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GEOLOGY OF THE EASTERN SØR RONDANE MOUNTAINS, EAST ANTARCTICA

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Abstract: The eastern Sør Rondane Mountains (71°40′–72°20′S; 26°30′–28°E), which was surveyed by the summer field party of JARE-29 in early 1988, is underlain by a high-grade migmatized gneissic complex consisting largely of metasedimentary and metavolcanic rocks, and subordinate metaigneous rocks and unmetamorphosed diorite and granite-pegmatite intrusions. Upper amphibolite to hornblende granulite-facies metamorphism was followed by an amphibolite-facies event, which is closely related with the migmatization. This sequence is indicated by the widespread occurrence of primary orthopyroxene- and sillimanite-bearing mineral assemblages, and secondary cummingtonite and green hornblende replacing pyroxenes and secondary biotite replacing garnet. Metadikes of biotitic schist, typically hornblende-biotite-plagioclase-quartz, which cut the gneisses, are considered to have been intruded between the two metamorphic events. A late, greenschist-facies event is suggested by the alteration of high-temperature mafic minerals to calcite, chlorite, epidote, muscovite and margarite. Earlier, recumbent isoclinal folds, and later upright more open folds could correspond to the early high-grade metamorphism and the amphibolite-facies event, respectively. Fault zones with displacements of several meters to 10 m or more are abundant and could also be related to the amphibolite facies event.

1. Introduction

Since the twenty-fifth Japanese Antarctic Research Expedition (JARE-25) in 1984, geological field work in the Sør Rondane Mountains, East Queen Maud Land, had been carried out by Japanese geologists every summer through JARE-28 (1987). They had extensively surveyed the western and central Sør Rondane Mountains (Fig. 1), and had characterized the geological and petrographic features of the metamorphic and plutonic rocks (KOJIMA and SHIRAISHI, 1986; ISHIZUKA and KOJIMA, 1987; SHIRAISHI and KOJIMA, 1987; ASAMI and SHIRAISHI, 1987; SAKIYAMA *et al.*, 1988; SHIRAISHI *et al.*, in press). Prior to these studies, Belgian geologists made reconnaissance surveys over a wide area of the mountains, including the northern nunataks in the eastern Sør Rondane Mountains, and reported their geological and geochronological results (VAN AUTENBOER *et al.*, 1964; PICCIOTTO *et al.*, 1964; VAN AUTENBOER, 1969; PASTEELS and MICHOT, 1970; VAN AUTENBOER and LOY, 1972). Soviet geologists also surveyed part of the Sør Rondane Mountains (*e.g.*, RAVICH and

KAMENEV, 1972). However, a substantial portion of the eastern Sør Rondane Mountains had not been geologically surveyed before 1987.

We, members of JARE-29, performed a geological survey in the eastern Sør Rondane Mountains during January, 1988 (ASAMI *et al.*, 1988; GREW *et al.*, 1988). However, we were not able to visit some nunataks of Trillingane and Isklakken and nunataks south of Eremitten (Fig. 1), because of a limited time to stay in the mountains. The present paper describes the geology of the surveyed area. A detailed petrological study of metamorphic rocks is given in another paper (GREW *et al.*, 1989).

2. Outline of Geology

The eastern Sør Rondane Mountains (71°40′–72°20′S, 26°30′–28°E), which lies east of Byrdbreen, includes a large exposure, Balchenfjella, and numerous nunataks (Fig. 1). Balchenfjella consists of two portions, a northern one situated west of Isklakken and a southern one southwest of Isklakken, which are connected with each other by a neck. In this paper, these portions are provisionally called northern Balchenfjella and southern Balchenfjella, respectively.

The generalized geological map of the surveyed area is illustrated in Fig. 1. The exposures examined in this area are composed of high-grade gneissic rocks accompanied by migmatite and small bodies of intrusive rocks. The intrusive rocks are mostly granite and pegmatite occurring as dikes and veins; a diorite intrusive constitutes a small nunatak. Granite also occurs as neosomes in migmatite. The absence of large intrusive masses is characteristic of the eastern Sør Rondane and contrasts with the western and central Sør Rondane Mountains where large masses of acid to intermediate plutonic rocks have been mapped (VAN AUTENBOER, 1969; KOJIMA and SHIRAISHI, 1986; ISHIZUKA and KOJIMA, 1987; SHIRAISHI and KOJIMA, 1987; SAKIYAMA *et al.*, 1988). Geological structure of the metamorphic rocks is complex due to the combined effects of folding and migmatization.

Rb-Sr biotite ages of 447 Ma and 450 Ma were obtained on amphibole-biotite gneiss and leucocratic pegmatite, respectively, from Trillingane nunataks, suggesting a late Ordovician age for plutonic activity (VAN AUTENBOER, 1969).

The rocks of the eastern Sør Rondane Mountains can be classified into the following types on the basis of the mode of occurrence, lithology and mineral assemblages.

A. Metamorphic rocks

A-1. Rocks of presumed sedimentary and volcanogenic origin

(1) Biotite-hornblende gneiss
(2) Hornblende gneiss
(3) Garnet-biotite gneiss and biotite gneiss
(4) Charnockitic gneiss
(5) Marble and calc-silicate rock
(6) Manganese quartzite
(7) Iron-rich mafic granulite

A-2. Rocks of presumed magmatic origin

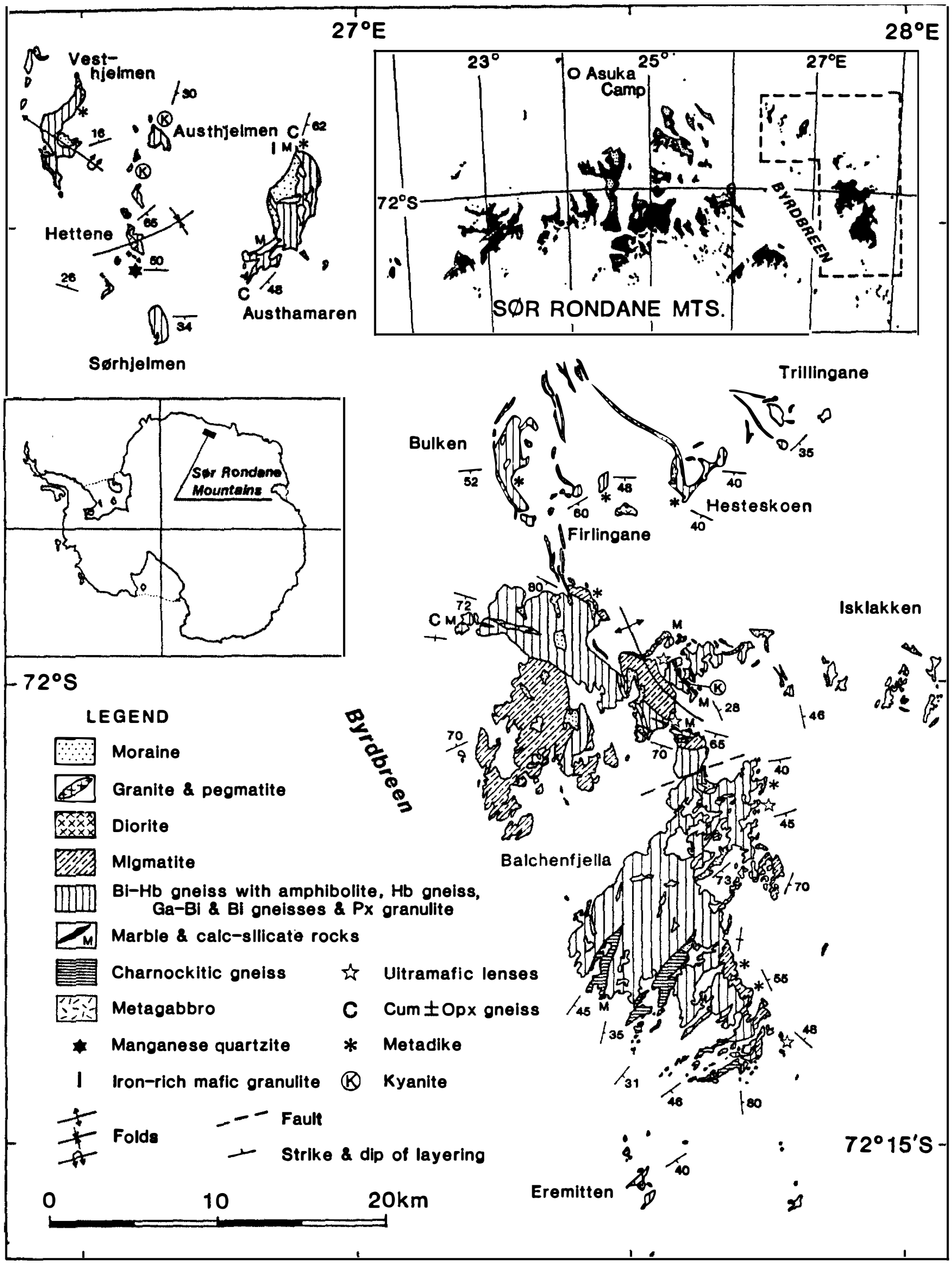

Fig. 1. Geological map of the eastern Sør Rondane Mountains including representative trends of compositional layering, major folds, and a possible major fault (dashed line).

(1) Ultramafic rocks
(2) Amphibolite and pyroxene granulite (=metabasite)
(3) Metagabbro
(4) Cummingtonite±orthopyroxene gneiss
(5) Metadike rocks

A-3. Migmatite

B. Unmetamorphosed plutonic rocks

(1) Diorite

(2) Granite and pegmatite

3. Metamorphic Rocks

The metamorphic rocks consist largely of biotite-hornblende gneiss and subordinate amphibolite, hornblende gneiss, garnet-biotite gneiss and biotite gneiss. These rocks are commonly migmatized by development of granitic neosomes, and intensively migmatized rocks are mapped as migmatite in Fig. 1. Charnockitic gneiss is restricted to the southern part of the area. Marble, calc-silicate rocks, manganese quartzite, iron-rich mafic granulite, ultramafic rocks, pyroxene granulite, metagabbro and cummingtonite$\pm$orthopyroxene gneiss are local. Metadike rocks are recognized at nine localities (Fig. 1).

Geological and petrographical characteristics suggest that seven types of metamorphic rocks are derived from sedimentary and volcanogenic precursors, while the remaining rocks have an igneous parentage. Mineral assemblages of rocks of A-1 and A-2 are given in Table 1. The reader is referred to GREW *et al.* (1989) for more detailed description of the rock types of particular petrologic interest.

3.1. Biotite-hornblende gneiss

The biotite-hornblende gneiss is the most abundant rock type. It is well-layered due to the alternation of biotite-hornblende-rich and quartzofeldspathic bands several millimeters to several centimeters thick (Plate 1A). Relative proportions of mafic and felsic minerals vary even within a band. This gneiss commonly alternates with amphibolite (Plate 1B) and hornblende gneiss and in places is accompanied by layers and lenses of garnet-biotite gneiss, calc-silicate rocks, marble and pyroxene granulite. Locally garnet is observable in the biotite-hornblende gneiss with the naked eye. At Austhamaren, garnetiferous biotite-hornblende gneiss is dominant.

3.2. Hornblende gneiss

The occurrence of the hornblende gneiss is as widespread as the amphibolite. This gneiss forms concordant hornblende-rich layers, several centimeters to several tens of centimeters thick, in the biotite-hornblende gneiss (Plate 1A). Unlike the amphibolite, the gneiss is well-layered with felsic bands. This gneiss is also associated with some calc-silicate rocks. Garnet and clinopyroxene are often visible in outcrops of the gneiss.

3.3. Garnet-biotite gneiss and biotite gneiss

These gneisses include pelitic, quartzofeldspathic and feldspathic rocks enriched in biotite, garnet, sillimanite and rarely corundum, hercynite, or gahnite. They occur in 0.5 to 3 m-thick layers intercalated in the biotite-hornblende gneiss (Plate 1C). Eight localities of sillimanite-garnet-biotite gneiss have been found. The sillimanite gneiss layers are best developed at the northeast end of southern Balchenfjella. Kyanite has been found in two sillimanite-garnet-biotite gneisses occurring around Austhjelmen and in a biotite-plagioclase-garnet schist from the eastern part of northern Balchenfjella (Fig. 1).

3.4. Charnockitic gneiss

The term charnockitic gneiss refers to a quartzofeldspathic rock containing orthopyroxene, which is to a variable extent replaced by cummingtonite. A dark-gray color on the broken rock surface is characteristic. This rock is commonly well-layered due to the alternation of felsic bands and more mafic bands (Plate 2A), but in places is poorly foliated. This gneiss occurs largely in the southern part of southern Balchenfjella, and is also found at Eremitten and a small nunatak northeast of Eremitten. We did not succeed in locating a distinct contact between the biotite-hornblende gneiss and the charnockitic gneiss; we infer this contact to be diffuse with mixing of the two rock types. Small lenses of two-pyroxene amphibolite are common in the charnockitic gneiss. Garnet is rarer in these lenses than in amphibolite from the northern part of the eastern Sør Rondane Mountains.

3.5. Marble and calc-silicate rocks

Marbles, which include calcitic and dolomitic varieties, occur mostly as concordant or subconcordant layers and lenses up to several tens of meters across in the biotite-hornblende gneiss (Plate 2B). At the north end of Austhamaren, a calcite marble layer is intercalated with iron-rich mafic granulite.

The calc-silicate rocks form small pods enclosed in the marble (Plate 2A), bands between the marble and adjacent gneisses, and layers and lenses up to a few meters across intercalated in the biotite-hornblende gneiss and amphibolite. Wollastonite was found in a calc-silicate layer at Eremitten and in calc-silicate lenses associated with calcite marble and iron-rich mafic granulite at the north end of Austhamaren.

3.6. Manganese quartzite

The quartzite was found at Hettene (Fig. 1). This rock occurs as a 0.5 m-thick layer in a rusty-weathering quartzitic unit several meters thick associated with quartzofeldspathic biotite-hornblende gneiss, garnet-biotite gneiss, graphite-rich quartzite and amphibolite (Fig. 1). The quartzite includes pigeonite-bearing cherty pods (GREW *et al.*, 1989).

3.7. Iron-rich mafic granulite

The iron-rich mafic granulite is a black, compact rock rich in garnet, fayalite, clinopyroxene and hornblende; orthopyroxene is minor. The rock occurs as a conformable layer fifteen meters thick in the garnetiferous biotite-hornblende gneiss at the north end of Austhamaren.

3.8. Ultramafic rocks

Ultramafics occur in lenses up to several meters across at four localities (Fig. 1), for example, in the migmatite in southern Balchenfjella (Plate 3A). These lenses include rocks rich in cummingtonite and calcic clinoamphibole; other lenses occur in the biotite-hornblende gneiss and include olivine-rich rocks. Between these lenses and the host rocks, reaction zones of micas and amphiboles are developed.

3.9. *Amphibolite and pyroxene granulite*

The amphibolite commonly occurs as dark-colored layers and lenses up to a few tens of meters across which are concordant or subconcordant with layers of the biotite-hornblende gneiss, hornblende gneiss, garnet-biotite gneiss, biotite gneiss and charnockitic gneiss. Some amphibolite lenses are associated with the calc-silicate rocks and manganese quartzite. The amphibolite is not as well-banded as the other gneisses and in places is massive. Garnet, clinopyroxene and orthopyroxene commonly appear in the amphibolite. A distinctive variety is the garnet amphibolite lens 4 by 10 m at Vesthjelmen (Plate 1B).

The pyroxene granulite is typically developed in a northwest-trending, marble-bearing belt, which is about 1 km wide and extends at least 4 km along strike from the north end of southern Balchenfjella into northern Balchenfjella. This rock is characteristically poorly foliated and dark-colored due to a dark gray color of plagioclase in addition to abundant mafic minerals such as garnet, clinopyroxene and orthopyroxene.

Pyroxene-bearing varieties of the amphibolite, together with pyroxene granulite and metagabbro, are grouped into mafic granulite in the petrology paper (GREW *et al.*, 1989).

3.10. *Metagabbro*

Metagabbro forms a lenticular body of resistant orthogneiss nearly one kilometer long within the migmatite belt near the end of southern Balchenfjella (Plate 2C). It appears black from a distance, while close up, it is poorly foliated and dark-colored like the pyroxene granulite and charnockitic gneiss. Lath-shaped plagioclase crystals are occasionally observed on the weathered surface.

3.11. *Cummingtonite±orthopyroxene gneiss*

This gneiss is characterized by cummingtonite knots developed in the plagioclase-rich matrix. The gneiss crops out at the north and south ends of Austhamaren and at the northwest corner of northern Balchenfjella. The rock from northern Balchenfjella occurs as a concordant layer several meters thick in the biotite-hornblende gneiss. In places, garnet is sporadically observed in this rock.

The cummingtonite gneiss from the north end of Austhamaren contains a distinctive orthopyroxene having textures suggestive of inverted pigeonite. This gneiss, together with the older metadike rock mentioned below, is interpreted to be part of a pre-metamorphic plutonic complex intrusive into marble-bearing metasediments (GREW *et al.*, 1989).

3.12. *Metadike rocks*

The metadike rocks are clearly discordant with the country metamorphic rocks. Two types of the metadike rocks are distinguished; garnetiferous amphibolite and biotitic schist. These two were emplaced during different stages.

The older metadikes are biotitic garnetiferous amphibolite found at Austhamaren and Hesteskoen (Fig. 1). The rock is locally broken into lenses (Plate 4A) and is recrystallized as completely as the surrounding gneisses. Metamorphic minerals include clinopyroxene at both localities and orthopyroxene at Austhamaren, indicating that the dikes have been deformed and metamorphosed in the granulite facies.

The younger metadikes are biotitic schist found at seven localities (Fig. 1). The dikes crosscut typical gneissic rocks such as the biotite-hornblende gneiss and amphibolite. In general, the crosscutting relationship of the dikes has not been destroyed by later deformation (Plate 4B). At one locality in the southeastern part of southern Balchenfjella, the biotitic metadike is undeformed and forms a planar body 1.5 to 2 m thick typical of dikes (trends N85°E, dips 35°S). At other localities, the metadikes are to varying degrees folded and even pinched out and broken. Moreover, metamorphic recrystallization has resulted in a biotite schistosity that is parallel or subparallel to the contacts of the metadikes. With few exceptions this schistosity has obliterated original igneous textures, although coarse grains in a few sections appear to be relict porphyritic plagioclase. Mafic minerals include hornblende, biotite, sphene, and in one section clinopyroxene. These characteristics of the younger dikes suggest that the surrounding gneiss as well as the dike rock were affected by amphibolite-facies metamorphism with deformation. Some of the younger metadikes are intruded by pink pegmatite. The younger biotitic metadike rocks appear to differ in petrographic character from the metadolerites in the western-central Sør Rondane Mountains (KOJIMA and SHIRAISHI, 1986; SHIRAISHI *et al.*, 1988).

3.13. Migmatite

Migmatites are widespread in Balchenfjella except the southern part. Agmatic, schollen, stromatic, folded, schlieren and nebulitic structures are characteristic (*e.g.*, Plates 3A, B and C). Paleosomes of the migmatite consist mainly of the biotite-hornblende gneiss, amphibolite, and hornblende gneiss commonly with clinopyroxene; ultramafic and garnet-biotite gneiss paleosomes are rare. Neosomes of the migmatite range from leucocratic granite to granodiorite containing biotite, hornblende and locally clinopyroxene. These are commonly foliated due to parallel or subparallel orientation of the mafic minerals. The foliated neosomes cut the neighboring country gneisses in some places (Plate 3B).

4. Plutonic Rocks

4.1. Diorite

The diorite constitutes the easternmost nunatak of Firlingane, which appears black from a distance in contrast to nunataks composed of the metamorphic rocks (Plate 4C). The rock is dark-gray, medium- to coarse-grained and massive. The constituent minerals are, in decreasing abundance, plagioclase, biotite, hornblende, clinopyroxene and minor quartz, as well as accessory sphene, apatite, zircon, allanite and ore minerals. A trace amount of K-feldspar is locally present. Chlorite and epidote are common alteration products of biotite and plagioclase, respectively. Clinopyroxene is usually rimmed by green hornblende and paler green amphibole, possibly actinolite. Subophitic texture is observed in some samples.

The diorite contains xenoliths of quartzofeldsapthic biotite-hornblende gneiss. Both rocks are cut by dikes of pink granite (Plate 4C).

4.2. *Granite and pegmatite*

Dikes and veins of granite and pegmatite are ubiquitous in the metamorphic rocks. These rocks are leucocratic, and usually massive but locally feebly gneissic. At least two stages of the granitic dikes and veins are recognizable: an earlier stage of white to light gray granite-pegmatite and a later stage of pink granite-pegmatite. The neosomes of the migmatite, together with the paleosomes, are cut by both stages of dikes and veins.

5. Metamorphism

Mineral assemblages observed in the metamorphic rocks except the migmatite are listed in Table 1. This list is intended to serve as a summary of the mineralogy of the rocks examined in thin section. Minerals occurring together in a given section are included in the assemblage (obviously secondary or relict phases are distinguished), but in some cases, not all these minerals crystallized in equilibrium during a single metamorphic event (GREW *et al.*, 1989).

The orthopyroxene- and garnet-clinopyroxene-bearing mineral assemblages are found over the entire area except for the Vesthjelmen-Austhjelmen-Sørhjelmen portion. The assemblage sillimanite-garnet-biotite-K-feldspar-plagioclase-quartz is characteristic of the entire area, but sillimanite at Austhjelmen is mostly fibrolite (see GREW *et al.*, 1989). Thus the metamorphic grade ranged from the upper amphibolite- to hornblende-granulite-facies of regional metamorphism. Kyanite from the two localities at Austhjelmen is found as inclusions in plagioclase in the gneiss of assemblage C4 in Table 1, and kyanite from northern Balchenfjella as inclusions in garnet in the rock of assemblage C8. These kyanites are considered to be prograde kyanite relics in contrast to the retrograde kyanite reported by ASAMI and SHIRAISHI (1987) from the western Sør Rondane Mountains (GREW *et al.*, 1989). The estimated peak conditions of 700–750°C and 7 kb (GREW *et al.*, 1989) imply that the upper amphibolite to hornblende granulite-facies metamorphism in this area is probably of the medium pressure type as is the case in the western and central Sør Rondane Mountains (ASAMI and SHIRAISHI, 1987; SHIRAISHI *et al.*, in press).

Orthopyroxene and clinopyroxene in the metabasites and charnockitic gneiss are often partially replaced by cummingtonite and green hornblende or paler green amphibole. Garnet is often embayed by biotite-plagioclase aggregates in the garnet-biotite gneiss and by hornblende-plagioclase aggregates in amphibolites and hornblende gneisses. The replacement is more extensive in the more intensively migmatized areas, so that these primary minerals, particularly orthopyroxene, are rare in the migmatized areas. Thus, the upper amphibolite- to hornblende granulite-facies metamorphism is considered to have been followed by an amphibolite-facies metamorphism that is closely related with migmatization.

Furthermore, high-temperature minerals, including amphiboles and biotite, listed in Table 1 are partially altered to low-temperature minerals such as calcite, chlorite, epidote, muscovite, and locally margarite and prehnite. These minerals suggest a late regressive stage in the greenschist facies.

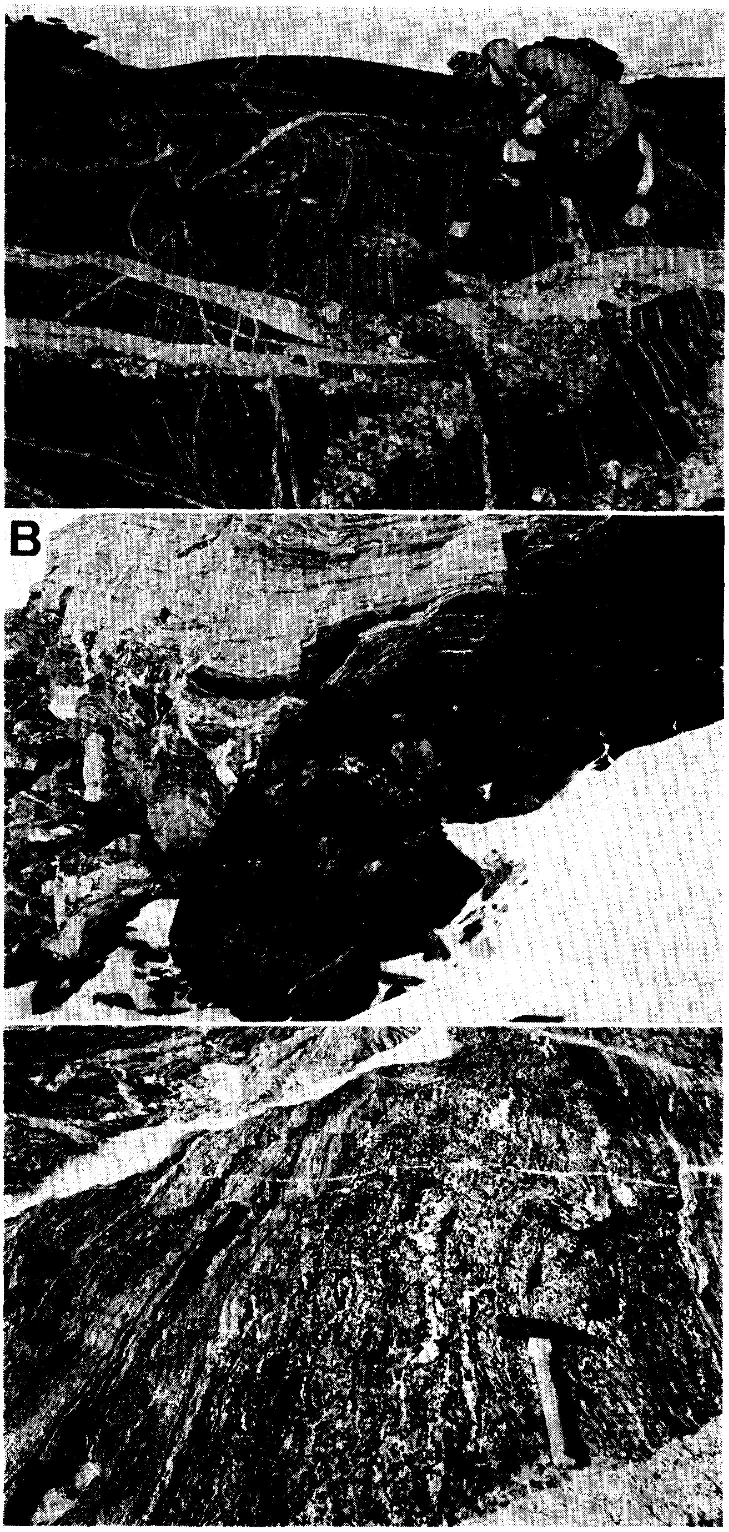

Plate 1. *A: Well-layered biotite-hornblende gneiss and hornblende gneiss, northern Balchenfjella. The gneisses are cut by dikes and veins of granite.*
B: Garnetiferous amphibolite lens in biotite-hornblende gneiss, Vesthjelmen.
C: Sillimanite-garnet-biotite gneiss layer in biotite-hornblende gneiss, northeast end of southern Balchenfjella.

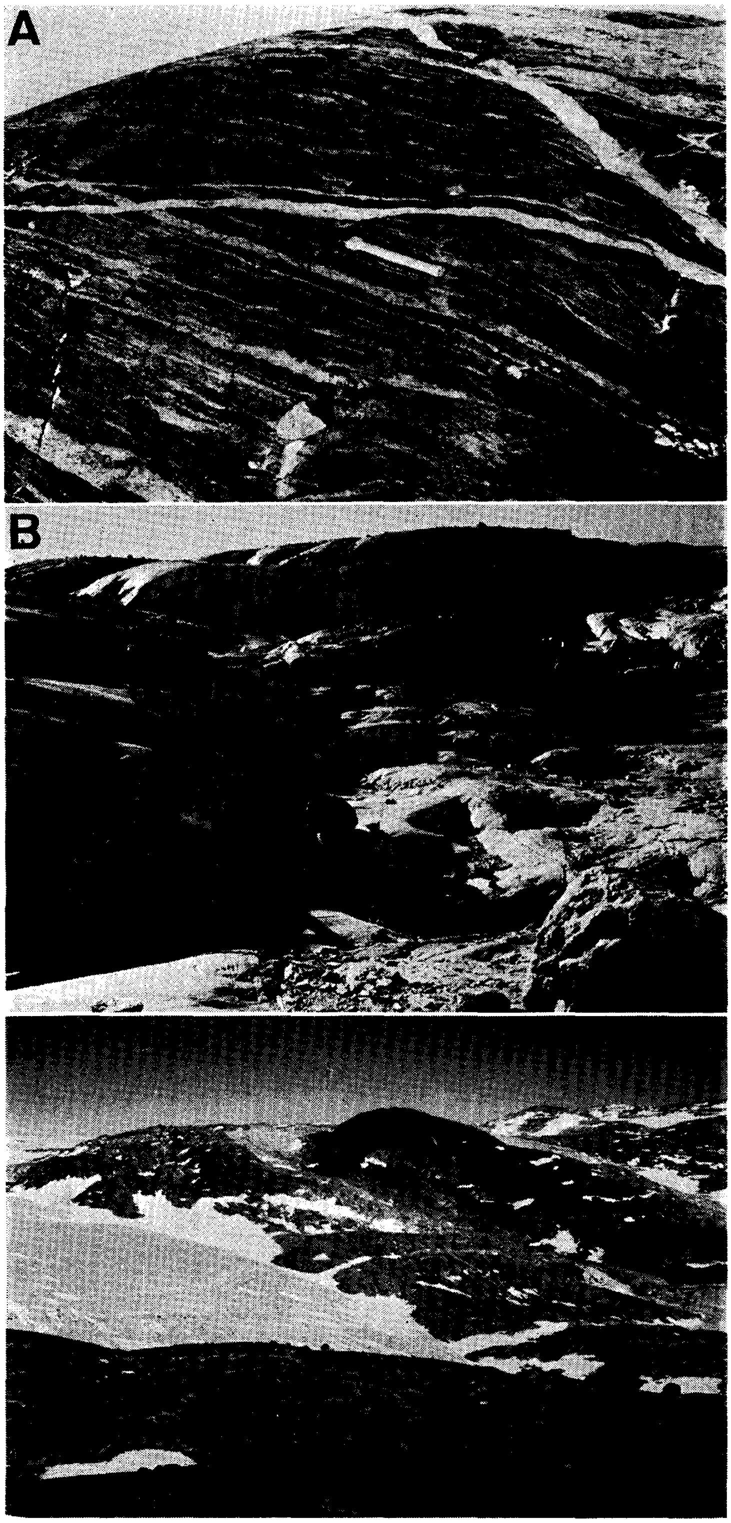

Plate 2. A: Layered charnockitic gneiss, southern part of southern Balchenfjella.
B: Dolomitic marble layer with calc-silicate pods, southeastern part of northern Balchenfjella.
C: Metagabbro lens (black knob) enclosed in a migmatite belt, north end of southern Balchenfjella. View from the north.

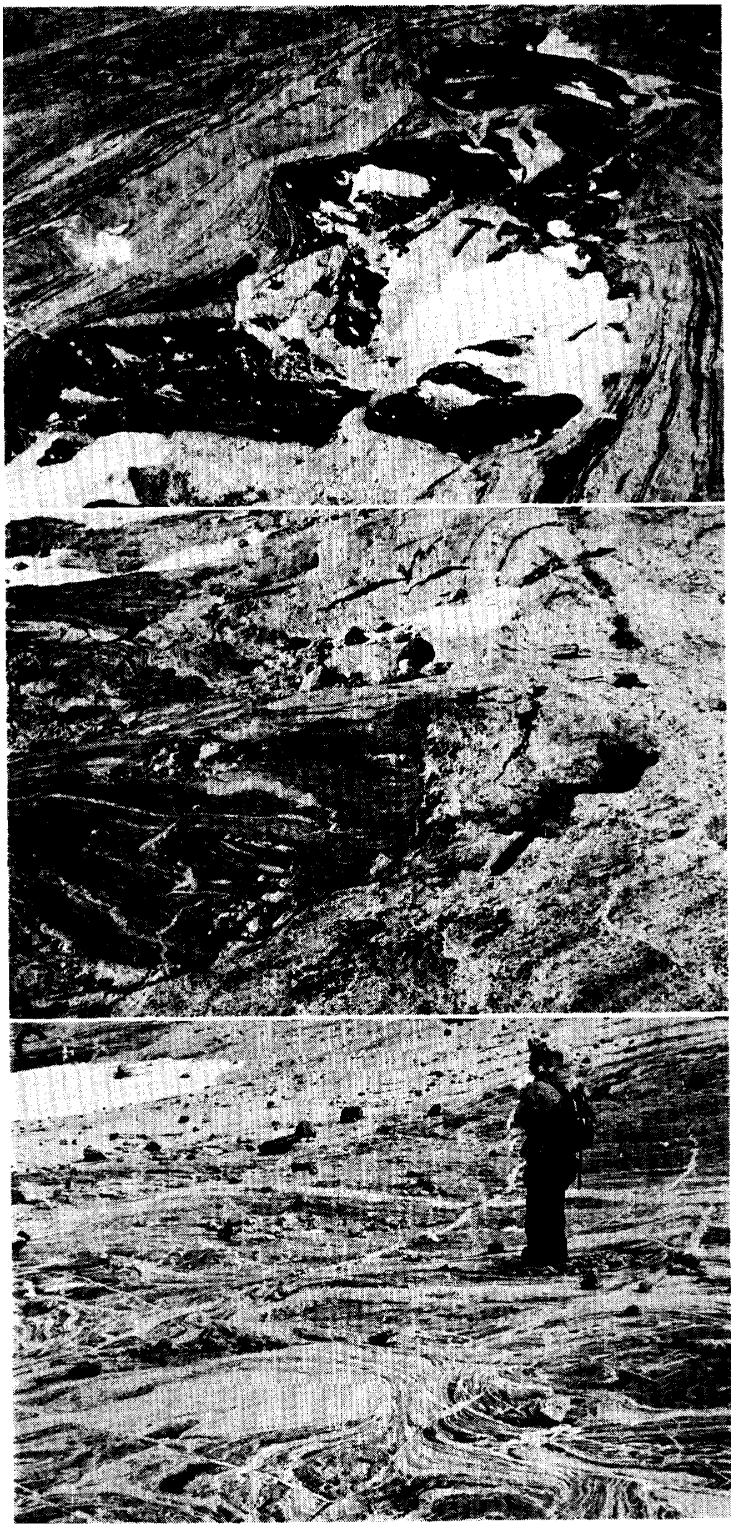

*Plate 3. A: Ultramafic lens in stromatic migmatite, southeastern part of southern Balchenfjella.
B: Discordant relation between nebulitic migmatite and adjacent gneisses, north end of southern Balchenfjella.
C: Migmatite with stromatic and folded structures, southeastern part of northern Balchenfjella.*

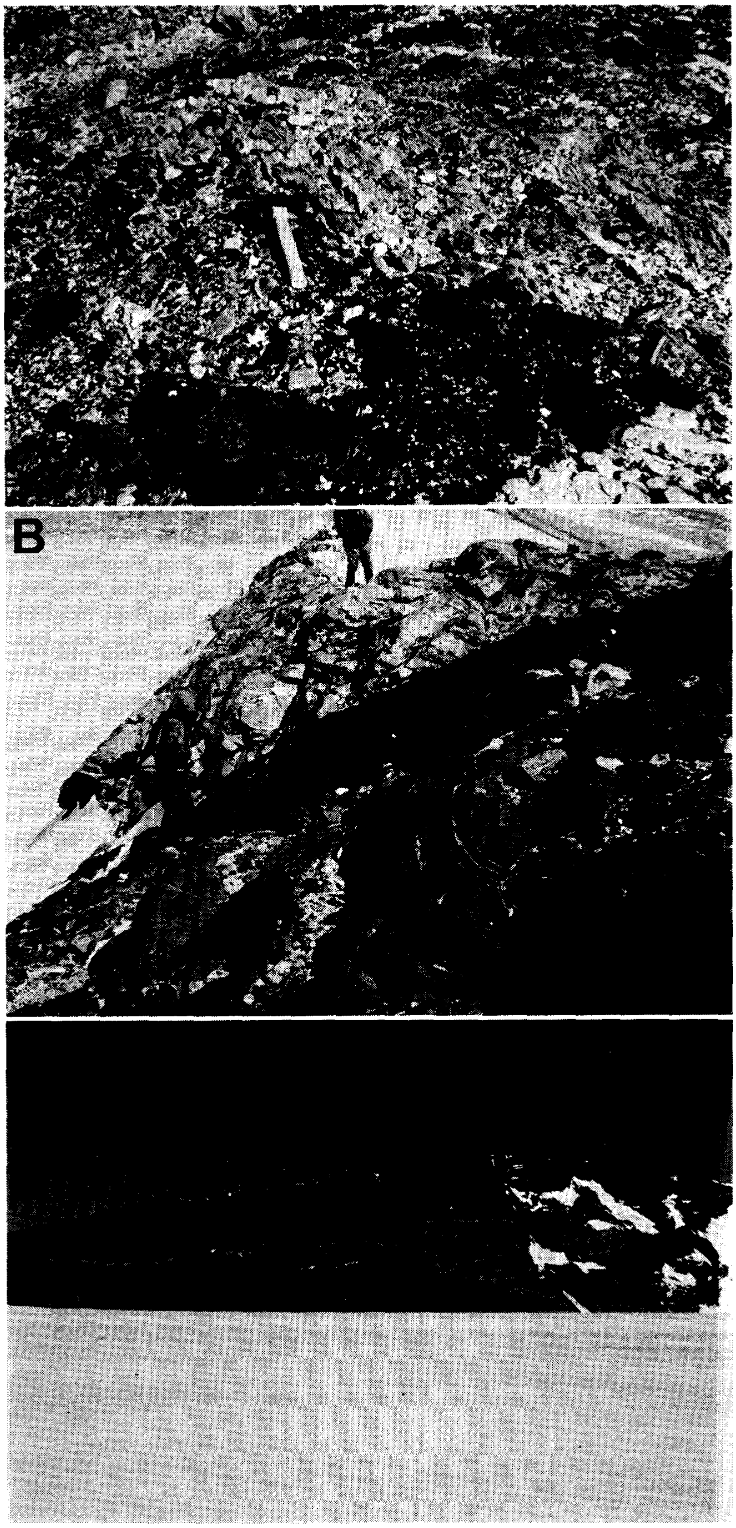

Plate 4. A: Metadike of garnetiferous amphibolite broken into lenses, Hesteskoen. Layering of surrounding biotite-hornblende gneiss trends nearly parallel to the direction of the hammer handle.
B: Metadike of biotitic schist crosscutting biotite-hornblende gneiss and amphibolite, Vesthjelmen.
C: Diorite enclosing quartzofeldspathic biotite-hornblende gneiss, Firlingane. Both rocks are intruded by pink granite dikes.

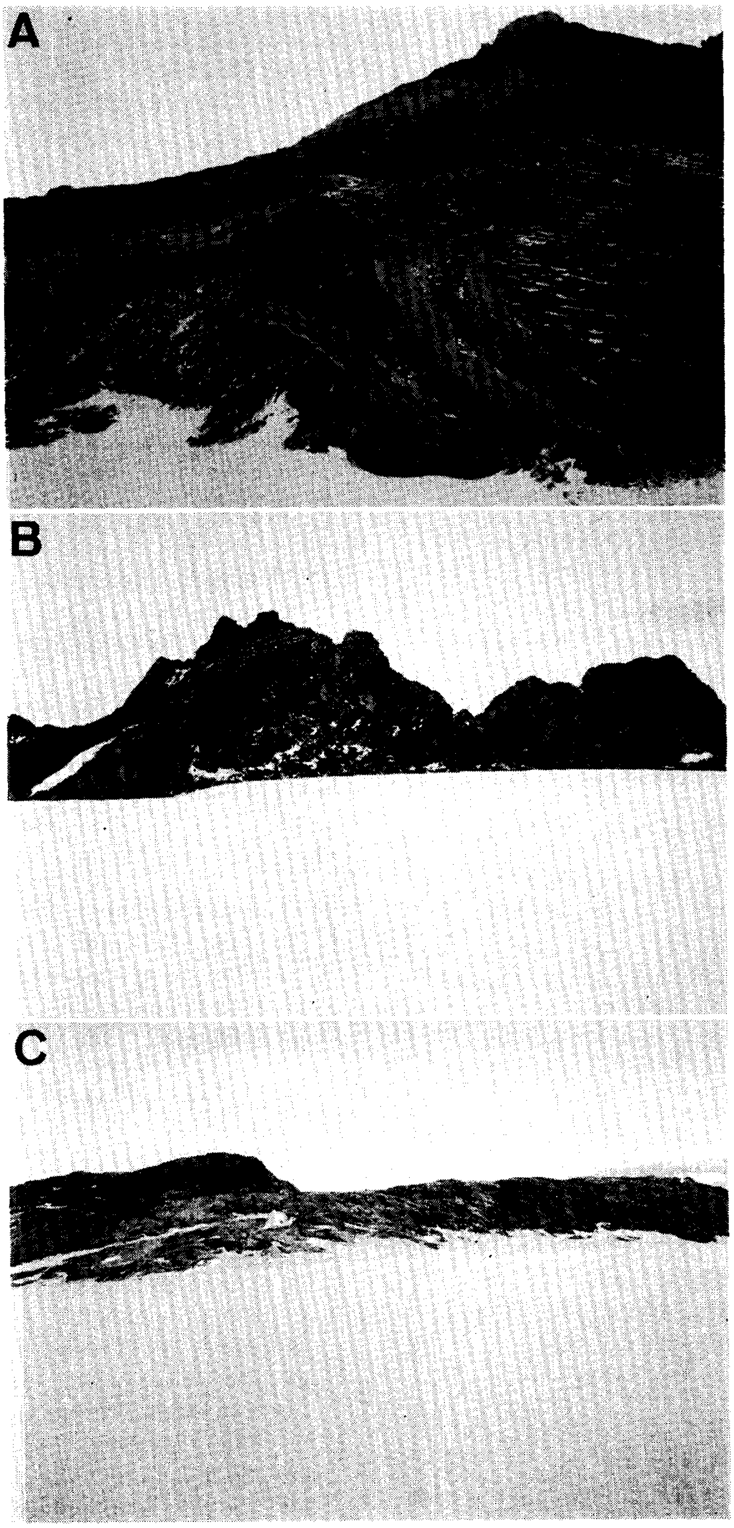

Plate 5. A: Recumbent isoclinal fold, Vesthjelmen. View from the east. Height of the cliff is about 100 m.
B: Axial part of a synform, Hettene. View from the southwest. Height of the cliff is about 50 m.
C: Open antiform in a migmatite belt, northern Balchenfjella. View from the southwest. Width of the exposure is about 500 m.

Table 1. Mineral assemblages of metamorphic rocks in the eastern Sør Rondane Mountains.

A. Biotite-hornblende gneiss
- A1. Hb+Bi+Pl+Qu±Kf
- A2. Cp+Hb+Bi+Pl+Qu [±Cum]
- A3. Cp+Hb+Bi+Pl+Kf+Qu
- A4. Ga+Hb+Bi+Pl+Qu [±Cum]
- A5. Ga+Hb+Bi+Pl+Kf+Qu
- A6. Ga+Cp+Hb+Bi+Pl+Qu [±Cum]
- A7. Ga+Cp+Hb+Bi+Pl+Kf+Qu
- A8. Ga+Op+Hb+Bi+Pl+Qu
- ⟨Ap, Zr, Opq; ±Aln, Sph⟩

B. Hornblende gneiss
- B1. Cp+Hb+Bi+Pl+Qu [Cum]
- B2. Op+Hb+Bi+Pl [Cum]
- B3. Op+Hb+Bi+Pl+Qu
- B4. Ga+Hb+Bi+Pl+Qu [Cum]
- B5. Ga+Hb+Bi+Pl+Kf+Qu
- B6. Ga+Cp+Hb+Bi+Pl+Qu
- B7. Ga+Cp+Hb+Bi+Pl+Kf+Qu
- ⟨Ap, Zr, Opq; ±Aln, Sph⟩

C. Garnet-biotite gneiss and biotite gneiss
- C1. Ga+Bi+Pl+Qu
- C2. Ga+Bi+Pl+Kf+Qu
- C3. Sil+Ga+Bi+Pl+Qu±Kf (Sp) [±Hög]
- C4. Sil+Ga+Bi+Pl+Kf+Qu(Ky)
- C5. Ghn+Ga+Bi+Pl+Qu+Sphl
- C6. Ga+Op+Bi+Pl+Qu [Cum]
- C7. Sp+Ga+Bi+Pl (Sil) [Hög, Mrg, Chl]
- C8. Sp+Crn+Ga+Bi+Pl (Ky, Gd, Qu)
- C9. Bi+Pl+Kf+Qu
- C10. Crn+Sp+Sil+Ga+Bi+Pl+Kf
- C11. Crn+Bi+Pl±Kf [Mrg]
- ⟨Ap, Zr, Opq; ±Ru, Mnz, Aln⟩

D. Charnockitic gneiss
- D1. Op+Bi+Pl+Kf+Qu
- D2. Op+Hb+Bi+Pl+Kf+Qu
- D3. Op+Cp+Hb+Bi+Pl+Kf+Qu
- D4. Cp+Hb+Bi+Pl+Kf+Qu
- D5. Op+Bi+Pl+Qu [Cum]
- ⟨Ap, Zr, Opq⟩

E. Marble and calc-silicate rocks

a. Marble
- E1. Sp+Fo+Phl+Cc+Do [±Chu, Chl, Aln]
- E2. Sp+Fo+Phl+Cc+Do [Chu, Tr; ±Chl]
- E3. Sp+Fo+Cp+Tr+Phl+Cc+Do
- E4. Cp+Prg+Phl+Cc
- ⟨Ap, Opq; ±Ru⟩

b. Calc-silicate rocks
- E5. Ga+Cp+Hb+Sc+Cc+Qu+Sph [Ep]
- E6. Ga+Cp+Sc+Cc+Qu+Sph+Aln [Ep]
- E7. Cp+Hb+Bi+Sc+Cc+Kf+Fl+Sph+Aln [Ep, Mu, Chl]
- E8. Cp+Hb+Sc+Cc+Kf+Qu+Sph [Ep]
- E9. Cp+Tr+Pl+Sc+Cc+Fl [Ep, Prh, Mu]
- E10. Sc+Cc+Pl+Kf+Qu+Sph [Ep]
- E11. Wo+Ga+Cp+Cc+Qu+Sph
- E12. Wo+Cp+Sc+Cc+Pl+Qu+Sph [Ga]
- ⟨±Zr, Ap, Opq⟩

F. Manganese quartzite
- F1. Ga+Bi+Pl+Qu
- F2. Ga+Pgt+Cp+Pxm+Qu [Tir]
- F3. Ga+Ac+Bi+Qu [Do, Chl]
- ⟨Ap, Opq; ±Zr, Sph, Aln⟩

G. Iron-rich mafic granulite
- G1. Ga+Fa+Op+Cp+Hb+Bi+Pl+Kf
- G2. Ga+Fa+Cp+Hb+Bi+Pl+Kf
- ⟨Ap, Zr, Aln, Opq⟩

H. Ultramafic rocks
- H1. Op+Cum+Bi
- H2. Op+Cum+Hb+Bi
- H3. Fo+Op+Bi
- H4. Fo+Op+Cum+Anth+Hb+Bi
- H5. Cp+Hb+Bi
- ⟨Ap, Opq; ±Zr, Aln⟩

I. Amphibolite
- I1. Hb+Bi+Pl±Qu
- I2. Cp+Hb+Bi+Pl
- I3. Cp+Hb+Pl
- I4. Cp+Hb+Pl+Kf+Qu
- I5. Op+Hb+Bi+Pl [±Cum]
- I6. Op+Cp+Hb+Bi+Pl [±Cum]
- I7. Ga+Hb+Bi+Pl [±Cum]
- I8. Ga+Hb+Bi+Pl+Qu
- I9. Ga+Cp+Hb+Pl+Qu
- I10. Ga+Cp+Hb+Bi+Pl [±Cum]
- I11. Ga+Cp+Hb+Bi+Pl+Kf
- I12. Ga+Cp+Hb+Bi+Pl±Qu±Cum
- I13. Ga+Cp+Hb+Bi+Pl+Kf+Qu
- I14. Ga+Op+Hb+Bi+Pl [±Cum]
- I15. Ga+Op+Hb+Bi+Pl+Qu
- I16. Ga+Op+Cp+Hb+Bi+Pl [Cum]
- I17. Ga+Op+Cp+Hb+Bi+Pl+Qu

Table 1. (*continued*)

I18. Sp+Cp+Hb+Pl [Bi, Mrg, ±Hög]
I19. Sp+Ga+Hb+Bi+Pl [±Hög]
⟨Ap, Zr, Opq; ±Aln, Sph, Mnz, Ru⟩

J. Pyroxene granulite
J1. Ga+Cp+Hb+Bi+Pl+Qu
J2. Ga+Op+Cp+Hb+Bi+Pl+Qu [Cum]
⟨Ap, Zr, Opq⟩

K. Metagabbro
K1. Ga+Op+Cp+Hb+Bi+Pl [Cum]
K2. Ga+Op+Cp+Hb+Bi+Pl+Qu [±Cum]
K3. Ga+Op+Cp+Hb+Bi+Pl+Kf+Qu
K4. Op+Cp+Hb+Bi+Pl+Qu
K5. Ga+Hb+Bi+Pl+Qu [Cum]
⟨Ap, Zr, Opq⟩

L. Cummingtonite±orthopyroxene gneiss
L1. Op+Cp+Hb+Bi+Pl [Cum]
L2. Hb+Bi+Pl [Cum]
L3. Bi+Pl+Qu±Ga [Cum]
⟨Ap, Zr, Opq⟩

M. Metadike rocks
a. Amphibolite
M1. Ga+Hb+Bi+Pl
M2. Ga+Hb+Bi+Pl+Kf+Qu
M3. Ga+Cp+Hb+Bi+Pl+Qu
M4. Ga+Op+Cp+Hb+Bi+Pl
⟨Ap, Zr, Opq; ±Aln⟩
b. Biotitic schist
M5. Hb+Bi+Pl+Qu±Kf
M6. Cp+Hb+Bi+Pl+Qu
⟨Ap, Sph, Opq⟩

Mineral abbreviations: Ac—actinolite, Aln—allanite, Anth—anthophyllite, Ap—apatite, Bi—biotite, Cc—calcite, Chl—chlorite, Chu—clinohumite, Cp—clinopyroxene, Crn—corundum, Cum—cummingtonite, Do—dolomite, Ep—epidote, Fa—fayalite, Fl—fluorite, Fo—forsterite, Ga—garnet, Gd—gedrite, Ghn—gahnite, Hb—hornblende, Hög—högbomite, Kf—K-feldspar, Ky—kyanite, Mnz—monazite, Mrg—margarite, Mu—muscovite, Op—orthopyroxene, Opq—opaque minerals, Pgt—pigeonite, Phl—phlogopite, Pl—plagioclase, Sphl—sphalerite, Prh—prehnite, Prg—pargasite, Pxm—pyroxmangite, Qu—quartz, Ru—rutile, Sc—scapolite, Sil—sillimanite, Sp—spinel, Sph—sphene, Tir—tirodite, Tr—tremolite, Wo—wollastonite, Zr—zircon.
⟨ ⟩: Accessory minerals. ( ): Inclusions in minerals. [ ]: Later minerals. Mineral assemblages of the samples studied by GREW *et al.* (1989) correspond to C3: (EG8801–)1704A, E1: 1814, E2: 1911A, E7: 2712B, E9: 1905, F2: 2807, F3: 2809, G1: 3006, I12: 1317, I18: 2911A, C5: MA88012305-1, and C8: HM88011803D.

6. Geological Structure

The metamorphic rocks of the eastern Sør Rondane Mountains are highly deformed. On the outcrop scale, the most conspicuous structure is compositional layering. In rocks inferred to be of metasedimentary and metavolcanic origin, the layering is usually parallel to the boundaries between different rock types such as the pelitic gneiss and biotite-hornblende gneiss, so that the present layering is interpreted to reflect original layers in the sedimentary and volcanogenic precursors. Strikes and dips measured on the layering of the gneisses are shown by stereographic projections in Fig. 2, and representative structural data are plotted in Fig. 1.

Small scale folds are common in many outcrops. In many cases, these folds appear to be related to fault zones, which have displacements of several meters to 10 m, locally more (GREW *et al.*, 1988). At Balchenfjella, the metadikes and metagabbro, as well as the migmatites and gneisses, are deformed by these fault zones, in which the rocks are recrystallized as well as folded by dragging along the faults. These fault zones appear to be related to the later amphibolite-facies metamorphism and migmatization.

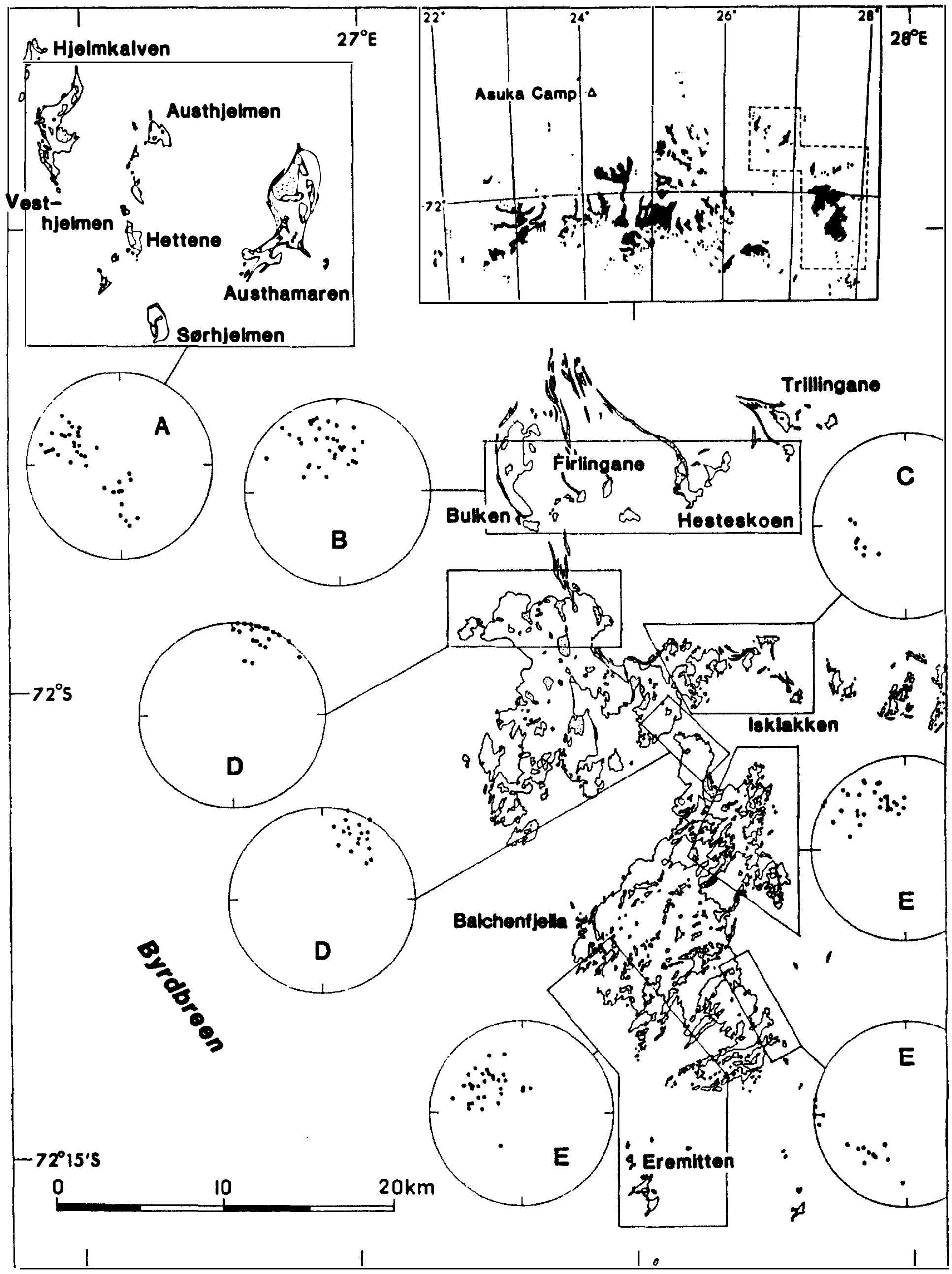

Fig. 2. Map showing stereographic plots of compositional layering in the metamorphic rocks. The letters A–E refer to five subareas each of which shows similar structural features.

At least two generations of large scale (macroscopic) folds are recognized. In order to better assess the distribution and extent of these folds, we have divided the map area into five subareas that on the basis of the stereographic plots of the structural data have similar structural features:

(A) Hettene subarea
(B) Firlingane subarea
(C) Isklakken subarea
(D) Northern Balchenfjella subarea

(E) Southern Balchenfjella subarea

In subarea A, two generations of macroscopic folds are found: (1) recumbent isoclinal folds, one of which is well displayed at Vesthjelmen (Plate 5A, same as VAN AUTENBOER and LOY, 1972, Fig. 2) and (2) upright NE-SW-trending, more open folds, such as a synform at Hettene (Plate 5B) (Fig. 1). An extension of axial part of the Vesthjelmen recumbent fold is exposed in the cliff of one of the nunataks west of Vesthjelmen, so we infer that the fold axis plunges gently northwest (Fig. 1). Recumbent folds are also exposed in a nunatak south of Hettene. Because the recumbent folds are nearly isoclinal, we infer from the girdle for subarea A that variations in structural trends in this subarea are mainly controlled by the NE-SW-trending second generation structures.

Another second-generation macroscopic fold, an open antiform, is exposed in northern Balchenfjella (Plate 5C and Fig. 1). The fold axis lies within the migmatite belt and this fold deforms the foliation of the migmatite as shown in Plate 5C. Consequently, subareas C and D are clearly correlated with each other. It is possible that subarea B is correlated with subarea C by a SE-trending synform presently covered by continental ice between Balchenfjella and Hesteskoen.

Subareas E are possibly parts of a unit distinct from the adjacent subarea D. Among subareas E, the structures in the southeasternmost part, which is also a migmatite area (Fig. 1), are somewhat different from the other two parts. This difference may be related to migmatization.

The timing suggests that the upright second generation folds and the fault zones could be related features, that is, deformation associated with the amphibolite-facies event and migmatization.

7. Metamorphic Evolution

On the basis of the results obtained from our geological and petrographic studies, we propose a tentative sequence of events, which will undoubtedly be modified as work continues.

(1) Deposition of sediments and volcanogenic rocks followed by emplacement of ultramafic rocks possibly as tectonically inserted mantle fragments.

(2) Magmatic activity, including emplacement of possibly pigeonite-bearing intrusions and mafic (presently garnet-rich) dikes (Austhamaren and Hesteskoen).

(3) Upper amphibolite (Vesthjelmen-Austhjelmen-Sørhjelmen) to hornblende granulite-facies metamorphism (Austhamaren-Hesteskoen-Balchenfjella), and recumbent isoclinal folding.

(4) Magmatic activity, which involved emplacement of (presently biotitic) dikes of intermediate composition.

(5) Amphibolite-facies metamorphism, migmatization, large scale open folding and extensive small scale deformation with development of fault zones.

(6) Plutonic activity, including diorite (Firlingane), and granitic dikes and veins.

(7) Greenschist-facies retrograde metamorphism, and formation of vein quartz with druses.

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References

ASAMI, M. and SHIRAISHI, K. (1987): Kyanite from the western part of the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 150–168.

ASAMI, M., MAKIMOTO, H., ANIYA, M., HAYASHI, M., IIMURA, Y., HAYASHI, T., NARAOKA, H., YONEZAWA, Y., FUJITA, S. and GREW, E. S. (1988): Sêru-Rondâne Sanchi chigaku chôsa hôkoku 1988 (JARE-29) (Report on the geological, geomorphological and geodetic field work and meteorite search in the Sør Rondane Mountains, 1988 (JARE-29)). Nankyoku Shiryô (Antarct. Rec.), **32**, 334–363.

GREW, E. S., ASAMI, M. and MAKIMOTO, H. (1988): Field studies in the eastern Sør Rondane Mountains, East Antarctica, with the 29th Japanese Antarctic Research Expedition (JARE). Antarct. J. U.S., **23**(5), (in press).

GREW, E. S., ASAMI, M. and MAKIMOTO, H. (1989): Preliminary petrological studies of the metamorphic rocks of the eastern Sør Rondane Mountains. Proc. NIPR Symp. Antarct. Geosci., **3**, 100–127.

ISHIZUKA, H. and KOJIMA, H. (1987): A preliminary report on the geology of the central part of the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 113–128.

KOJIMA, S. and SHIRAISHI, K. (1986): Note on the geology of the western part of the Sør Rondane Mountains, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **43**, 116–131.

PASTEELS, P. and MICHOT, J. (1970): Uranium-lead radioactive dating and lead isotope study on sphene and K-feldspar in the Sør-Rondane Mountains, Dronning Maud Land, Antarctica. Eclogae Geol. Helv., **63**, 239–254.

PICCIOTTO, E., DEUTSCH, S. and PASTEELS, P. (1964): Isotopic ages from the Sør-Rondane Mountains, Dronning Maud Land. Antarctic Geology, ed. by R. J. ADIE. Amsterdam, North-Holland, 570–578.

RAVICH, M. G. and KAMENEV, YE. N. (1972): Kristallicheskiy Fundament Antarkticheskoy Platformy (Crystalline Basement of the Antarctic Platform). Leningrad, Gidrometeoizdat, 658 p.

SAKIYAMA, T., TAKAHASHI, Y. and OSANAI, Y. (1988): Geological and petrological characters of the plutonic rocks in the Lunckeryggen-Brattnipene region, Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **2**, 80–95.

SHIRAISHI, K. and KOJIMA, S. (1987): Basic and intermediate gneisses from the western part of the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 129–149.

SHIRAISHI, K., KANISAWA, S. and ISHIKAWA, K. (1988): Geochemistry of post-orogenic mafic dike rocks from the eastern Queen Maud Land, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **2**, 117–132.

SHIRAISHI, K., ASAMI, M., ISHIZUKA, H., KOJIMA, H., KOJIMA, S., OSANAI, Y. *et al.* (in press): Geology and metamorphism of the Sør Rondane Mountains, East Antarctica. Proc. 5th Int. Symp. Antarct. Geosci. Cambridge, 1987.

VAN AUTENBOER, T. (1969): Geology of the Sør-Rondane Mountains. Geologic Maps of Antarctica, ed. by C. CRADDOCK *et al.* New York, Am. Geogr. Soc., Pl. VIII (Antarct. Map Folio

Ser., Folio **12**, ed. by V. C. BUSHNELL).

VAN AUTENBOER, T. and LOY, W. (1972): Recent geological investigations in the Sør-Rondane Mountains, Belgicafjella and Sverdrupfjella, Dronning Maud Land. Antarctic Geology and Geophysics, ed. by R. J. ADIE. Oslo, Universitetsforlaget, 563–571.

VAN AUTENBOER, T., MICHOT, J. and PICCIOTTO, E. (1964): Outline of the geology and petrology of the Sør-Rondane Mountains, Dronning Maud Land. Antarctic Geology, ed. by R. J. ADIE. Amsterdam, North-Holland, 501–514.

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