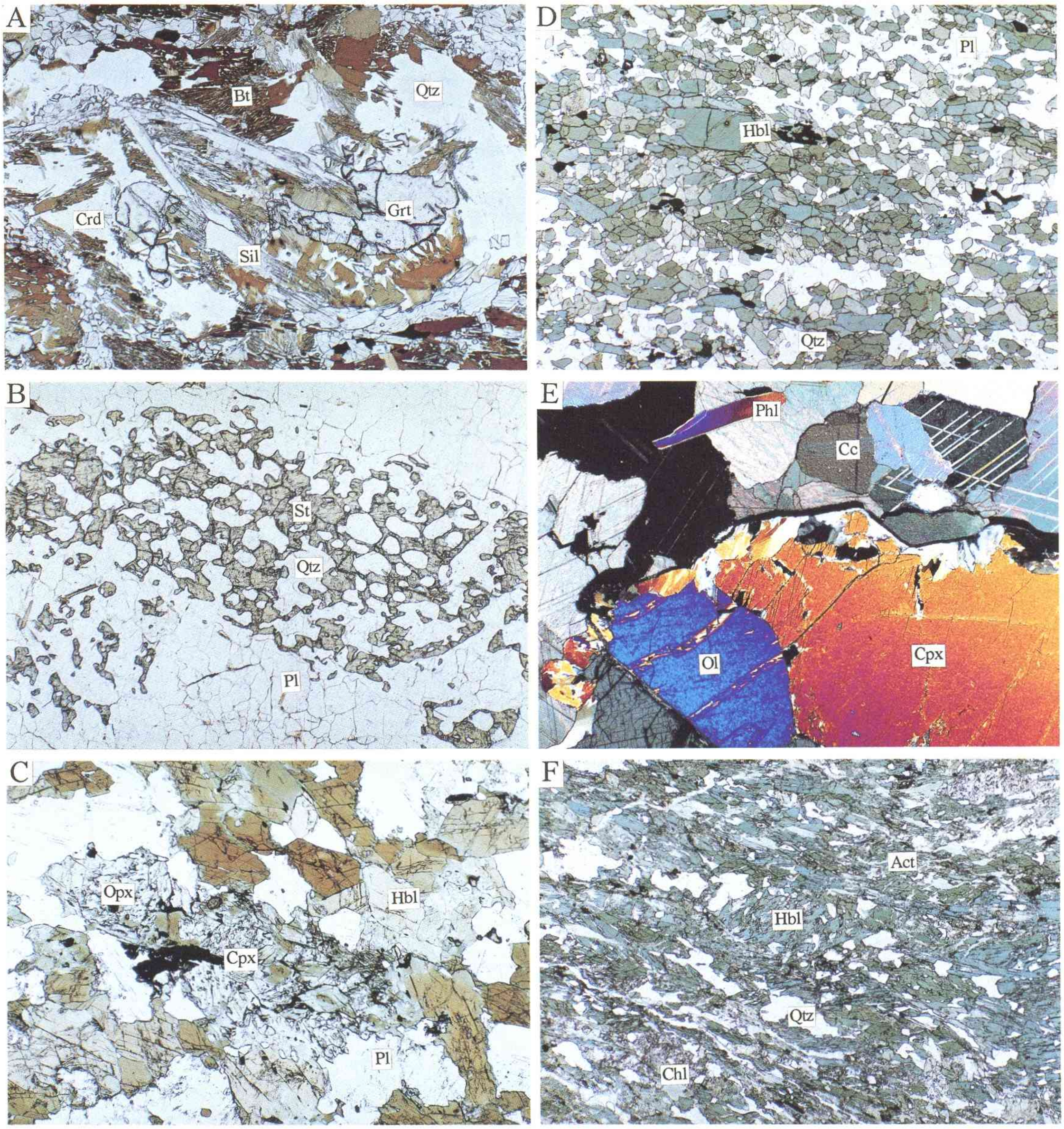
C. *Photomicrograph of cummingtonite-bearing garnet-biotite gneiss (A90012002E) in Menipa. Grt: garnet, Kfs: K-feldspar. Open nicol. Wideth of field of view is 3.2 mm.*

D. *Typical mode of occurrence of goldmanite-bearing calcareous metapelite layer in graphitic orthopyroxene-biotite gneiss in Menipa.*

E. *Photomicrograph of vanadian grossular with symplectic intergrowth (kelyphite rim) of goldmanite, plagioclase and vanadian clinopyroxene (A90012004). Gld: goldmanite, Gro: grossular. Open nicol. Width of field of view is 3.2 mm.*

F. *Photomicrograph of goldmanite in the outside of kelyphite rim (O90012004). Note that the color of garnet is more greenish than those in the kelyphite rim. Cpx: clinopyroxene, Rt: rutile. Open nicol. Width of field of view is 1.2 mm.*

Plate 4



A. *Photomicrograph of garnet-cordierite-sillimanite-biotite gneiss in Austkampane (O87012701A). Note corundum in sillimanite. Crd: cordierite, Sil: sillimanite. Open nicol. Width of field of view is 3.2 mm.*

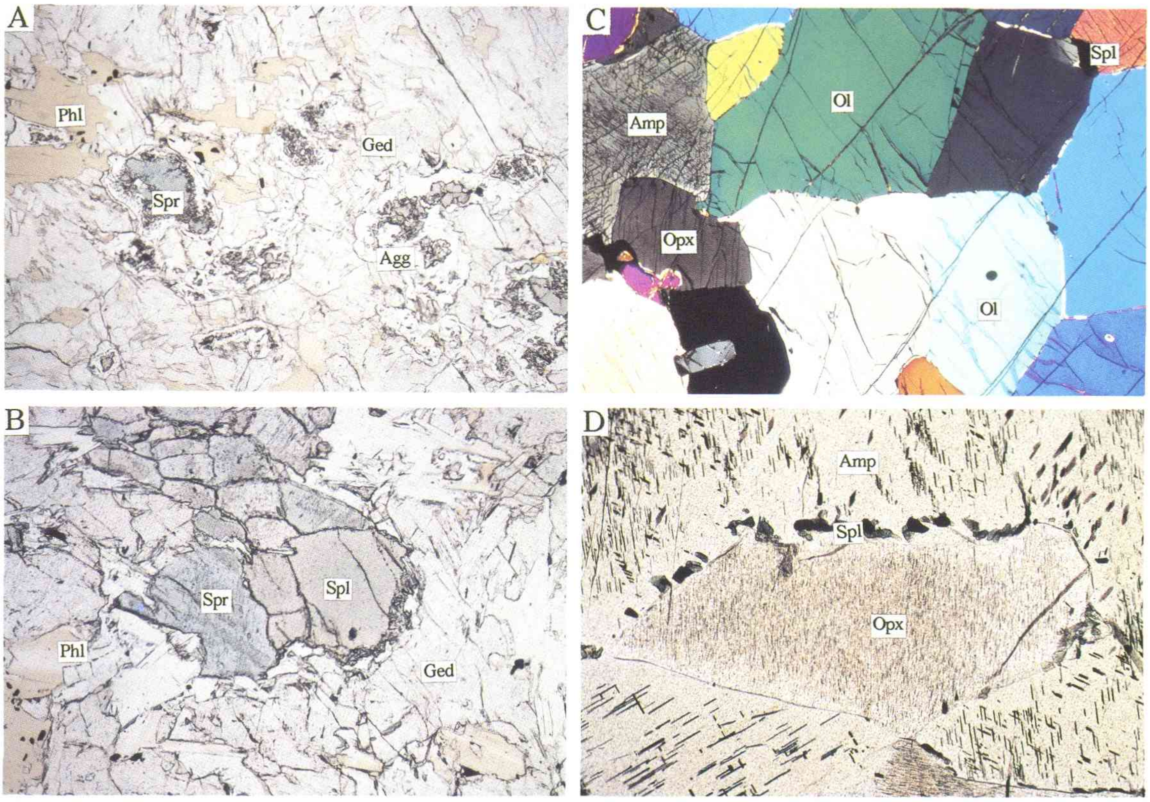
B. *Photomicrograph of staurolite-bearing garnet-biotite gneiss (A90012405F) at southern nunatak of Mefjell. St: staurolite. Open nicol. Width of field of view is 3.2 mm.*

C. *Photomicrograph of two pyroxene- and garnet-bearing amphibolite from NE terrane in Brattnipene (O87011306B). Open nicol. Width of field of view is 3.2 mm.*

D. *Photomicrograph of fine-grained amphibolite from SW terrane in Mefjell (A90012405G). Open nicol. Width of field of view is 3.2 mm.*

E. *Photomicrograph of calc-silicate rock (A90011905C-1) in Menipa. Phl: phlogopite, Cc: calcite, Ol: olivine. Cross nicol. Width of field of view is 3.2 mm.*

F. *Photomicrograph of amphibole schist (O87012107) in Walnumfjellet. Act: actinolite, Chl: chlorite. Open nicol. Width of field of view is 3.2 mm.*



A. *Photomicrograph of sapphirine-bearing granulite (B86010903C) in Austkampane. Leucocratic aggregates part (Agg) composed of sapphirine+plagioclase+cordierite±spinel±corundum. Spr: sapphirine, Ged: gedrite. Open nicol. Width of field of view is 3.2 mm.*

B. *Photomicrograph of sapphirine-bearing granulite (B86010903C) in Austkampane. Spl: spinel. Open nicol. Width of field of view is 1.6 mm.*

C. *Photomicrograph of meta-ultramafic rock (B86010905) in Austlampane. Amp: amphibole. Cross nicol. Width of field of view is 3.2 mm.*

D. *Photomicrograph of meta-ultramafic rock (B86010905) in Austlampane. Vermicules of spinel occurring along the margin of amphibole. Note that the lamellae of ilmenite develop within amphibole. Open nicol. Width of field of view is 1.6 mm.*

Plate 6

A. *Close up of Mefjell granite at northern Mefjell.*

B. *Lunckeryggen syenite at northern Lunckeryggen. Note that dark part is layered syenite and leucocratic part is quartz syenite intrusion.*

C. *Lunckeryggen granite (right side) intruded into metatonalite (left side) in southern Lunckeryggen, viewed from helicopter above Gjelbreen.*

A. Dufek granite, viewed from Gjelbreen. Note dark colored metamorphic rock blocks and dolerite dykes.

B. Close up of Dufek granite at southern Dufek. Note the granite intrude into host metamorphic rocks with forming layered type migmatitic rock.

C. Close up of dolerite dyke at northern Dufek. Arrow at upper right points toward top of photograph.

D. Photomicrograph of biotite granite in Mefjell (A90012401C). Open nicol. Width of field of view is 3.2 mm.

E. Photomicrograph of biotite granite in Dufek (A90011207). Open nicol. Width of field of view is 3.2 mm.

F. Boundary between leyerd syenite (left dark part) and qrartz syenite (right leucocratic part) in Lunckeryggen (O87011205). Note amazonite in quartz syenite. Width of the slab is 20 cm.

Antarctic Geological Map Series

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