THE GEOLOGY OF MANNEFALLKNAUSANE AND PART OF VESTFJELLA, DRONNING MAUD LAND

By L. M. Juckes

Abstract. The rocks exposed at Mannefallknausane are Basement Complex gneisses, including a charnockitic variety, intruded by basic dykes and sills. A differentiated sill 5 m. thick is described, and the differentiation is believed to have resulted from gravitational settling of olivine and clinopyroxene in an undersaturated magma.

At "VA Nunataks" in Vestfjella, flat-lying altered intermediate to basic lavas are intruded by Jurassic dolerite "sills". Intermediate lavas also occur at "VB Nunataks", where they have been thermally metamorphosed, and a specimen of troctolite suggests the presence of a relatively large basic differentiated intrusion.

The geochemistry of the minor dolerite intrusions shows that they have a variable but low silica content and a low potash content compared with the Ferrar dolerites of Victoria Land. Analyses of dolerites from other parts of Dronning Maud Land and Coats Land exhibit similar characteristics and it is suggested that this may reflect a greater variation in the chemical composition of the Jurassic parental magma than hitherto suspected.

In western Dronning Maud Land between lat. 73°45′ and 74°40′S., and long. 14°15′ and 14°50′W. there are two distinct groups of nunataks, the southern of which, Mannefallknausane,* is the smaller, whereas the northern group, Vestfjella, is much larger (Fig. 1).

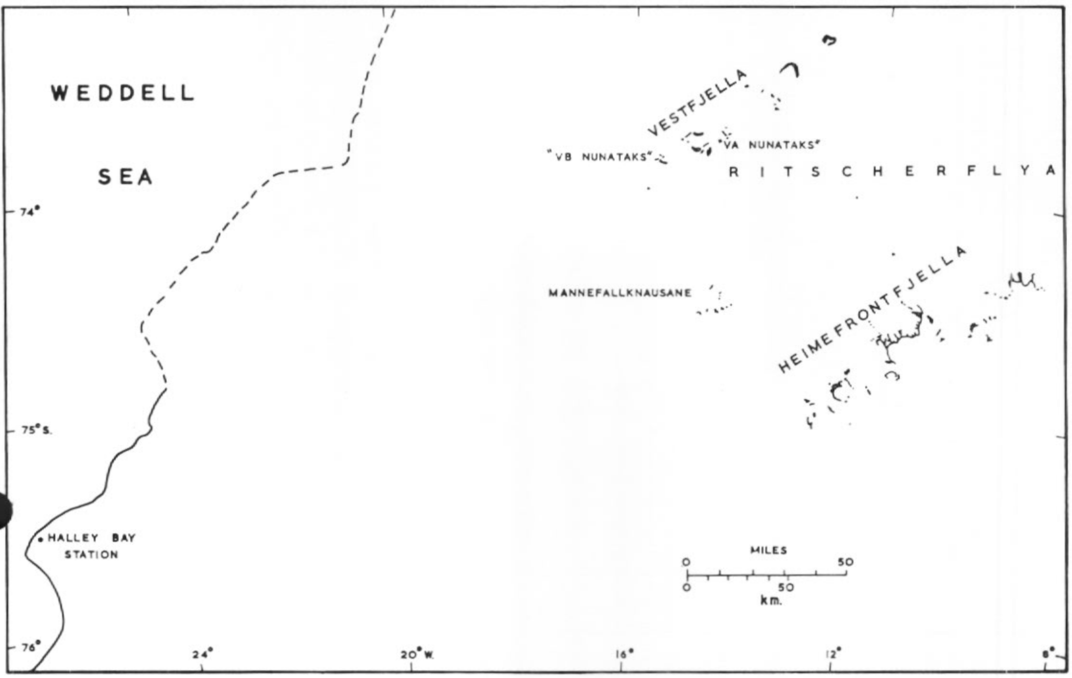

Fig. 1. Sketch map of parts of Coats Land and Dronning Maud Land, showing the location of Mannefallknausane and Vestfjella in relation to the Halley Bay station.

During the Norwegian-British-Swedish Antarctic Expedition, 1949–52, Vestfjella were photographed and examined from the air by Dr. E. F. Roots. Although Roots (1953) did not mention the geology of Vestfjella (referred to as "Kraulfjella"), the shading for Vestfjella

* Previous to 1967 this nunatak group was known as "Milorgknausane".

on his map was described in the key as "clastic sedimentary rocks, intimately invaded by dioritic and gabbroic sills; isolated exposures of sediments or igneous rocks".

In 1962, G. Blundell and M. J. Winterton, from the British Antarctic Survey station at Halley Bay, visited the southern part of Vestfjella and collected several geological specimens. Blundell (1964) measured and discussed the natural remanent magnetism of one of these specimens; Rex (1967) determined its isotopic age and Brown (1967) described its petrology.

In February 1965, the author visited Mannefallknausane and carried out a brief geological survey of Wildskorvene, Wilsonberga and Baileyranten (Fig. 2), and the following year

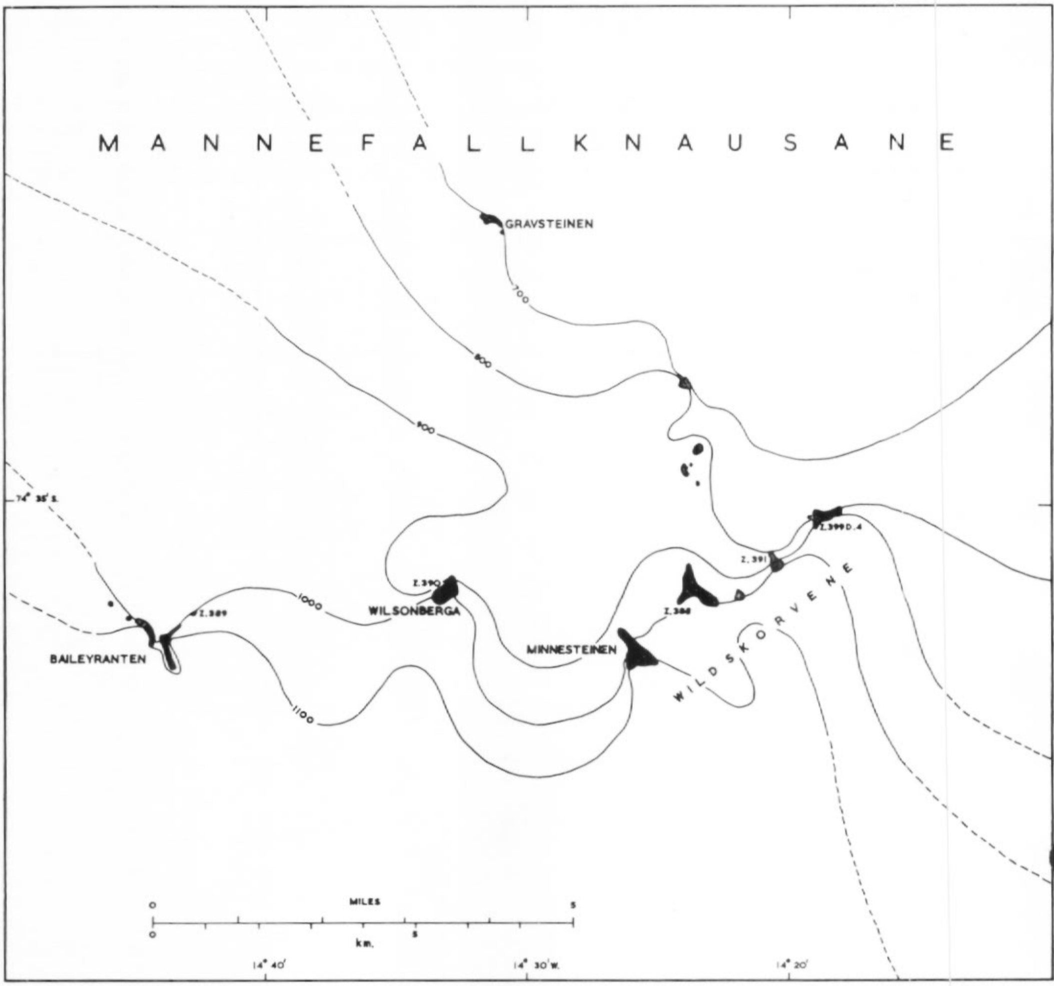

Fig. 2. Sketch map of Mannefallknausane, showing the stations visited in February 1965, and the location of specimen Z.399D.4. The contour interval is 100 m.

G. Lovegrove made a small but more representative collection of specimens which are described here. The late D. P. Wild collected specimens in February 1965 at several localities in Vestfjella and these are also described here.

Physiography

Since there are no accurate maps of Vestfjella, the following physiographic descriptions are partly based on field notes, field maps and photographs.

The wide, severely crevassed valley between Mannefallknausane and Vestjella is formed by a west-flowing ice stream fed by much of Ritscherflya. This valley is asymmetrical with its lowest part about 10 km. south of Vestfjella. In Mannefallknausane, the rock masses of Baileyranten, Wilsonberga and Wildskorvene hold back the higher ice sheet to the south, which breaks through this line of nunataks in a series of crevassed slopes and ice falls. The shapes of some of the nunataks forming Mannefallknausane, particularly Minnesteinen (Fig. 3), suggest that they were at one time completely covered by the ice sheet. At station Z.388 there is a *roche moutonnée* with traces of glacial polish and well-preserved striae, the trend of which is 155° true, and hence the direction of ice movement was probably to the north-west.

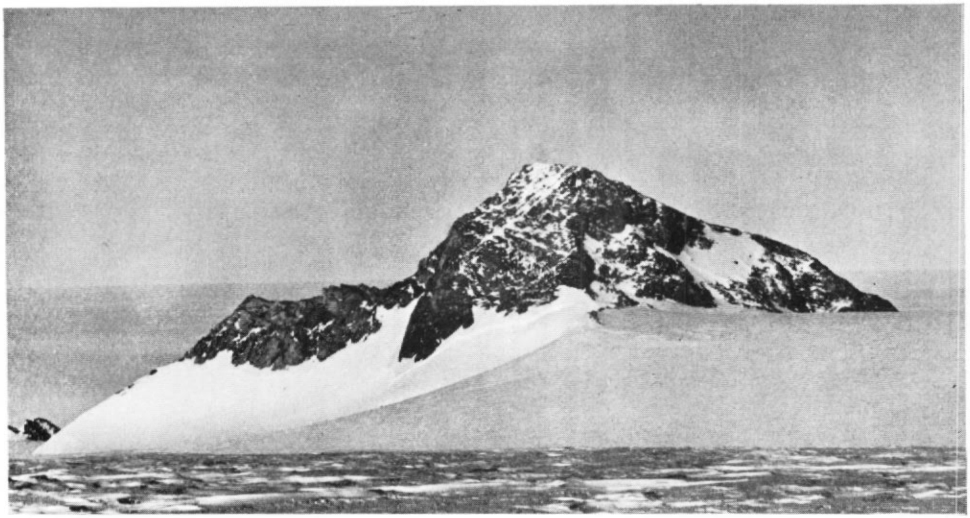

Fig. 3. Minnesteinen viewed from the south-west. The smooth south-eastern flank probably acquired its shape at a time when the ice sheet completely covered the nunatak. (Photograph by G. Blundell.)

Only the south-western part of Vestfjella has been reached overland and this is separated from the remainder of the range by a large ice rise. The nunatak group "VA Nunataks" reached by Blundell and Winterton comprises a large number of nunataks, probably rising as high as 300 m. above the snow level, on either side of an eastward-flowing glacier about 5 km. wide. The group of small nunataks farther to the south-west is referred to here as "VB Nunataks".

Geology

Gneissic and possibly plutonic rock types of the Basement Complex form nearly all of the exposures in Mannefallknausane. These rocks are intruded by basic dykes and sills which have chilled margins. At "VA Nunataks", sub-horizontal altered intermediate to basic volcanic rocks have been intruded by dolerites. The geology of "VB Nunataks" is more complex, and the main rock types are basic igneous rocks which have been thermally metamorphosed to varying degrees.

Mannefallknausane

Basement Complex

Since the age relationships between the rock types at Mannefallknausane are not known, they will be described in order of abundance in the field.

Red granite-gneiss. A granite-gneiss containing large red feldspar porphyroblasts set in a finer groundmass of quartz and dark minerals is the commonest rock type at Wildskorvene. A thin-section examination reveals that the minerals in this rock have undergone considerable post-crystallization deformation. Perthitic microcline, plagioclase and granular quartz all show signs of granulation, and the original ferromagnesian minerals have been altered by shearing to an aggregate of biotite, chlorite and quartz or feldspar (Z.399D.6). As a result of shearing, the porphyroblasts consist of aggregates of microcline, but a few small patches of myrmekite appear to post-date the deformation.

Charnockitic gneiss. Baileyranten is composed of a coarse, dark green-brown charnockitic gneiss, which may also occur in some of the outcrops north of Wildskorvene. In specimen Z.389.1 grey-green feldspar porphyroblasts attain a length of 2 cm. and there are small interstitial patches of dark minerals. The porphyroblasts are of untwinned perthitic potash feldspar and there are also smaller grains of andesine ($Ab_{66}An_{34}$) which are usually albite-twinned but sometimes on the pericline law. Tongue-like embayments of myrmekite often replace the potash feldspar marginally. There are scattered prisms of a pale orthopyroxene (eulite containing 83 per cent of ferrosilite) with $2V\alpha = 83°$. Hornblende (α = pale brown, β = green, γ = dark green), the dominant ferromagnesian mineral, appears to replace some of the orthopyroxene. Accessory minerals include biotite, magnetite, apatite and rods of zircon.

A weathered specimen of this rock (Z.390.1) was collected at Wilsonberga and, although there is no orthopyroxene in the thin section, there are patches of brown alteration products similar to those associated with the partly weathered orthopyroxene in specimen Z.389.1. In this rock plagioclase is in excess of potash feldspar and therefore it may be a weathered enderbitic gneiss (Tilley, 1936).

White porphyroblastic gneiss. Large outcrops of this rock type occur both at Wildskorvene and in the nunataks to the north, sometimes interbanded with other gneisses (personal communication from G. Lovegrove). The porphyroblasts of perthitic microcline and untwinned potash feldspar (up to 4 cm.) are set in a groundmass of strained quartz and sericitized plagioclase. Ragged biotite flakes and a little muscovite form decussate patches and there is some apatite, magnetite and zircon.

Dolerite intrusions

The gneisses of the Basement Complex are intruded by narrow basic dykes and sills with chilled margins. The sills, which are composed of olivine-dolerite, usually follow the prominent sub-horizontal jointing of the gneisses, although they are sometimes deflected by other joints. The thickest sill recorded, at Gravsteinen, is more than 12 m. thick, whereas the one exposed at station Z.391 is only 5 m. thick. The petrology and geochemistry of these intrusions are described on p. 70.

Vestfjella

"VA Nunataks"

Lavas. Flat-lying altered lavas with dolerite intrusions and minor intercalations of tuffaceous sandstone are the only rock types recorded from "VA Nunataks". Neither the top nor the bottom of the sequence was seen in the field.

In the hand specimen the lavas are vesicular and they have a green or greenish grey colour as a result of alteration. The least altered specimen (Z.395.2) is a pyroxene-andesite with a marked flow structure. The plagioclase is andesine ($Ab_{64}An_{36}$) and the fine clinopyroxene crystals are probably pigeonite. The vesicles are filled with chlorite, prehnite, calcite and quartz. The other specimens are altered to a fine greenish unidentifiable aggregate in which the outlines of the plagioclase laths are still discernible and the outlines of former phenocrysts and vesicles are clearly visible.

Tuffaceous sandstone. Interbedded with the andesitic lavas are beds of tuffaceous sandstone of unknown thickness. In the hand specimen this rock (Z.395.5) is a dense, well-indurated grey-green rock with an almost conchoidal fracture. The constituent minerals are quartz, devitrified glass (partly replaced by epidote), polysynthetically twinned plagioclase, augite, microcline, brown hornblende, zircon and green hornblende. The quartz grains, which are strained and sometimes composite, appear to have been derived from a metamorphic terrain or from a pre-existing sedimentary rock. In contrast, the fresh and angular nature and the distinct crystal or cleavage faces of some of the augite grains suggest that they are of pyroclastic origin.

Dolerite. The dolerite intrusions at "VA Nunataks" are probably sills or sheets. Although D. P. Wild did not specifically record this fact, he stated that he had not observed any faults, dykes or other transgressive features.

The petrology and geochemistry of a specimen of dolerite from "VA Nunataks" are described together with specimens from Mannefallknausane on p. 70.

"VB Nunataks"

Lavas. Specimens of amphibolized basic or intermediate vesicular lavas were collected at station Z.396. Hornblende, sometimes containing residual cores of augite, is the most abundant mineral and it forms ragged stumpy prisms in the groundmass and rods in the vesicles. Andesine laths, dusty with inclusions, are sometimes replaced by epidote. The vesicles contain chlorite, hornblende, epidote, plagioclase, calcite and quartz.

Basic granular hornfels. The specimens from station Z.397 are allotriomorphic rocks of the type Wells (1951) has described as "basic granular hornfelses" (Fig. 4a). Bytownite-labradorite

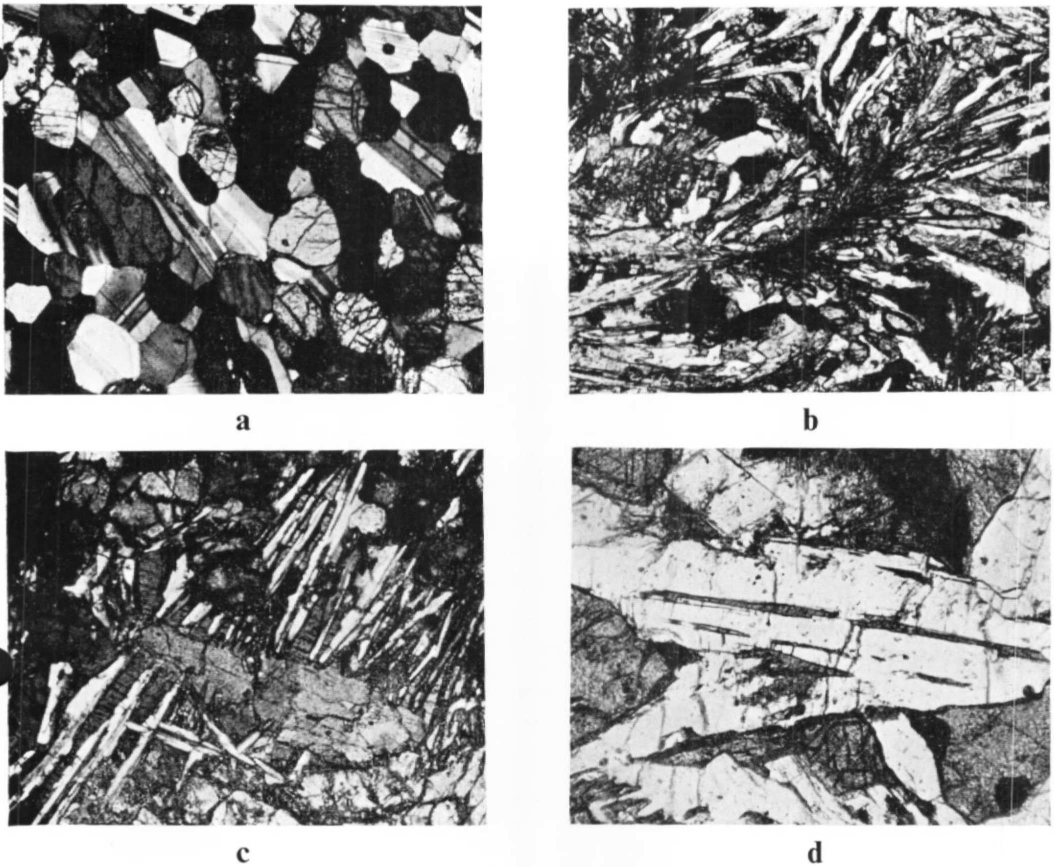

Fig. 4. a. A basic granular hornfels consisting of polysynthetically twinned plagioclase, augite and a little olivine (high relief), and magnetite; "VB Nunataks", Vestfjella (Z.397.1; X-nicols; ×50).
b. A frond-like termination on a prismatic clinopyroxene crystal in a chilled olivine-dolerite from Wildskorvene, Mannefallknausane (Z.391.5; ordinary light; ×50).
c. Sub-variolitic plagioclase laths penetrating the margins but not the cores of augite crystals; olivine-dolerite; Wildskorvene, Mannefallknausane (Z.391.6; X-nicols; ×50).
d. Plagioclase with a median stringer of augite; olivine-dolerite; Wildskorvene, Mannefallknausane (Z.391.4; ordinary light; ×50).

($Ab_{30}An_{70}$), forming about 50 per cent of the rock, occurs as crystals about 1 mm. long which are usually twinned and show a distinct preferred orientation. Inclusions of augite, magnetite and small unidentified rod-like crystals are common but most of them are comparatively large and the rock has a fresh appearance. The augite crystals are either scattered or aggregated and they contain rounded inclusions of plagioclase and magnetite, and rounded grains of magnetite about 0·1 mm. in diameter are distributed throughout the rock. Olivine forms occasional rounded crystals but it also occurs as skeletal forms as if filling interstices.

Similar rocks are associated with the basic intrusion of Ardamurchan, where Wells (1953) suggested they had been formed by four separate processes: thermal metamorphism of basalt or dolerite, autometamorphism of early chilled gabbro, intrusion of basic dykes into hot gabbro and metasomatism of sedimentary rocks. Any one of these processes could reasonably account for the occurrence at "VB Nunataks" but, in view of the known presence of amphibolized basalt nearby at station Z.396, the first process is perhaps the most likely.

Troctolite. The only specimen from station Z.398 is a troctolite, which appears to have formed through the gravitational accumulation of olivine in a basic intrusion. In the hand specimen it is a granular medium- to coarse-grained rock composed predominantly of white plagioclase and honey-coloured olivine with a few dark grey clinopyroxene crystals. A thin-section examination shows that the plagioclase is bytownite which is slightly zoned and invariably twinned on the albite law; Carlsbad twinning is less common. Olivine forms rounded crystals which are sometimes associated with or rimmed by orthopyroxene. Augite, which forms occasional large crystals ophitically enclosing small plagioclase laths, is polysynthetically twinned parallel to {100}, and some of the crystals also exhibit simple twinning parallel to this direction. Following the terminology of Wager and others (1960), this rock can be classified as a plagioclase-olivine-augite adcumulate. Since very slow crystal accumulation is necessary for the formation of adcumulates, this is likely to occur only in intrusions considerably larger than the known basic dykes and sills in Mannefallknausane and Heimefrontfjella.

Dolerite Intrusions

Petrology

Modal analyses and the mineralogy of dolerite specimens from Mannefallknausane and Vestfjella are given in Table I. Pyroxene compositions were determined from the 2V and the β refractive index (Deer and others, 1963*a*, p. 132–33). The olivine compositions were derived from the 2V, and the plagioclase compositions from extinction angles on albite twins in the finer-grained rocks and combined Carlsbad-albite twins in other rocks.

Dykes

Two dolerite dykes about 0·6 m. wide intrude the gneisses at Wildskorvene. Granular augite and labradorite ($Ab_{39}An_{61}$) are the main constituents of the groundmass, where they are sometimes separated by dark mesostasis containing feldspar microlites. The occasional euhedral olivine phenocrysts have been replaced by bowlingite or by antigorite and magnetite. Some phenocrysts of plagioclase, zoned but not twinned, are also present.

Sills

Specimen Z.395.1 from "VA Nunataks", Vestfjella, is a fresh, medium-grained subophitic dolerite which was probably intruded as a sill (p. 69). Bytownite, augite, ilmenite and an orange-brown alteration product are the main constituents (Table I). In some cases the orange-brown material appears to replace an earlier mineral but in others it is interstitial, possibly resulting from the alteration of glass or mesostasis.

Specimens collected at least 5 km. south-west of station Z.395 contain pigeonite and hypersthene (Brown, 1967), and it seems likely that there are a number of dolerite intrusions at "VA Nunataks".

A series of specimens collected from the sill at station Z.391 (Wildskorvene, Mannefallknausane) and a specimen (Z.399D.4) from an adjacent outcrop at Wildskorvene show that there are marked differences in composition at different levels in the sill (Fig. 5). Specimen Z.399D.4 was collected from what appears to be an extension of the same sill, about 1 km.

TABLE I. MODAL ANALYSES AND MINERALOGY OF DOLERITES FROM MANNEFALLKNAUSANE AND VESTFJELLA, DRONNING MAUD LAND

	1	2	3	4	5	6	7	8	9
Plagioclase	37·6*	27·8	22·2	26·4	45·3	53·5	43·0	45·4	24·9
Clinopyroxene	36·1	38·0	26·4	47·5	40·7	31·9	31·5	36·3	46·2
Biotite	—	1·0	3·5	—	0·9	tr	3·0	—	—
Olivine	—	28·2	43·3	10·3	1·6	6·1	0·4	—	19·8
Pseudomorphs†	5·8	—	—	8·3	—	—	—	2·0	—
Opaques	—	4·1	2·7	6·4	6·2	5·0	13·7	1·4	7·8
Calcite	—	—	—	—	tr	—	—	—	—
Mesostasis	20·5	—	—	—	—	—	4·8	14·9	—
Others‡	—	0·9	1·9	1·1	5·3	3·5	3·6§	—	1·3
PHENOCRYSTS									
Plagioclase:									
Composition	An_{67-74}	—	—	—	—	—	—	—	—
GROUNDMASS									
Olivine:									
$2V_\gamma$	—	90°±3°	94°±3°	88°±3°	100°±4°	109°±5°	114°±5°	—	85°±5°
Composition	—	Fa_{14}	Fa_{23}	Fa_{11}	Fa_{35}	Fa_{53}	Fa_{64}	—	Fa_{4}
Plagioclase:									
Composition	An_{61}	An_{58}	An_{61}	An_{58}	An_{63}	An_{60}	An_{65-45}	An_{72}	An_{60}
Clinopyroxene:									
$2V_\gamma$	51°	54°	56°	52°	50°	51°	43°	55°	52°
β	1·698	1·701	1·700	1·710	1·702	1·698	1·717	1·704	1·702
Composition (Ca.Mg.Fe)	42.35.23	44.32.24	46.32.22	41.28.31	41.33.26	42.35.23	33.27.40	45.30.25	42.32.26
Identity	Augite	Augite	Salite	Ferro-augite	Augite	Augite	Ferro-augite	Salite	Augite

tr Trace.

* Including 1·9 per cent present as phenocrysts.
† Of chlorite, etc.; probably after olivine.
‡ Mainly viridite.
§ Includes epidote.

Variations of ±3° in the 2V measurements of the olivines are considered to be experimental error; larger variations reflect zoning and differences of composition between crystals in the same thin section.

1. Z.388.1 Dolerite dyke, Wildskorvene, Mannefallknausane.
2. Z.391.6 Olivine-dolerite (cumulate), 15 cm. above the base of a sill 5 m. thick, Wildskorvene, Mannefallknausane.
3. Z.391.1 Picrodolerite (cumulate), centre of the sill at Wildskorvene, Mannefallknausane.
4. Z.391.5 Chilled olivine-dolerite, upper margin of the sill at Wildskorvene, Mannefallknausane.
5. Z.391.4 Olivine-dolerite, 15 cm. below the upper margin of the sill at Wildskorvene, Mannefallknausane.
6. Z.391.2 Olivine-dolerite, 0·6 m. below the upper margin of the sill at Wildskorvene, Mannefallknausane.
7. Z.399D.4 Iron-rich dolerite, near the top of a thin sill, Wildskorvene, Mannefallknausane.
8. Z.395.1 Dolerite, "VA Nunataks", Vestfjella.
9. Z.391.3 Chilled olivine-dolerite, lower margin of the sill at Wildskorvene, Mannefallknausane.

north-east of station Z.391 and at the same altitude. Only the uppermost 0·5 m. of the sill is exposed where the specimen was collected, but exposures on the other side of the nunatak indicate that the total thickness is approximately the same as at station Z.391.

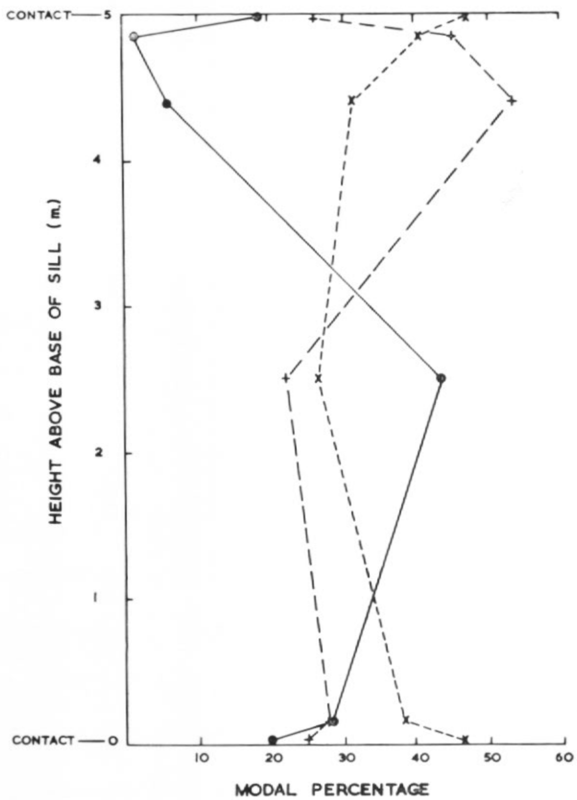

Fig. 5. Variation in the modal percentages of olivine, clinopyroxene and plagioclase at different levels in the sill at station Z.391, Wildskorvene, Mannefallknausane.
● Olivine. × Clinopyroxene. + Plagioclase.

Although the modal percentages of the minerals vary in the different specimens, the composition of each individual mineral is relatively constant except for those which crystallized from the residuum of the magma. The plagioclase is labradorite (approximately $Ab_{40}An_{60}$), although in the upper part of the sill where the plagioclase is zoned the rims are more sodic. The clinopyroxene of the upper chilled margin is ferro-augite (Fig. 6) but at most levels within the sill it is a calcic augite. Specimen Z.391.1, a cumulate, contains salite with a composition close to that of the augite in the other specimens, but in specimen Z.399D.4, which is a product of late crystallization, iron enrichment has resulted in the formation of ferro-augite. The composition of the olivine varies more widely; at most levels within the sill it is chrysolite but in the last to crystallize it is either hyalosiderite or hortonolite.

Although there appears to be a continuous gradation between the rock types at different levels in the sill, it can be divided into three main petrological units: a chilled marginal zone, a lower or olivine-rich zone and a narrow upper zone representing the final differentiate of the magma.

The few millimetres at the sill margin are formed by a cryptocrystalline chilled rock containing olivine phenocrysts and small octahedra of picotite. The olivine crystals are euhedral with a maximum length of about 0·7 mm., although there are some exceptionally elongated crystals and also instances of adjacent euhedra with the same optical orientation. Both of these phenomena have been ascribed by Drever and Johnston (1957) to rapid crystallization of phenocrysts *in situ*. The reason for the difference in clinopyroxene composition (Table I) at the upper and lower contacts is not known but it may be related to the different habits assumed by the mineral. At the lower contact the clinopyroxene is granular, whereas at the upper margin it forms feather-like or dendritic crystals (Fig. 4b).

Where the rock is coarser-grained, the textural relationships reflect the order of crystallization of the minerals. Olivine, the first mineral to form, does not contain inclusions of plagioclase

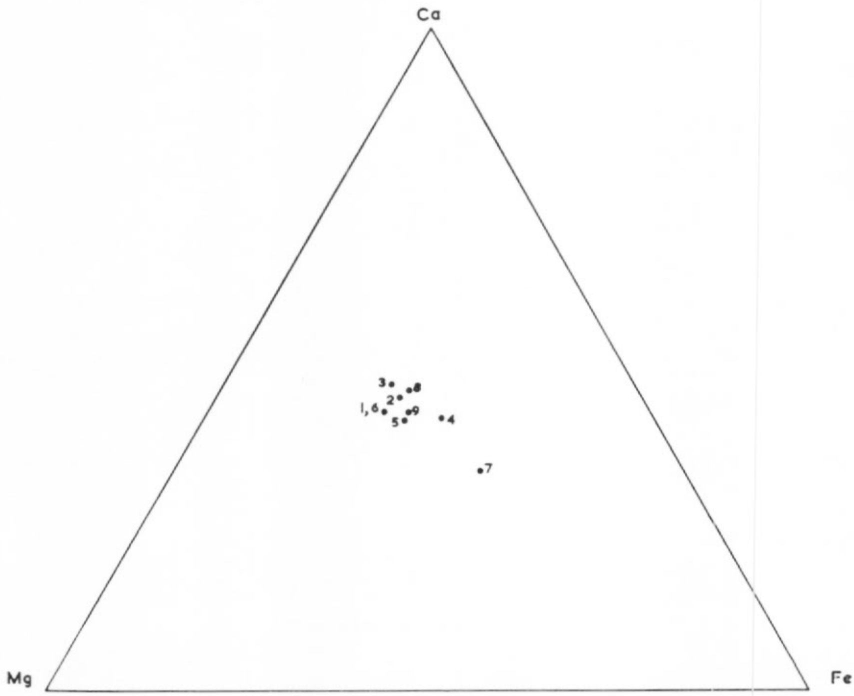

Fig. 6. Triangular variation diagram on the coordinates Ca–Fe–Mg (atomic per cent), showing the optically determined compositions of clinopyroxenes in dolerites from Mannefallknausane and Vestfjella. The numbering of the specimens is the same as in Table I.

or clinopyroxene but it is sometimes enclosed by the latter mineral. The augite crystals often enclose plagioclase laths but frequently the cores of large augites are conspicuously free of plagioclase laths which penetrate their margins (Fig. 4c). It is probable that the augite began to crystallize before the plagioclase, possibly at a higher level from which it then sank.

In the lower zone, which in fact extends above the centre of the sill, the most significant feature is the high proportion of modal olivine. In specimen Z.391.1, olivine forms 43 per cent of the rock, which would be classified as a picrodolerite. The texture of the rock is hypidiomorphic and coarse.

Zoned plagioclase is predominant in the upper zone and the laths frequently contain median stringers of clinopyroxene, sometimes aligned along the albite twin planes (Fig. 4d). The olivine is richer in iron than at other levels and slight variations of 2V in individual crystals are believed to be due to zoning. This olivine often forms optically continuous skeletal crystals which enclose plagioclase laths and which are partly altered to aggregates of finely divided material. In specimen Z.399D.4, which is the extreme differentiate found, there are small patches of granophyric mesostasis. This rock also contains a very small amount of iron-rich olivine (approximately $Fo_{36}Fa_{64}$).

Deuteric alteration is restricted to the partial replacement of the iron-rich olivine in the upper part of the sill by a fine green aggregate of unidentifiable material. In the field, occasional sheaves of prehnite were observed lining joint planes. Zeolites are rare and the only recorded example is in the thin section of specimen Z.391.5, showing the upper contact of the sill with the country rock. This mineral forms radiating aggregates with parallel extinction, it is length fast and biaxial positive with a large 2V; these optical properties agree with those of mordenite (Deer and others, 1963*b*).

Walker (1958) has discussed the phenomenon of variation within dolerite intrusions and suggested six possible causes: crystal fractionation, pegmatitic or aplitic segregation and intrusion, hydrothermal reaction, fusion, rheomorphism and metasomatism of the wall rock, multiple intrusion and assimilation of wall rock. For the sill at Wildskorvene both the mineralogy of the rock and the sharp contacts with the country rock preclude all of these causes except crystal fractionation and multiple intrusion. Sharp banding, discontinuities in texture or composition were not observed in the field, although the differences between the various levels were visible as gradual changes in texture and in the relative proportions of the light and dark minerals. Because of this and the comparatively constant compositions of the individual minerals, multiple intrusion is unlikely to have been the cause of differentiation, whereas crystal fractionation would satisfactorily explain the observed features. The olivine-rich rocks are considered to have resulted from gravitational settling of olivine, and the relatively constant modal percentages of clinopyroxene throughout the sill (Fig. 5) suggest that, while the magma was being displaced upward by the sinking olivine, the clinopyroxene was also sinking but more slowly than the olivine.

Hamilton (1964) has suggested that some of the basic sills in Victoria Land have been differentiated by liquid fractionation. However, this process is unlikely to have affected the sill at Wildskorvene, because the scarcity of zeolites and the limited deuteric alteration indicate that the volatile content was low.

Flowage differentiation (Bhattacharji and Smith, 1964) may have affected the magma during its emplacement but this process alone does not appear to be capable of causing late-stage iron enrichment. The plagioclase : pyroxene ratio would also remain relatively unaffected by the olivine concentration in a flowage-differentiated intrusion, whereas Fig. 5 shows that the modal percentages of these minerals vary independently of one another.

Crystal settling in small bodies of magma appears to be uncommon and Walker (1958) has suggested that, while olivine-dolerite intrusions are more likely to be affected by this process, it is usually restricted to intrusions thicker than 30·5 m. In all cases where crystal settling is known to have occurred in small bodies of magma, it is significant that the magma is unusually undersaturated. Fuller (1939) has noted the concentration of olivine by gravity in olivine-basalt flows, some of which are only 46 cm. thick, and he considered that the low viscosity of the magma reflected the high volatile content, as shown by the texture and the presence of zeolites. A similar conclusion was reached by Mathews and others (1964), who studied olivine concentration in the lower parts of lava pillows in Iceland, although the thermal studies by Yagi (1964) suggested that the viscosity was not unreasonably low.

The above examples of crystal settling can be compared with the Little Whin Sill, in which Dunham and Kaye (1965) found no evidence for crystal settling although their calculations showed that the cooling time was sufficiently long for early-formed olivine and clinopyroxene to have sunk in the magma. They concluded that crystal settling had been prevented by the abundant nucleation which resulted in the formation of a mass of tiny crystals when the magma was chilled on intrusion, and that the dominant controls affecting crystal settling were the degree of chilling and the sill thickness. They have also pointed out that a comparison with synthetic systems implies that the magma composition (which contained about 5 per cent normative quartz) was close to the ternary point at which olivine, plagioclase, orthopyroxene and clinopyroxene precipitate simultaneously.

The investigations of Yoder and Tilley (1962) and Yagi (1964) have shown that the crystallization temperature of olivine in an olivine-tholeiite magma increases considerably with the normative olivine content, whereas the crystallization temperatures of plagioclase and clinopyroxene are scarcely affected. Yoder and Tilley (1962) found that in two tholeiites containing 1·92 per cent normative quartz and 9·14 per cent normative olivine, respectively, the temperature differences between the crystallization of the olivine and the appearance of the next silicate phase (clinopyroxene) were 25° and 50°C, respectively. However, Yagi (1964) found that an increase in the amount of normative olivine from 10·52 to 24·06 per cent in Icelandic lavas raised the crystallization temperature of the olivine from 1194° to 1335°C. In the first case, plagioclase was the first mineral to crystallize but in the second there was a difference of 140°C between the appearance of the olivine and the plagioclase.

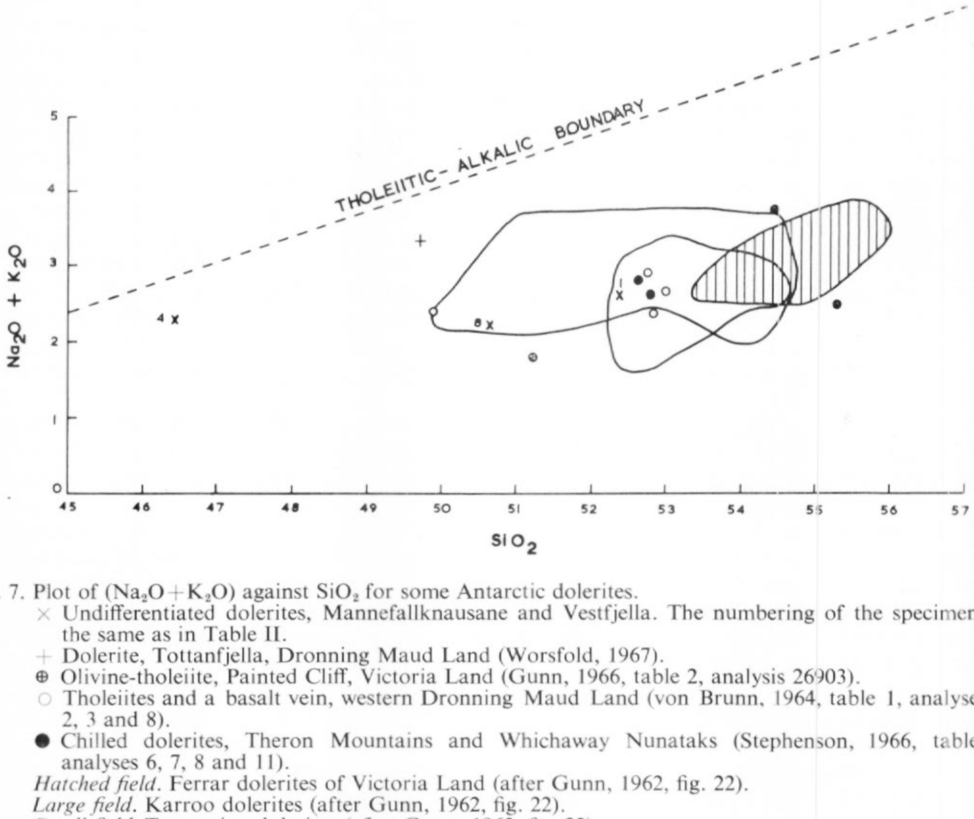

Fig. 7. Plot of (Na_2O+K_2O) against SiO_2 for some Antarctic dolerites.
× Undifferentiated dolerites, Mannefallknausane and Vestfjella. The numbering of the specimens is the same as in Table II.
\+ Dolerite, Tottanfjella, Dronning Maud Land (Worsfold, 1967).
⊕ Olivine-tholeiite, Painted Cliff, Victoria Land (Gunn, 1966, table 2, analysis 26903).
○ Tholeiites and a basalt vein, western Dronning Maud Land (von Brunn, 1964, table 1, analyses 1, 2, 3 and 8).
● Chilled dolerites, Theron Mountains and Whichaway Nunataks (Stephenson, 1966, table 4, analyses 6, 7, 8 and 11).
Hatched field. Ferrar dolerites of Victoria Land (after Gunn, 1962, fig. 22).
Large field. Karroo dolerites (after Gunn, 1962, fig. 22).
Small field. Tasmanian dolerites (after Gunn, 1962, fig. 22).
Tholeiitic-alkalic boundary. After Macdonald and Katsura (1964, fig. 1).

It is therefore suggested that the behaviour of a chilled magma is affected by its degree of undersaturation. If the normative olivine content is high and the temperature difference between the crystallization of olivine and the succeeding silicate phase is large, then the initial drop in temperature may be within this difference. Only olivine will form initially and this is less likely to form a fine crystal mesh such as formed in the Little Whin Sill (Dunham and Kaye, 1965). Under these conditions, a low viscosity may be retained sufficiently long for the early-formed crystals to sink (or float).

Geochemistry

Eight new chemical analyses of dolerites are given in Table II; two of these are of chilled rocks (Z.388.1, 391.5) and one is of a specimen (Z.395.1) whose field relations are unknown. The other five specimens (Z.391.1,2,4,6, 399D.4) and the chilled rock (Z.391.5) apparently represent stages in the differentiation of an undersaturated magma.

TABLE II. CHEMICAL ANALYSES OF DOLERITES FROM MANNEFALLKNAUSANE AND VESTFJELLA, DRONNING MAUD LAND

	1	2	3	4	5	6	7	8
SiO_2	51·19	45·62	43·89	46·01	48·52	47·85	48·26	49·28
TiO_2	1·17	1·34	1·05	1·69	1·84	1·95	4·24	1·39
Al_2O_3	13·23	9·23	7·20	11·59	12·85	12·91	11·15	13·20
Fe_2O_3	5·23	3·05	1·02	6·14	5·03	4·79	5·87	3·33
FeO	6·07	10·74	12·05	9·09	7·47	8·62	12·00	7·99
MnO	0·16	0·19	0·19	0·18	0·17	0·18	0·23	0·17
MgO	7·56	17·39	24·30	10·84	7·08	6·69	4·29	7·55
CaO	10·25	9·32	7·29	10·97	12·47	12·29	8·78	11·89
Na_2O	2·11	1·70	1·40	2·11	2·39	2·49	2·82	2·00
K_2O	0·47	0·11	0·18	0·16	0·19	0·23	0·95	0·14
H_2O+	1·51	0·94	0·92	0·99	1·15	1·05	0·23	1·80
H_2O-	0·65	0·09	0·18	0·35	0·31	0·26	0·41	0·50
P_2O_5	0·32	0·22	0·03	0·16	0·11	0·13	0·59	0·26
CO_2	Nil	0·22	0·20	0·19	0·22	0·14	0·05	0·11
TOTAL	99·92	100·16	99·90	100·47	99·80	99·58	99·87	99·61
				ANALYSES LESS TOTAL WATER (Recalculated to 100)				
SiO_2	52·36	46·03	44·42	46·41	49·34	48·69	48·63	50·64
TiO_2	1·20	1·35	1·06	1·71	1·87	1·98	4·27	1·43
Al_2O_3	13·53	9·31	7·29	11·69	13·07	13·14	11·24	13·56
Fe_2O_3	5·35	3·08	1·03	6·19	5·12	4·88	5·92	3·42
FeO	6·21	10·83	12·20	9·17	7·60	8·78	12·09	8·21
MnO	0·17	0·19	0·19	0·18	0·17	0·18	0·23	0·18
MgO	7·73	17·55	24·60	10·94	7·20	6·81	4·32	7·76
CaO	10·48	9·40	7·38	11·07	12·68	12·51	8·85	12·22
Na_2O	2·16	1·71	1·42	2·13	2·43	2·53	2·84	2·06
K_2O	0·48	0·11	0·18	0·16	0·19	0·23	0·96	0·14
P_2O_5	0·33	0·22	0·03	0·16	0·11	0·13	0·60	0·27
CO_2	Nil	0·22	0·20	0·19	0·22	0·14	0·05	0·11
				NORMS				
Q	7·68	—	—	—	2·23	0·60	5·30	3·45
or	2·84	0·66	1·07	0·97	1·14	1·38	5·65	0·85
ab	18·26	14·50	11·54	18·00	20·56	21·44	24·04	17·38
an	25·81	17·38	12·99	21·87	24·17	23·78	15·07	27·36
ne	—	—	0·24	—	—	—	—	—
di	19·20	21·19	17·73	24·66	29·43	29·61	20·36	24·97
hy	15·41	10·58	—	13·35	10·73	11·72	11·38	17·42
ol	—	27·64	52·38	8·12	—	—	—	—
mt	7·75	4·46	1·50	8·98	7·41	7·07	8·57	4·96
il	2·27	2·56	2·02	3·24	3·55	3·76	8·11	2·71
ap	0·78	0·53	0·07	0·38	0·27	0·31	1·41	0·64
cc	—	0·50	0·46	0·43	0·51	0·33	0·11	0·26
				ELEMENT PERCENTAGES				
Si^{+4}	24·48	21·52	20·77	21·70	23·07	22·76	22·73	23·67
Al^{+3}	7·16	4·93	3·86	6·17	6·92	6·95	5·95	7·18
Fe^{+3}	3·74	2·15	0·72	4·33	3·58	3·41	4·14	2·39
Mg^{+2}	4·66	10·59	14·84	6·60	4·34	4·11	2·61	4·68
Fe^{+2}	4·83	8·42	9·48	7·13	5·91	6·82	9·40	6·38
Na^{+1}	1·60	1·27	1·05	1·58	1·80	1·88	2·11	1·53
Ca^{+2}	7·49	6·72	5·27	7·91	9·06	8·94	6·33	8·73
K^{+1}	0·40	0·09	0·15	0·13	0·16	0·19	0·80	0·12
Ti^{+4}	0·72	0·81	0·66	1·03	1·12	1·19	2·56	0·86
Mn^{+2}	0·13	0·15	0·15	0·14	0·13	0·14	0·18	0·14
P^{+5}	0·14	0·10	0·01	0·07	0·05	0·06	0·26	0·12
C^{+4}	—	0·06	0·05	0·05	0·06	0·04	0·01	0·03
O^{-2}	44·65	43·19	42·99	43·16	43·80	43·51	42·92	44·17
Position [(⅓Si + K) − (Ca + Mg)]	−3·59	−10·05	−13·04	−7·15	−5·55	−5·27	−0·56	−5·40
Fe	64·8	50·0	40·7	63·5	68·6	71·3	83·8	65·2
Mg	35·2	50·0	59·3	36·5	31·4	28·7	16·2	34·8
Fe	56·3	47·0	38·9	58·0	60·1	62·4	71·0	58·1
Mg	30·6	47·0	56·5	33·4	27·5	25·0	13·7	31·0
Alk	13·1	6·0	4·6	8·6	12·4	12·6	15·3	10·9
Ca	78·9	83·2	81·5	82·2	82·2	81·2	68·5	84·1
Na	16·9	15·7	16·2	16·4	16·3	17·1	22·8	14·7
K	4·2	1·1	2·3	1·4	1·5	1·7	8·7	1·2

1. Z.388.1 Dolerite dyke, Wildskorvene, Mannefallknausane.
2. Z.391.6 Olivine-dolerite (cumulate), 15 cm. above the base of a sill 5 m. thick, Wildskorvene, Mannefallknausane.
3. Z.391.1 Picrodolerite (cumulate), centre of the sill at Wildskorvene, Mannefallknausane.
4. Z.391.5 Chilled olivine-dolerite, upper margin of the sill at Wildskorvene, Mannefallknausane.
5. Z.391.4 Olivine-dolerite, 15 cm. below the upper margin of the sill at Wildskorvene, Mannefallknausane.
6. Z.391.2 Olivine-dolerite, 0·6 m. below the upper margin of the sill at Wildskorvene, Mannefallknausane.
7. Z.399D.4 Iron-rich dolerite, near the top of a thin sill, Wildskorvene, Mannefallknausane.
8. Z.395.1 Dolerite, "VA Nunataks", Vestfjella.

(All analyses by L. M. Juckes.)

Analyses 1, 4 and 8 (Table II, water-free) are plotted on the coordinates SiO_2 and (Na_2O + K_2O) in Fig. 7. Included in this diagram are the fields for the Ferrar dolerites of Victoria Land, the Karroo dolerites of South Africa and the Tasmanian dolerites (after Gunn, 1962), analyses of four chilled dolerites from the Theron Mountains and the Whichaway Nunataks, Coats Land (Stephenson, 1966), analyses of three tholeiites and a basalt vein from western

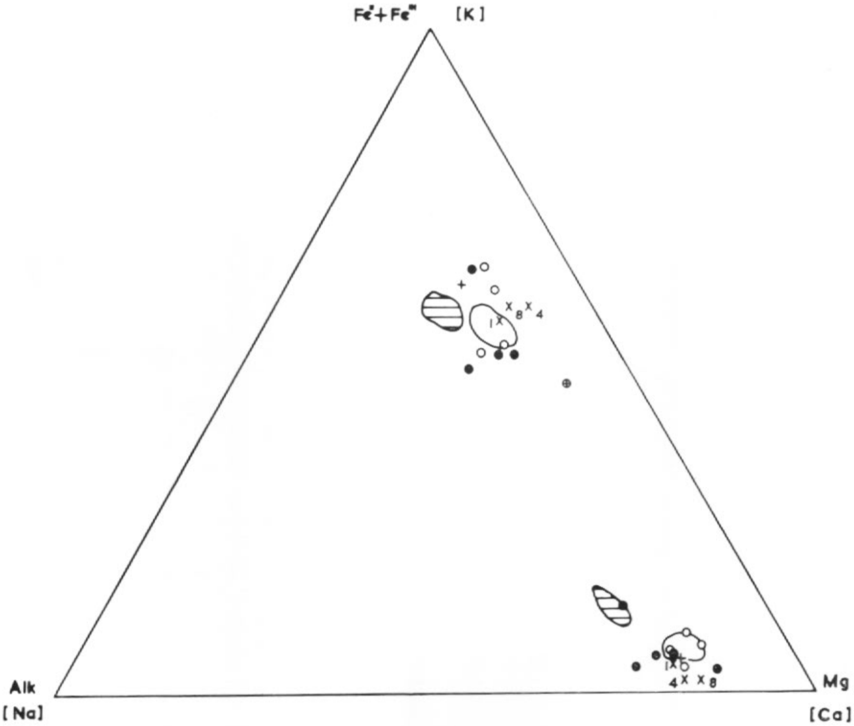

Fig. 8. Triangular variation diagrams plotted on the coordinates (Fe″+Fe‴)–Mg–Alk (upper part of diagram) and Ca–Na–K (lower part of diagram).

- × Undifferentiated dolerites, Mannefallknausane and Vestfjella. The numbering of the specimens is the same as in Table II.
- + Dolerite, Tottanfjella, Dronning Maud Land (Worsfold, 1967).
- ⊕ Olivine-tholeiite, Painted Cliff, Victoria Land (Gunn, 1966, table 2, analysis 26903).
- ○ Tholeiites and a basalt vein, western Dronning Maud Land (von Brunn, 1964, table 1, analyses 1, 2, 3 and 8).
- ● Chilled dolerites, Theron Mountains and Whichaway Nunataks (Stephenson, 1966, table 4, analyses 6, 7, 8 and 11).

Hatched field. Pigeonite-tholeiites of Victoria Land (after Gunn, 1966, table 2, analyses 4229, 4266, 4174, 4074 and 4080).

Unshaded field. Hypersthene-tholeiites of Victoria Land (after Gunn, 1966, table 2, analyses 4012, 4285, 4083 and 4144).

Dronning Maud Land (von Brunn, 1964), and an analysis of a dolerite from Tottanfjella, Dronning Maud Land (Worsfold, 1967). The wide scatter of the plotted points suggests that, while the larger intrusions of Victoria Land may have a limited compositional range in comparison with the Karroo and Tasmanian suites (Gunn, 1962), the Ferrar suite in fact varies widely in composition on a continental scale. All of the dolerites from Dronning Maud Land and two of the four from Coats Land are deficient in silica in comparison with the Victoria Land dolerites, and this may signify a greater variation in the composition of the dolerite parental magma than hitherto considered by other authors.

These rocks have also been plotted on triangular variation diagrams with the coordinates (Fe″+Fe‴)–Mg–Alk and Ca–Na–K (Fig. 8), which show that there is little variation in these elements and that it does not follow any clear pattern. However, it is apparent that the dolerite intrusions of Dronning Maud Land and Coats Land have a consistently lower potassium content than the more acid Victoria Land intrusions.

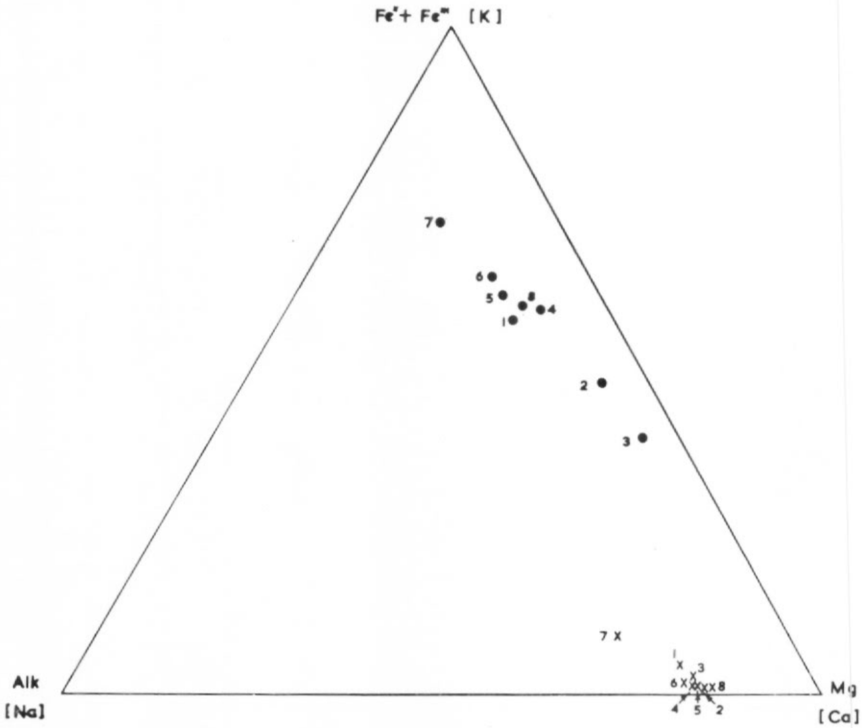

Fig. 9. Triangular variation diagrams plotted on the coordinates (Fe″+Fe‴)–Mg–Alk (●) and Ca–Na–K (×) for dolerite specimens from Mannefallknausane and Vestfjella. The numbering of the specimens is the same as in Table II.

The geochemistry of the differentiated sill at Wildskorvene seems to reflect the differentiation mechanism (p. 73). The settling of olivine and possibly augite crystals from the upper part of the sill has resulted in enrichment in iron in the upper levels and in magnesium at the base. The differentiation trend indicated by the positions of these rocks on triangular variation diagrams with the coordinates (Fe″+Fe‴)–Mg–Alk and Ca–Na–K (Fig. 9) shows that enrichment in alkalis was only significant in the final stages.

Regional Correlation

The Basement Complex gneisses of Mannefallknausane are typical of the granulite facies of regional metamorphism (Turner and Verhoogen, 1960). These gneisses are part of the Basement Complex of eastern Antarctica which is exposed at many other localities. The charnockitic gneiss is particularly significant in that it forms an extension of the east Antarctic charnockite province of Klimov and others (1964*a*).

The lavas of "VA Nunataks", Vestfjella, are intruded by dolerite with an age of 168±6 or 172±6 m. yr. (Rex, 1967), and the same lavas may extend to "VB Nunataks" where they appear to have been thermally metamorphosed. The age of the lavas themselves is not yet known; their possible equivalents in other areas include the unaltered basalts of Heimefrontfjella, which overlie (?) Lower Permian sediments and the altered basic to intermediate lavas and tuffs north of Pencksøkket (Roots, 1953). von Brunn (1964) tentatively suggested a Jurassic age for the latter volcanic sequence but Klimov and others (1964*b*) considered it to be either Precambrian or Lower Palaeozoic.

Both the absolute age of a dolerite specimen from "VA Nunataks", Vestfjella (Rex, 1967), and its mineralogical composition (Brown, 1967) show it is apparently related to the Ferrar suite of Victoria Land, and it is therefore possible that the dolerite intrusions described here are of the same age. The specimen of troctolite from "VB Nunataks" is a product of more complete crystal fractionation than hitherto recorded in any other intrusion in east Antarctica except Dufek Massif (Aughenbaugh, 1961) and hence its age and affinities are uncertain.

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REFERENCES

AUGHENBAUGH, N. B. 1961. Preliminary report on the geology of the Dufek Massif. *IGY Glaciol. Rep.*, No. 4, 155–93.

BHATTACHARJI, S. *and* C. H. SMITH. 1964. Flowage differentiation. *Science, N.Y.*, N.S., **145**, No. 3628, 150–53.

BLUNDELL, D. J. 1964. Orientated dolerite sample from Dronning Maud Land. *British Antarctic Survey Bulletin*, No. 4, 57.

BROWN, J. W. 1967. Jurassic dolerites from the Falkland Islands and Dronning Maud Land. *British Antarctic Survey Bulletin*, No. 13, 89–92.

BRUNN, V. VON. 1964. Note on some basic rocks in western Dronning Maud Land. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 415–18.)

DEER, W. A., HOWIE, R. A. *and* J. ZUSSMAN. 1963*a*. *Rock-forming minerals. Vol. 2. Chain silicates*. London, Longmans, Green and Co. Ltd.

———., ———. *and* ———. 1963*b*. *Rock-forming minerals. Vol. 4. Framework silicates*. London, Longmans, Green and Co. Ltd.

DREVER, H. I. *and* R. JOHNSTON. 1957. Crystal growth of forsteritic olivine in magmas and melts. *Trans. R. Soc. Edinb.*, **63**, Pt. 2, No. 13, 289–315.

DUNHAM, A. C. *and* M. J. KAYE. 1965. The petrology of the Little Whin Sill, County Durham. *Proc. Yorks. geol. Soc.*, **35**, Pt. 2, 229–76.

FULLER, R. E. 1939. Gravitative accumulation of olivine during the advance of basaltic flows. *J. Geol.*, **47**, No. 3, 303–13.

GUNN, B. M. 1962. Differentiation in Ferrar Dolerites, Antarctica. *N.Z. Jl Geol. Geophys.*, **5**, No. 5, 820–63.

———. 1966. Modal and element variation in Antarctic tholeiites. *Geochim. cosmochim. Acta*, **30**, No. 9, 881–920.

HAMILTON, W. 1964. Diabase sheets differentiated by liquid fractionation, Taylor Glacier region, south Victoria Land. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 442–54.)

KLIMOV, L. V., RAVICH, M. G. *and* D. S. SOLOVIEV. 1964*a*. Charnockites of east Antarctica. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 455–62.)

———., ———. *and* ———. 1964*b*. Geology of the Antarctic platform. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 681–91.)

MACDONALD, G. A. *and* T. KATSURA. 1964. Chemical composition of Hawaiian lavas. *J. Petrology*, **5**, Pt. 1, 82–133.

MATHEWS, W. H., THORARINSSON, S. *and* N. B. CHURCH, 1964. Gravitative settling of olivine in pillows of an Icelandic basalt. *Am. J. Sci.*, **262**, No. 8, 1036–40.

REX, D. C. 1967. Age of a dolerite from Dronning Maud Land. *British Antarctic Survey Bulletin*, No. 11, 101.

ROOTS, E. F. 1953. Preliminary note on the geology of western Dronning Maud Land. *Norsk. geol. Tidsskr.*, **32**, Ht. 1, 18–33.

STEPHENSON, P. J. 1966. Geology. 1. Theron Mountains, Shackleton Range and Whichaway Nunataks (with a section on palaeomagnetism of the dolerite intrusions, by D. J. Blundell). *Scient. Rep. transantarct. Exped.*, No. 8, 79 pp.

TILLEY, C. E. 1936. Enderbite, a new member of the charnockite series. *Geol. Mag.*, **73**, No. 7, 312–16.
TURNER, F. J. *and* J. VERHOOGEN. 1960. *Igneous and metamorphic petrology*. 2nd edition. New York, Toronto and London, McGraw-Hill Book Company, Inc.
WAGER, L. R., BROWN, G. M. *and* W. J. WADSWORTH. 1960. Types of igneous cumulates. *J. Petrology*, **1**, Pt. 1, 73–85.
WALKER, F. 1958. The causes of variation in dolerite intrusions. (*In* CAREY, S. W., *ed. Dolerite: a symposium*. Hobart, University of Tasmania, 1–25.)
WELLS, M. K. 1951. Sedimentary inclusions in the hypersthene-gabbro, Ardnamurchan, Argyllshire. *Mineralog. Mag.*, **29**, No. 214, 715–36.
————. 1953. The structure and petrology of the hypersthene-gabbro intrusion, Ardnamurchan, Argyllshire. *Q. Jl geol. Soc. Lond.*, **109**, Pt. 4, No. 436, 367–95.
WORSFOLD, R. J. 1967. *The geology of southern Heimefrontfjella, Dronning Maud Land*. Ph.D. thesis, University of Birmingham, 176 pp. [Unpublished.]
YAGI, K. 1964. Pillow lavas of Keflavik, Iceland, and their genetic significance. *J. Fac. Sci. Hokkaido Univ.*, Ser. 4, **12**, No. 2, 171–82.
YODER, H. S. *and* C. E. TILLEY. 1962. Origin of basalt magmas: an experimental study of natural and synthetic rock systems. *J. Petrology*, **3**, Pt. 3, 342–532.