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Geology of Schirmacher Range (Dakshin Gangotri), East Antarctica

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ABSTRACT

An area of 35 sq km in the Schirmacher Range of Queen Maud Land East Antarctica was geologically mapped on scale 1 25 000. Six major lithological units (a) banded gneiss (b) alas kite (c) garnet biotite gneiss (d) calc gneiss khondalites and associated migmatites (e) augen gneiss and (f) streaky gneiss are delineated. The rocks have suffered an early metamorphism under granulite facies conditions and an early migmatization leading to the development of charnockitic rocks. Over a large part of the area the granulite facies assemblages have suffered complete or partial diapthoresis under amphibolite facies conditions. This was contemporaneous with extensive granitisation. The rocks have undergone an early deformation during the development of the charnockitic rocks and have subsequently suffered four generations of superposed folding. Two sets of second generation folds F_{2A} and F_{2B} are isoclinal and approximately coaxial in most places. In addition there are two generations of open upright folds (F_3 and F_4) with northerly and easterly striking steep axial surfaces. Open recumbent folds (F_5) have developed only locally. The major part of granitisation was broadly synchronous with the F_2 folding since the dominant gneissic foliation is axial planar to F_2 folds. Narrow ductile shear zones are distributed throughout the area. The earliest shear zones are parallel to the dominant gneissic foliation the mylonitic foliation and lineation being parallel respectively to F_2 axial planes and F_2 hinges in neighbouring unsheared rocks. The late shear zones and discrete shear surfaces cut across the F_2 axial surfaces.

INTRODUCTION

The Precambrian basement of the East Antarctic shield is mostly covered with ice and out crops are restricted along the narrow coastal zone. The Schirmacher Range emerges as a rock oasis between the continental ice sheet and the coastal ice shelf occupying an area of 35 sq km between 77° 44 30 - 70°46 30 south latitudes and 11°22 4 - 11°54 00 east longitudes. The major mountain system of Queen Maud Land runs for about a thousand kilometres approximately parallel to the coast line and has been studied by several workers (Roots 1953 Autenboer et al 1964 Craddock 1972, Juckes 1972 Ravich 1972 1982 Kamenev 1972 Ravich and Kamenev 1975). The Schirmacher Range is situated approximately half way between the main mountain range and the present coast line.

Unlike the main mountain range the Schirmacher Range forms a group of low lying hills of about 50 to 200 m high interspersed with a few glacial lakes. To the north of the range there are frozen ake in aleds on the ice surface with dendritic water channels cutting into the ice. On the south side the continental ice cap extends upto the main mountain range and beyond. The approximate thickness of this ice cap ranges from 500m to 3 km. A prominent glacial tongue of this ice sheet over rides the southern face of the range in the eastern part (Fig 1). The northern face is generally steep (Fig 2). The rocks of Schirmacher Range show extensive glacial erosion with prominent U-shaped valleys glacial striations (Fig 3) on the rock surface with thick moraine cover in the lower altitudes. Frost shattering in the rocks is evident in a few places. Wind erosion is dominant at high altitudes where the rocks exhibit pitted surface (Fig 4).

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Fig 1 Glacial tongue overriding the southern face of Schirmacher Range

The Schirmacher Range belongs to the East Antarctica Charnockite Province (Klimov et al 1964 Ravich 1972 1982 Kamenev 1972 1982 Ravich & Kamenev 1975) the largest area of granulite facies rocks in the world. The rocks have undergone multiple episodes of metamorphism migmatization and deformation (Grew 1978 1982 Hofmann 1982 Oliver et al 1972 Tingey 1982). The compositional variation of gneisses is due to the non uniformity of the metamorphic rocks and the selective nature of granitisation and ultra metamorphism (Klimov et al 1964 Ravich 1972 a b 1982 Kamenev 1972 a b).

GEOLOGICAL MAPPING

The main lithological varieties are charnockites granite gneisses gneissose migmatites of different varieties relicts of metabasic rocks calc-silicates and aluminous gneiss. The area can be mapped out into six major lithological units (a) banded gneiss (b) alaskite (c) garnet biotite gneiss (d) calc gneiss khondalite and associated migmatites (e) augen gneiss and (f) streaky gneiss. The relicts of metabasic rocks aluminous gneiss and charnockite are small to be mapped separately on the present scale of mapping which is 1 25 000. The Schirmacher range runs roughly E-W. The six lithological units have an ENE trend intersecting the hill range at a low angle (Fig 5).

GENERAL DESCRIPTION OF THE MAIN LITHOLOGICAL UNITS

Banded gneiss

Occupies the major portion of the eastern Schirmacher Range and displays prominent banding (Fig 6a 9). The layers show large compositional differences and the major units being (1) pyroxene granulite and biotitised pyroxene granulites (2) brownish-red garnetiferous and pyroxene-bearing variety without notable amphibole or biotite (3) gneisses containing coarse elongate homogeneously distributed lenses of dark minerals composed mainly of pyroxene. The darker varieties of these gneisses

Fig 2 Steep northern face of Schirmacher Range with frozen lake in left foreground and with dunes in the ice shelf in background.

Fig 3 Glacia Seasons

Fig 4 Plied and honeycomb ake surface produced by wind erosion

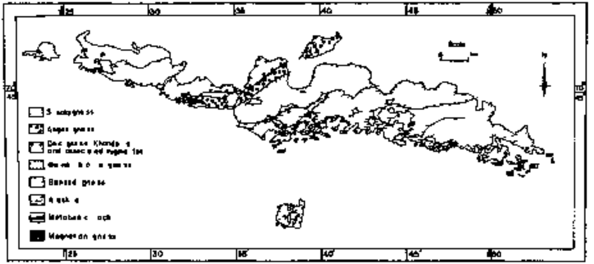

Fig 5 Geological map of Schimacher Range

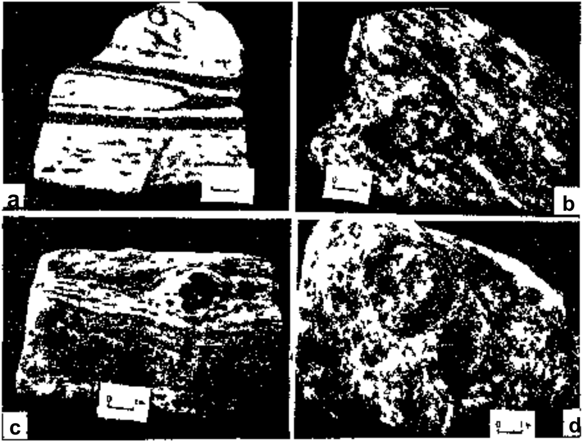

Fig 6 (a) Banded gneiss with epetition of amphibo te bands by socl nal F_2 folding. Gneiss of foliation is axial planar to the F_2 fold (b) Garnet biotite gneiss. The front surface parallel to foliation show l near arrangement of fer omagnes an minerals (c) Calc gneiss with a migmatitic band (d) Magmatised calc gneiss. In the left side a diffused band of pegmatte contains isolated flecks of biotite.

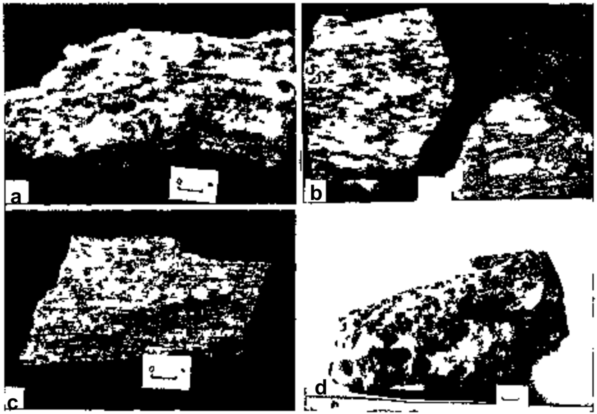

Fig 7 (a) Granite gneiss (b) Augen gneiss (c) Streaky gneiss (d) Pegmatite in charnock tic rock with coarse crystals of garnet and pyroxene

grade into the pyroxene granulite which in its turn grades into a somewhat lighter coloured gneiss (Fig 7a) where the dark clots are composed essentially of biotite with some amphiboles (4) Along with the granite gneisses and pyroxene granulites, there are some light grey rocks which are essentially enderbitic in composition without any well marked lineation.

Alaskite

Light grey or off white in colour without distinct colour banding and contains variable amounts of garnet. In hand specimen the foliation is in a very fine scale marked by thin translucent flattened grains of quartz.

Garnet biotite gneiss

They are characterised by the presence of large elongate clots of garnet and biotite (Fig 6b). A few thin discontinuous bands of biotitised amphibolite run through this gneiss but there is no regular banded character.

Calc gneiss khondalites and associated migmatites

These are layered with individual layers varying from a few centimetres to a few metres. The colour banding in the calc-gneiss is partly represented by variable calc silicate assemblages in different.

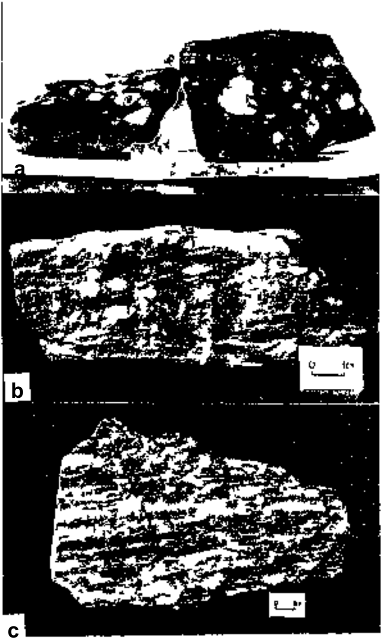

Fig 8 (a) Protomylonite with very coarse fragments of quartzofeldspathic material in fine granulated groundmass (b) Granite mylonite with porphyroclastic garnet and augen of feldspars (c) Granite schist with well developed lineation on the mylonitic foliation

Fig 9 Moderately dipping banded gneiss

layers and partly by lit par lit emplacement of granitic material (Fig 6c and d). Banding is accentuated by thin zones of mylonite which alternate with less sheared rocks. A separate body of pyroxene granulite without any internal colour banding occurs as a mappable unit within the northeastern part of the band.

Although khondalites occur in association with banded gneisses alask ite and calc gneisses are mostly concentrated within this unit. The rock is characterised by light brownish yellow colour mottled with coarse crystals of garnet with a rude banding of alternate garnet rich and quartzo feldspathic bands megascopically visible specks of graphite and a lineation marked by sillimanite prisms.

Augen gneiss

A thick band of augen gneiss runs through the west central part of the Schirmacher Range. The augens are composed mostly of very coarse feldspar and sometimes with coarse quartz feldspar clots (Fig 7b) on a matrix of coarse elongate clusters of biotite and fine grained quartz and feldspar. The rock is occasionally garnetiferous. The augen and the biotite rich clusters mark out a prominent lineation on the foliation surface. Occasionally the feldspar augen in the core is transluscent and has a thin rim of opaque white granulated material. The augen gneiss does not show colour banding and is mostly devoid of enclaves or bands of pyroxene granulite or amphibolite but remnants of charnockitic rocks are found.

Streaky gneiss

Occurs in the western most end of the Schirmacher Range with a general appearance similar to the garnet biotite gneiss but distinguished by much finer size of the dark streaks and by the absence of garnet (Fig 7c). It is much more schistose or well foliated than the garnet biotite gneiss and shows evidence of much more penetrative shearing. The streaky gneiss contains several large enclaves of pyroxene granulites with gradational contacts and remnants of charnockitic rocks.

PETROGRAPHY

Pyroxene granulites

The pyroxene granulites (Fig 11a) occur as layers within the banded gneiss and are composed of hypersthene clinopyroxene and plagioclase ($An_{50\ 55}$) with ilmenite or titanomagnetite as accessories. Most of the rocks have a polymetamorphic assemblage with hornblende and biotite developing at the expense of the pyroxenes. Biotite has developed either directly from the pyroxene or at the expense of hornblende. The rocks have undergone varying intensities of ductile shearing from slightly deformed rocks with bent cleavages of pyroxenes and undulatory plagioclase to typical mylonites with fluxion texture.

Calc gneisses

The most common assemblages are plagioclase ($An_{50\ 75}$) - diopside - sphene diopside - garnet - plagioclase - quartz - calcite - sphene calcite - scapolite plagioclase - diopside - sphene with or without quartz calcite - diopside - garnet - scapolite - sphene - plagioclase - quartz. Large variations in the relative amount of minerals are seen from layer to layer.

The least modified and least deformed members of the calc gneiss show a coarse xenoblastic granular texture. With progressive intensities of ductile shearing the rock shows a weak undulatory extinction and peripheral refinement of grains to final development of a typical mylonitic texture.

In sheared varieties intense biotitisation of the earlier mafic minerals is noted. In sheared zones the rock has been converted to a phyllonite which shows extremely fine subparallel flakes of biotite running through strongly elongate lenticular clusters of finely granulated quartz and plagioclase (Fig lib). In these zones there are no relicts of pyroxene. In less sheared zones of mylonite diopside dccurs in clusters of granulated fragments drawn out in a lenticular form (Frg 11 b). Fragments of garnet also occur within a matrix of fine grained quartz and feldspar. Most of the rocks show post molynitic recrystallisation of quartz and feldspar within the fine grained ground mass. In thin section it is noted that the mylonitic foliation is superimposed on an earlier foliation (Fig 11b). The earlier foliation marked by a colour banding forms isoclinal folds. A new mylonitic cleavage marked by flakes of biotite and strongly elongate porphyroclasts of quartz runs along the axial planes of these folds and cuts across the noses of the folds. The axial planar mylonitic foliation is broadly contemporaneous with a period of isoclinal folding which itself had developed by the folding of an earlier generation of foliation.

Charnockitic rocks

There are patches of charnockitic rocks within all the six major lithological units of this area. The principal mineral assemblages are hypersthene - plagioclase (An_{25-35}) - diopside-quartz hyper sthene - plagioclase - garnet - quartz - K feldspar - (biotite) hypersthene - plagioclase - quartz - browil hornblende - biotite hypersthene - plagioclase - K feldspar - quartz - (hornblende) hyper shene - diopside - garnet - plagioclase - quartz - K feldspar. In general enderbitic assemblages.

Fig 10 Late basic igneous dike

(Tilley 1936) are more common than charnockite *sensu stricto.* A common feature of a major part of the charnockitic rocks is the occurrence of garnet. Texturally two types are recognised one showing a coarse xenoblastic granular texture (Fig 11c) and the other showing coarse inter locking texture with sutured grain borders. Similar differences in the texture of South Indian charnockitic rocks were recorded by Subramaniam (1959). The textures indicate that biotite and hornblende are retro grade in nature and clearly replace pyroxenes often forming rims around them. The anorthite content of plagioclase varies between An_{25} and An_{35}. The moderately sheared rocks show a mortar texture with coarse strongly undulose porphyroclasts of pyroxene with narrow granulated rims. The quartzo feldspathic portions show a drastic grain refinement with a few medium to coarse porphyroclasts set in a fine grained groundmass.

In general the charnockitic rocks show a weakly defined foliation marked by a rude banding of the pyroxene-rich bands or streaks alternating with thicker quartzofeldspathic bands. A correlation between the intensity of mylonitisation and the amount of biotite in these rocks can be made. The undeformed well formed biotite flakes indicate that biotitisation was initiated during a shearing movement but its recrystallisation outlasted deformation.

Alaskite

The major part of the rock is composed of quartz and feldspar (Fig 11d). The undeformed varieties contain some garnet. Feldspar in some varieties is almost entirely K-feldspar while others both plagioclase and microcline are dominant. Biotite is present in small quantities and the texture indicates that it is a late mineral and is replacing garnet.

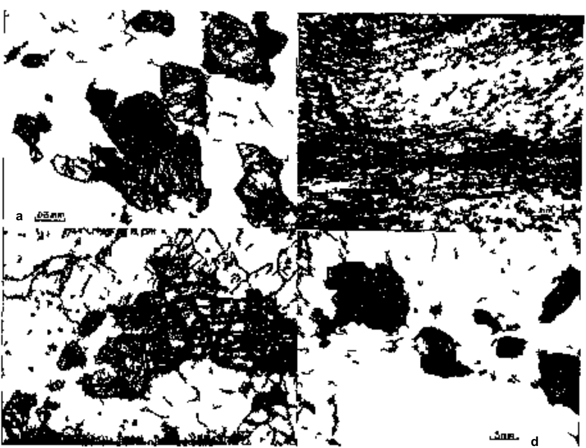

Fig 11 (a) Pyloxene granul te with hypersthene and piagioclase feidspar. Scale bar 0 3 mm
(b) Sheared calc gneiss with extensive biotitisation. A elicti pyroxene g a n s seen in the central part. A new foliation has been super imposed on an ea l e foliation at an acute angle. Scale bar 0 1 mm
(c) Ende bite with hype sthene diopside and piagioclase. Scale ba 0 3 mm.
(d) Alaskite with garnet quartz and feldspa. Scale ba 0 3 mm.

The undeformed alaskite shows a typical granitic texture. With increasing deformation the rock becomes more and more foliated and lineated and the most intensely deformed representatives have an appearance of a granite mylonite (Fig 8b and c). With increasing mylonitization the following textural changes are noticed (1) a reduction in the grain size (2) development of a micro banding of alternate quartz rich and feldspar rich bands and (3) alteration of garnet to biotite. The mylonites show varying degrees of recrystallisation and grain growth in granulated groundmass. Such effects are mostly noticeable in the mylonite zones which are parallel to the regional gneissic foliation. Along the easterly trending and steeply dipping mylonite zones there is very little sign of grain growth within the groundmass.

The microbanding of sheared alaskites is shown by thin ribbons of quartz alternating with some what thicker zones of fine grained feldspar and some quartz (Fig 12 a and b). The matrix may show either small equant grains with smooth grain borders or very fine grains with sutured borders. Along the steeply dipping discordant zones of mylonites the texture is often characterised by strongly undulatory elongate porphyroclasts of microline set within a very fine grained mosaic with fluxion texture. Such porphyroclasts are generally rare within low dipping mylonite zones which are parallel to the regional foliation.

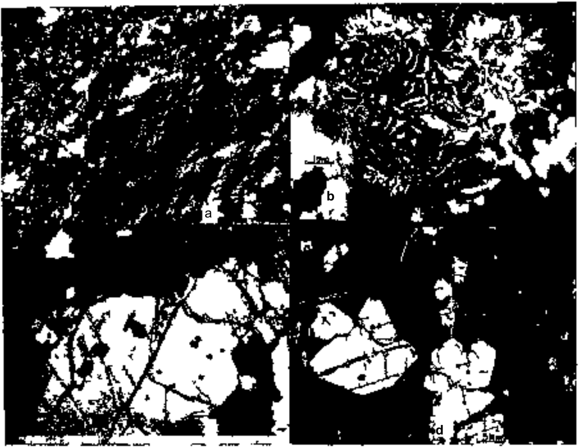

Fig 12 (a) Sheared alask te ribbons of quartz sweep past porphyroclast of feldspar. Crossed polar zers Scale bar 0 3 mm.
(b) A long ribbon of quartz swerve around deformed porphyroclast of macrocline. Crossed pola zers. Scale ba 0 3 mm.
(c) Khondal te with coarse crystals of garnet showing transverse fractures deformed sillimante and quartz. Scale bar 0 3 mm.
(d) Replacement of garnet by biotite in garnet biotite gneiss. Scale bar 0 3 mm.

Sheared alaskites almost always show long ribbons of quartz (Fig 12 a) similar to those reported from leptynites and quartzofeldspathic granulites. In the present instance the quartz ribbons occur only in those leucocratic gneisses which have undergone fairly extensive reduction of the grain size of feldspar. Although some of the ribbons are weakly undulatory or grade lengthwise into zones of fine equigranular matrix of quartz the majority of the ribbons do not show any sign of optical strain even when a single ribbon sweeps around a porphyroclast (Fig 12b) and traces out an isoclinal fold of the foliation. The extremely elongate character of these quartz grains their strict parallelism with foliation and the absence of optical strain in many of the extremely elongate grains suggest that the ribbon structure had developed by late tectonic grain growth.

The mylonitisation of the alaskites is always associated with biotitisation of garnet. Garnet in such rocks mostly occurs as armoured relicts or as small irregular relict grains distributed within the biotite. The flakes of biotite within the clots are often randomly oriented. Although most of the flakes are unstrained, a few show bent cleavage lamellae. Thus, the crystallisation of biotite at the expense of garnet, although clearly connected with mylonitisation, must have outlasted the deformation.

Khondalites

The khondalites have mineral assemblage of quartz -perthite -garnet -sillimanite with graphite. In thin section the rock shows a microbanding with rows of coarse strongly elongate xenoblastic grains of garnet with closely spaced transverse fractures (Fig 12c). The garnet rich bands alternate with other gently undulating thin quartzofeldspathic bands some of which are very rich in sillimanite. The preferred dimensional orientation of sillimanite marks out a well developed schistosity. The elongate grains often show undulose extinction and folded cleavage lamellae. Some of the quartzofeldspathic bands show a moderate intensity of mylonitisation. Along the more sheared zones quartz and K feld spar form fine grained texture with sutured grain borders. Within such a fine grained matrix occur elongate strongly undulant porphyroclasts of micro perthite. The less sheared zones show medium to coarse elongate grains of quartz and feldspar with smooth grain borders. The deformed sillimanite grains are rarely associated with a small amount of muscovite. The texture suggests an alteration of sillimanite to muscovite. The rocks contain a small amount of biotite along the periphery of garnet. The khondalites are spatially associated closely with charnockitic rocks and sometimes with the alaskites.

Garnet biotite gneiss

The garnet-biotite gneisses are composed of quartz - plagioclase - K-feldspar-gamet-biotite. Apatite and ore minerals are present as minor constituents. The K-feldspar is mostly microcline but some of the rocks contain a fair amount of micro-perthite. In thin section, the rocks show a banding of alternate quartz feldspar bands and garnet biotite bands. Partial replacement of garnet by biotite is fairly common (Fig 12d). The rock shows varying amounts of mylonitisation. The unsheared portions are composed of large slightly elongate grains of feldspars and weakly undulant quartz with sutured grain borders and with very well-developed deformation lamellae. This texture is almost invariably associated with clusters of medium sized equant grains with smooth grain borders. The sheared zones are generally very narrow and are composed of fine grains of quartz and feldspar with varying intensity of recrystallisation. The fine grained matrix of some of the rocks show a profuse development of myrmekite which occasionally embays into neighbouring grains of K-feldspar.

Augen gneiss

The mineral assemblage is quartz - K feldspar- plagioclase - hornblende - biotite. In the biotite rich portions the rock shows medium sized or small polygonal grains of plagioclase. Within the clusters of plagioclase occur elongate clots of biotite. In such biotite and plagioclase rich portions there is a small amount of medium grained quartz. Elsewhere large elongate clusters of weakly undulant quartz grains with sutured grain borders are present.

Large or very large grains of K-feldspars (microcline and/or untwinned K feldspar) occur in the medium sized or fine grained groundmass (Fig 13 a). In the rocks least affected by shearing such large grains of microcline are few and where the rocks are somewhat more sheared the large microcline grains take a strongly elongate shape. The grains of microcline show a marginal grain refinement. The large ovoids of microcline sometimes include medium sized optically continuous islands of plagioclase.

The augen gneiss in Schirmacher Range has developed by a combination of processes. In the initial stage the large feldspar grains have grown as porphyroblasts within a granulated matrix. They were then deformed and have undergone cataclasis. The groundmass of these rocks show a

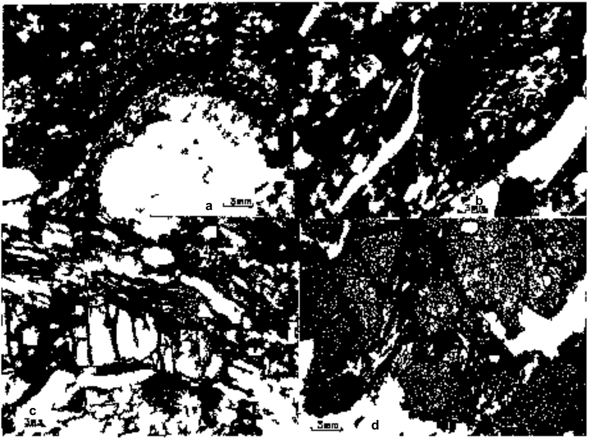

Fig 13 (a) Deformed augen of macrocline occurring in a granulated groundmass Crossed polaizers Scale ba 0 3 mm.
(b) My mekite in groundmass of augen gneiss. Crossed polaizers. Scale ba 0 1 mm.
(c) Hypersthene garnet ock. Scale ba 0 3 mm.
(d) Phenocrys of o vine and augite in a very fine groundmass of basartic dike.

significant amount of myrmekite (Fig 13b). The occurrence of very irregular grains of myrmekite with their vermicular quartz accentuates the appearance of the mortar texture of the rocks. The small grains of plagioclase occurring within the groundmass often have clear sodic rims.

With increase in the intensity of shearing the large augen are themselves traversed by narrow zones of shear with a fine grained matrix of microcline with some myrmekite growth in them. In certain cases a large augen is divided by narrow zones of shear into a number of separate and smaller augens. These indeed are porphyroclastic augens.

Streaky gneiss

The major mineral constituents are quartz-plagioclase ($An_{25\ 35}$) biotite - garnet - (ore) (apatite). Microcline is observed as a minor constituent. Hornblende or actinolite occur in small quantities in association with biotite. The intensity of shearing is strongly variable. In the least deformed members the rock contains clusters of medium sized unstrained grains of plagioclase and quartz with polygonal outlines. There are also clusters of coarse grains of plagioclase more or less equant and with smooth or sutured grain borders. Rarely the larger grains are anti perthitic (patch type). The clusters of quartz and plagioclase show a close association of moderately strained or completely unstrained grains. Biotite generally occurs in strongly elongate coarse clusters and mark out a foliation.

The linear arrangement of the biotite clusters, in the mesoscopic scale along with the undeformed character and random orientation of the flakes indicate that crystallisation of biotite is broadly syntectonic with crystallisation outlasting deformation. The association of sheared plagiociase with large unstrained grains of plagioclase without any peripheral granulation also indicate a broadly syntectonic growth of plagioclase. Nevertheless there are sheared members of streaky gneiss in which alt the quartz and feldspar have undergone a strong shearing. The biotite flakes in sheared streaky gneisses are much finer and are aligned parallel to the foliation surface. However, each individual flake is well formed and undeformed. In the mesoscopic scale the foliation surface of the mylonitic rocks remain parallel to the foliation surface of the unsheared rocks. The mineral lineations marked out by biotite flakes in both varieties are aslo parallel. This would suggest that the fabrics of the sheared and the unsheared varieties of streaky gneiss were produced in a single progressive deformation.

In certain portions of the streaky gneiss the dark elongate clusters of biotite contain a fairly large amount of garnet in medium sized xenoblastic grains. Some of the garnets are biotitised, while others show smooth grain borders.

Amphibolites

Several bands of amphibolite occur in the central part of the Schirmacher Range. The larger bands are few hundred metres along with a width of 50 metres composed of coarse well formed xenoblastic grains of amphibole (hornblende or actinolite) and plagioclase feldspar (oligoclase - andesine) with smooth grain borders. The amphiboles mark out a lineation on the foliation surface. Instances of small relict grains of hypersthene and clinopyroxene within amphibole are noted. Amphibolites have been partially biotitised but do not show any sign of mylonitisation.

Magnesian gneiss

These gneisses composed of hypersthene, clinopyroxene, plagioclase feldspar and talc occur in isolated patches in the banded gneiss and show various degrees of alteration and granitisation. The amphibole is generally cummingtonite but in some cases tremolite is also present. With progressive granitisation and retrogression, the amount of biotite and amphibole increases. Again with increasing granitisation the amount of plagioclase feldspar increases with large plates of oligoclase-andesine enclosing islands of the ferro-magnesian minerals. The magnesian gneiss is generally coarse grained and without any foliation or mineral lineation.

Pyroxene-garnet rock

The gneisses in some localities contain narrow (less than 50 cm thick) concordant bands of a dark poorly foliated or massive coarsely crystalline rock composed dominantly of ferro-magnesian minerals. About 90 per cent of the rock is made up of coarse and very coarse grains of garnet and hypersthene (fig 13c). Small amounts of quartz and plagioclase feldspar occur as blebs within larger grains of pyroxene and garnet.

Late intrusives

These are of two types, one metamorphosed and other unmetamorphosed or fresh.

In the east-central part of the range a discordant 50cm wide thin dike, with brownish-grey colour is observed. The rock is composed of biotite and K-feldspar with some amount of epidote and tiny needles of apatite. The undeformed character of the biotite especially the large transverse flakes indicate that biotite has undergone post tectonic recrystallisation.

Dikes (Fig 10) and sills ranging in width from 15 cm to 50 cm of fine grained dark grey rocks are occasionally noticed in the western part of the Schirmacher Range. In thin section the rock shows medium to coarse phenocrysts of both olivine and augite in nearly equal amounts. The phenocrysts are all euhedral (Fig 13d) and sometimes partly corroded by the groundmass. The groundmass consists mostly of randomly oriented microlites of pyroxene with interstitial iron ore and plagioclase feldspar. These dikes and sills are very fresh without any sign of post crystalline deformation.

METAMORPHISM

Textures indicative of a prograde character of the granulite facies metamorphism were nowhere found in the Schirmacher Range. However textures suggestive of super position of amphibolite facies metamorphism on granulite facies rocks are present. The amphibolites or other amphibolite facies rocks show a prominent schistosity axial planar to the F_2 folds and a lineation essentially parallel to the F_2 axes. Alteration of pyroxene to amphibole along microscopic shear zones in pyroxene granulites indicate that the granulite facies - amphibolite facies transition was broadly coeval with F_2 folding. Evidence of a much lower grade metamorphism as indicated by chloritisation of hornblende grains represents a very minor event.

MIGMATIZATION

Two clearly distinct episodes of migmatization can be recognised the first was under granulite facies conditions leading to development of charnockitic rocks and the second leading to the development of quartzo feldspathic gneisses. The process of migmatization in charnockite is indicated by their nonhomogeneous character their gradational contacts and development of a migmatitic banding. Pegmatites with very coarse crystals of hypersthene and garnet (Fig 7d) show diffuse borders with charnockitic rocks.

Evidences of the early migmatization is obscured by extensive granitisation - migmatization of a later period evidenced by the development of different varieties of megascopic migmatitic fabric viz (i) agmatites with irregular fragments of amphibolites or pyroxene granulites separated by granitic and pegmatttic bodies (Fig 14) (ii) banded structure with paleosome layers of regular widths alternating with granitic layers (Fig 6a 9) (iii) veined structure with long tapering quartzo-feldspathic veins alternating with granite gneisses (Fig 15) (iv) schlieren structure with long lenticular ghostly remnants of paleosome running parallel to one another through a quartzo feldspathic granitic material (v) nebulitic structure with diffuse patches of neosome and irregular ghostly remnants of paleosome (Fig 27) and (vi) fleck structure with diffuse irregular veins of replacement pegmatite flecked by large isolated clots of biotite (Fig 6d).

The emplacement of pegmatite along F_2 axial surfaces (fig 16) occurrence of the dominant foliation of the gneisses parallel to the axial surface of the F_2 folds along with the presence of coarse completely unstrained flakes of biotite subparallel to the gneissic foliation and the association of deformed and completely undeformed large grains of quartz and feldspar in the nonmylonitised gneisses indicate that the second period of migmatization was broadly contemporaneous with the F_2 folding.

The major period of granitisation syntectonic with F_2 folding, must also be broadly contemporaneous with the development of the ductile shear zones parallel to the dominant gneissic foliation. This is indicated by the profuse development of myrmekite in the granulated matrix of granite mylonites, clear correlation of the intensity of granulation and the amount of biotitisation in the enclaves of pyroxene granulites and calc-gneisses and by the emplacement of pegmatite along concordant shear zones.

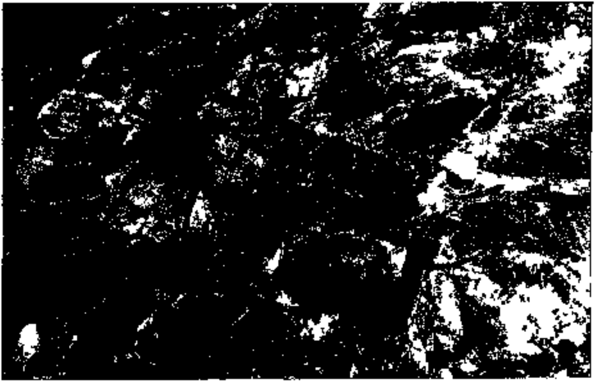

Fig 14 Agmatite with enclaves of pyroxene granulite and amphibolite

Fig 15 Veined structure in magmatite. The foliation and axial surfaces are intersected by a later foliation of pegmatitic gneiss

Fig 16 Emplacement of pegmatite at low angle to F_2 axial surface

Fig. 17. Late pegmatite cutting across all earlier structures

A certain amount of granitic activity continued even during the development of some of the late shear zones which intersect the gneissic foliation. This is indicated by the emplacement of granite pegmatites along (Fig 29) the shear zones and discrete shear fractures (Fig 30) and by the occurrence of undeformed pegmatite veins cutting across all earlier structures (Fig 17).

STRUCTURE

Foliation

The calc-gneiss shows a compositional banding ranging in scale from a few mm to several metres. The coarseness of the bands is suggestive of original bedding. However, the layering is isoclinally folded and transposed and in the major part the layering and schistosity are parallel. Thus, original banding has been considerably modified by transposition, shearing and metamorphic segregation.

Apart from the colour banding in the calc-gneisses the earliest foliation recognisable is a migmatitic banding in the charnockitic rocks. The dominant foliation in the different varieties of unsheared gneisses is marked by the folia of ferruginous minerals occurring within a quartzo feldspathic groundmass. With increase in the intensity of shearing the foliation acquires a mylonitic character. In some of the rocks, and specially in the alaskites, a microbanding has developed not only by an alternation of mafic and quartzo-feldspathic minerals, but also by the occurrence of very long ribbons of quartz running through a fine grained quartzo-feldspathic groundmass. It is noteworthy that the dominant mylonitic foliation is approximately parallel to the regional foliation of the gneisses.

Although there is a considerable range of variation in the attitude of dominant gneissic foliation throughout the area (Fig 18) the generalised strike is 80° with a generalised southerly dip of 25°

Lineation

Excepting the pyroxene granulites and some of the charnockitic rocks all the other lithologic units show a well-marked lineation. The lineation may be represented by (a) Parallel, leaf-shaped clusters of ferruginous minerals with or without a preferred linear arrangement of individual grains (Fig 19). In the unsheared gneisses such leaf-shaped folia show a moderate elongation with an axial ratio less than 2. With increasing intensity of shearing these dark folia on the schistosity surface become strongly elongated while the individual mineral grains within each of them show a more and more well-marked linear arrangement (b) A mineral lineation marked by linear arrangement of prismatic grains of amphibole and tabular or leaf-shaped individual flakes of biotite on the foliation surface (c) A linear arrangement of the longest axes of prolate augen of the augen gneiss. The size of the individual augen is generally of the order of a few centimetres. These megascopically visible augens are generally composed of both quartz and feldspar (d) A mylonitic lineation (Fig 8c) formed by a linear arrangement of very fine tabular or prismatic crystals parallel arrangement of strongly stretched grains of quartz and feldspar streaks of granulated quartz and feldspar or ferruginous minerals and a fine rodding structure of very long quartzo-feldspathic domains.

The lineation shows a fairly wide range of variation in attitude, although the majority of them have a low to moderate plunge. The majority of lineations lie on the generalised foliation surface with variable angle with the strike direction. There is a strong maximum of the lineation plots close to a line plunging 20° towards S 40°W. Foliation and lineation in the mylonitised and nonmyionitised rocks are essentially parallel. Non-penetrative linear structures like fold mullions slickenside striae and boudin axes are present throughout the area.

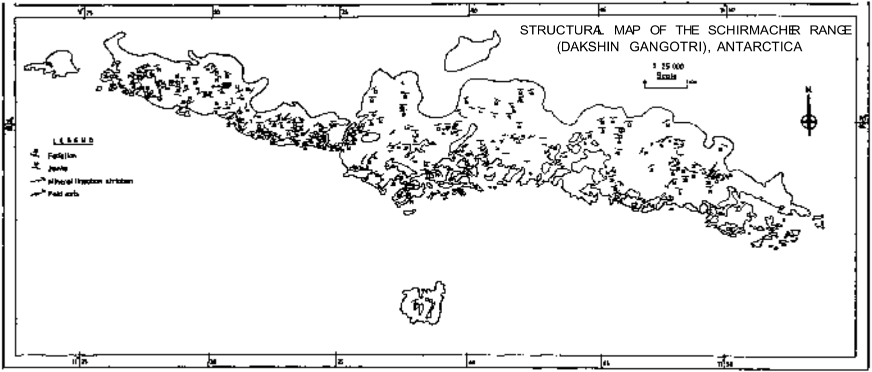

Fig 18. Structural map of Schirmacher Range

Fig 19 Linear on marked by leaf shaped c us e s o fa ug nous minerals on for a on surface

Fig 20 soc na F_{2A} folds in calc-gneiss

Superposed folding

The rocks of the Schirmacher Range have undergone an early deformation (D_1) during the development of the charnockitic rocks. Apart from tectonic layering in these rocks there is no other evidence of this early deformation. The rocks subsequently suffered four generations of superposed folding. Two sets of broadly coaxial folds of the second generation F_{2A} and F_{2B} are most frequently seen in the mesoscopic scale F_{2A} is strictly isoclinal either occurring as rootless intrafolial folds or as folds with very high amplitude wavelength ratios (Figs 20 23). F_{2B} is also isoclinal or very tight and is occasionally strongly asymmetric (Figs 6a 21 23 24) F_{2A} can be identified only when its axial surface is found to be refolded by F_{2B}. The axial surface of F_2 has an average E-W strike and mode rate southerly dip. Its average orientation is approximately parallel to that of the regional foliation of the gneisses (Fig 23 6a). In the mesoscopic scale the dominant gneissic foliation is indeed found to be an axial plane foliation associated with the F_2 folding. The F_2 hinges are parallel to the lineation of the gneisses and have a moderate plunge towards SW. The majority of F_2 folds have a fairly large pitch (about 60°) on the axial surface. Exposed hinges of clearly identifiable F_{2A} folds are not common. Where such hinges are identifiable as F_{2A} they are essentially parallel to the F_{2B} axis. However both hook shaped and crescent shaped outcrops of F_{2A} - F_{2B} interference patterns can be seen implying that F_{2A} and F_{2B} are not necessarily coaxial everywhere.

F_3 represents a set of upright folds with subvertical axial surfaces striking N-S to NNE-SSW and with fold hinges plunging SSW. Where F_3 has been superimposed on F_2 on a mesocopic scale the hinges of the two systems of folds are found to be approximately parallel with the axial surfaces of the two systems at a high angle to one another (Figs 23 24, 25). The intensity of deformation during F_3 folding is much smaller than that, of F_2. The F_3 folds usually show an interlimb angle of about 90° (Fig 22) although in some localities tight F_3 folds can be seen with interlimb angles ranging between 50° and 30°. In such areas of fight F_3 folds a northerly striking steep crenulation cleavage has developed parallel to the axial surface of the folds.

F_4 fold hinges are exposed in a few places but their prevalence is often indicated by a variation of the amount of dip along with a constancy of the strike direction of the general gneissic foliation. The majority of the F_4 folds are asymmetrical and with an easterly striking very steep axial plane. Unlike all the earlier generations of folds which have a high pitch of fold axes on their axial surfaces the F_4 hinges show a very low pitch with a plunge of less than 10° towards east or west (Fig 25). The folds are moderately open with an average interlimb angle of 90°. The lineations and the F_2 fold hinges are deformed by F_4 folds.

The last generation of folding represents a weak localised deformation and can be seen in only those places where the moderately low dipping regional attitude of foliation has been significantly steepened by F_4 folding. Thus in the central part of Schimacher Range where the area is traversed by 11° 42 E longitude (Fig 18), E-W striking vertical foliations are common. Some open recumbent folds (F_5) on roughly E-W trending subhorizontal axis have developed on such vertical or subvertical planes.

Boudinage

Boudinage and pinch-and-swell structures occur throughout the area (Fig 26, 27). Very large boudins several metres thick and few tens of metres length of concordant amphibolites and pyroxene granulites occur on cliff faces on the northern side of the eastern part of Schirmacher Range (Fig 26). Boudinage and pinch-and-swell structures have developed in enclaves of metamorphic rocks and concordant pegmatites. Internal boudinage (Cabbold et al 1971) is observed within gneisses.

Fig 23 F_2 o d in magma e

Fig 22 SW plunging up gh F3 folds in banded gneiss

Fig 23 Interference of F_{2A} and F_{2B} and F_3 folds in calc-gneiss. F_{2A} hinges exposed in left and central part are refolded isoclinally by F_{2B} folds. The gentle undulations with steep axial surfaces are because of F_3 fold. Note partially granitised boudinage and pinch - and swell structure along the general trend of gneissic foliation. The lower part of the figure shows a zone of protomylonite.

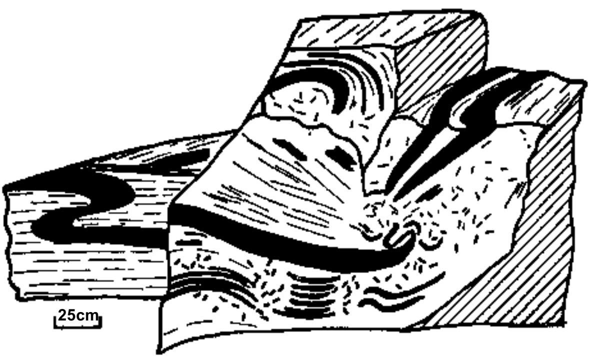

Fig 24 F_2 and F_3 folds in banded gneiss. In lower left a F_2 fold is exposed on a vertical surface. The undulations in the foreground and in the upper part are due to upright F_3 fold.

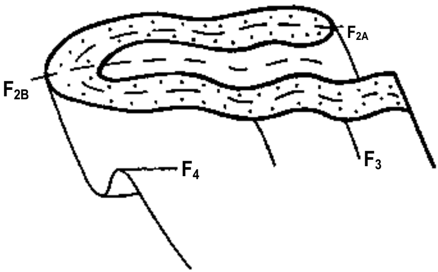

Fig 25 Generalised diagram showing interrelation amongst F_{2A} F_{2B} F_3 and F_4 folds

Fig 26 Large boudins of amphibolites and pyroxene granulites exposed on a hillface of Schirmacher Range

The shapes of boudins indicate that there was both pre-boudinage and post-boudinage plastic deformation (Lloyd & Ferguson, 1981). The structures range from pinching and swelling to development of barrel-shaped boudins with slightly incurved edges (Fig 27) or development of lenticular or fishhead boudins rectangular boudins are rather rare. The boudins associated with shearing often have a characteristic rhombic shape.

In major part boudinage was broadly contemporaneous with granitisation as indicated by the development of pegmatite in the nodes between boudins and by partial granitization of the boudins of amphibolites and other metamorphic rocks (Fig 23 27). Boudinage has occurred mostly during F_2 folding and also during all later deformations.

Some of the boudinage structures in the bands of pyroxene granulite show a rather uncommon geometry with the internal foliation of the boudins making an angle to the foliation of the host rocks. They are developed by displacements along shear planes at an acute angle to the foliation. However, translatory movements alone cannot explain the angle between the internal foliation of the boudins and the foliation of the enveloping gneiss. With progressive deformation the slices of pyroxene granulite bands along with their bounding slip surfaces must have rotated so that the angle between the slip planes and the foliation of the enveloping gneiss has been progressively reduced. The early-formed boudins have often been deformed by the later folds sometimes with short individual boudins deformed into half-waves (Fig 28) (Sengupta, 1983, 1985).

Shear zones and shear fractures

The shear zones and shear fractures are mainly of three types (1) the most common variety of ductile shear zones are parallel to the gently dipping axial surfaces of F_2 folds (Fig 23) with the mylonitic foliation parallel to the regional foliation of the gneisses and the mylonitic lineation essentially parallel to the F_2 axis. (2) steep or subvertical shear zones. Among these there were some with E to ENE strike and others with N to NE strike (Fig 29). (3) clean-cut closely spaced steeply dipping shear fractures striking at a moderately high angle to the regional foliation and the axial surfaces of the F_2 (Fig 30).

The first type of shear zones with width of a few metres is responsible for the extensive mylonitisation. This shearing movement has converted the gneisses to a schistose variety along fairly thick zones. Along these shear zones the rock may show the characteristic fabric of a true mylonite or the mylonite may grade into tectonic breccia or protomylonite (Waters and Campbell 1931) with the mylonitic foliation sweeping around megascopically visible elongate clasts.

The mylonitic foliation and lineation in the first type of shear zones are parallel respectively to the axial surfaces and axes of the F_2 folds of neighbouring non-mylonitised rocks implying that the mylonitisation occurred in continuation of movements which gave rise to the F_2-folds. Large thin sections of a sheared calc-gneiss show that the earliest folds are strictly isoclinal with a form surface represented by a fine colour banding. These are deformed to second generation folds of varying tightness ranging from isoclinal to moderately tight. The quartzose portions occurring at the cores of these folds show strongly elongate undulose grains with peripheral grain refinement. The elongate grains of quartz mark out a foliation which is axial planar to the second generation folds and show a slight fanning over fold arches. In more micaceous rocks the axial planar nature of the mylonitic foliation is clearly seen. In such rocks the earlier cleavage marked by biotite is found to be crenulated in comparatively less sheared segments. The narrow mylonitic domains run parallel to the axial surfaces of the crenulations. Within such domains the earlier foliation is either completely destroyed or is recognisable by the occurrence of rootless isoclinal folds on a fine colour banding.

Fig 27 Boudinage and pin and Swe s uc u e n amph bo e enc a es n foreground ghos y emnan s o pa a y g an sed boudins o m a nebu c s uc u e

Fig 28 Folding of boudins

Fig 29 Emplacement of pegmatite along the northerly striking steeply dipping shear zone at a high angle to the regional foliation

Fig 30 Steep dipping discrete shear fractures cutting across gently dipping gneissic foliation. Note pegmatite emplacement along some of the fractures.

In many of the rocks the mylonitic foliation as examined in both mesoscopic and the microscopic scales is itself deformed to folds of varying tightness. The style and orientation of the tighter folds are similar to that of the F_2 folds. It appears that the mylonitic foliation in this area is a fairly complex structure. It has caused a transposition of an earlier structure and with progressive deformation has itself been transposed.

The development of the first type of shear zones was at least partly contemporaneous with granitisation. This is indicated by (1) the axial planar orientation of the mylonitic foliation with reference to F_2 folds (2) the emplacement of pegmatites along the shear zones (3) by the profuse development of myrmekites within the matrix of granite mylonites and (4) by extensive synkinematic biotitisation of pyroxenes garnet and amphibole in the mylonitised rocks.

Second type of ductile shear zones the steep dipping ones though later than the first type and the F_2 folds whose axial surfaces they intersect cannot be very late features as there has been emplacement of some pegmatites along these shear zones (Fig 29). The temperature during the development of these shear zones could not have been very low since the rocks have responded in a ductile manner. The temperature must have been high enough for crystallisation of biotite at the expense of garnet and development of a fine microbanding parallel to the foliation.

Along certain impersistent microscopic shear zones the ferro magnesian minerals have been extensively chloritised. It is likely that the shearing movement continued to a fairly late stage of the metamorphic cycle.

The discrete shear fractures of the third type (Fig 30) are much later than the ductile shear zones

MINERALISATION

Disseminated grains of pyrite chalcopyrite, galena and some associated sulphide minerals are present in the calc gneisses and the associated migmatites. Surficial limonitic encrustations mala chite stains and graphite rich bands are noted in various parts.

SUMMARY

The rocks of the Schirmacher Range have undergone an early metamorphism under granulite facies conditions and an early migmatization leading to the development of charnockitic rocks. This was superimposed by an amphibolite facies metamorphism and extensive granitisation. The rocks have suffered superposed folding of at least five generations of which the second deformation is the most important. Second generation folds F_{2A} and F_{2B} are isoclinal and are approximately coaxial in most places. The dominant E-W striking gneissic foliation is axial planar to the F_2 folds. This was followed by two generations of open upright folding with northerly (F_3) and easterly (F_4) striking steep axial surfaces. Open recumbent folds (F_5) have developed only locally.

The earliest shear zones have developed during the F_2-deformation. The late shear zones and discrete shear fractures cut across the F_2-axial surfaces. The widespread granitisation is broadly contemporaneous with the development of F_2-folds and the early concordant shear zones.

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APPENDIX

Preliminary petrographic studies of rocks from Gruber Range, Wolthat Mountains

The third expedition also collected some rock samples from the Gruber Range of the Wolthat Mountains which is situated approximately 80 km south of Schirmacher Range. Preliminary petrographic studies show that the Gruber Range contains amphibolite, garnet-biotite gneiss and other varieties of quartzo-feldspathic gneiss similar to the Schirmacher range. In addition, there is a fairly large body of anorthosite. In hand specimen the anorthosite shows a coarse grained texture with large brownish-grey plates of labradorite separated by thin rims of a fine white groundmass. In thin section, the rock shows a xenoblastic granular texture with coarse grains of labradorite set within a fine- or medium- grained mosaic of equant grains with smooth grain borders. While the large plates of plagioclase often show a weak strain with bent twin lamellae, the fine groundmass is thoroughly recrystallised. Apart from plagioclase, the anorthosites contain a small amount of clinopyroxene.

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