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LAYERED INTRUSIONS IN THE FERRAR DOLERITES, ANTARCTICA

BERNARD M. GUNN
University of Otago, Dunedin, New Zealand

ABSTRACT

The Ferrar Dolerites are of Lower to Middle Jurassic age and occur as sheets, sills, bosses, dikes and related lavas throughout 60,000 square miles of Antarctica. Undifferentiated dolerite consists of augite, pigeonite, plagioclase and interstitial mesostasis, but in several sills and dike-like bodies hypersthene is found in large amounts in a zone extending from about 150 to about 400 feet above the base of a sill 800 feet thick. Lenses of bytownitic anorthosite are found within the hypersthene zone. In the upper parts of the sills the dolerite is granophyric and contains lenses of coarse-grained pegmatoid and sometimes bands of granophyre. Chilled margins have about 45% total pyroxene, 5% MgO, 53% SiO_2; whereas the hypersthene zones have 60–70% pyroxene, 17–21% MgO; compared with the granophyres and pegmatoids which have 7–10% pyroxene, 1–3% MgO and up to 67% SiO_2.

The crystallization of hypersthene is thought to be governed by several factors including composition of magma and pressure.

INTRODUCTION

Dolerites of tholeiitic affinities are now known to be exposed over a distance of 2,800 miles across the Antarctic continent though the width of outcrop seldom exceeds 20 miles. The name Ferrar Dolerites was proposed for them by Harrington (1958) and such dolerites have been described or reported from Oates Land (Browne, 1923; Klimov and Solovyev, 1958), the Arctic Institute Range (Weihaupt 1961), along the entire length of the Victoria Mountain System from Terra Nova Bay to the Horlick Mountains (Ferrar, 1907; Webb and McKelvey, 1959; Gunn and Warren, 1962; Skinner, 1961; Laird, 1961; Gunn and Walcott, 1962; Gould, 1931; Long, *pers. comm*), from the Whichaway Nunataks and Theron Mountains (Stephenson, *pers. comm*) and from the western Dronning Maud Land mountains (Roots, 1953).

In the McMurdo Sound region a sheet of dolerite known as the Basement Sill is intruded into the metamorphic and plutonic basement rocks and is 700 to 900 feet thick. A second sill (the Peneplain Sill) is 900 to 1300 feet thick and is intruded between the Kukri Peneplain surface which is cut across the Basement rocks, and the overlying flat-bedded Beacon Sandstone. The Beacon Sandstone is about 6000 feet thick and into this are intruded three or four discontinuous sills, the total thickness of dolerite in any one section in the sandstone being about 2000 feet. Dolerite also forms bosses a few miles in diameter and elongate dike-like bodies up to 20 miles long, one or two miles wide and not less than about 5000 feet thick. Tholeiitic lavas, pillow lavas and pyroclastics of the same age as the Ferrar Dolerites are known from near the upper Mawson Glacier and the Darwin Mountains (Gunn and Warren 1962) and also from near the upper Beardmore and Mill Glaciers (Grindley, *pers. comm*). These rocks are here referred to as the Ferrar Volcanics.

The age of the Ferrar Dolerites is now known to be younger than Lower or possibly Middle Jurassic on the basis of plant fossils whereas potassium/argon absolute age determinations give an age of 170×10^6 years for a dolerite from Mt. Obruchev in Oates Land (Starik *et al.*, 1959) and 162×10^6 years for a dolerite from the Victoria Dry Valley (McDougall, *pers. comm*). Using the time scale of Kulp (1961) the absolute ages are also compatible with a L-M Jurassic age.

PHASE LAYERING IN THE FERRAR DOLERITES

Phase layering of minerals occurs only in sills more than 500 feet in thickness and then only in those bodies in which hypersthene has crystallized. In four of five sills of 700 to 1300 feet in thickness and in the two large dike-like bodies studied by the writer hypersthene has crystallized in the interior of the bodies in large amounts but appears in the marginal phase only in the very magnesian Egerton Sill. In four other sills a marginal zone about 150 feet in thickness contains augite, pigeonite, plagioclase and interstitial mesostasis only, whereas hypersthene occurs in a zone extending from about 150 to about 400 feet above the base of the sill. The greatest concentration is found near the base of this zone where hypersthene may make up 60 to 70% of the rock, but it decreases in quantity upward suggesting gravitational settling.

In contrast to the situation in many other tholeiitic intrusions olivine has not been found in the Ferrar dolerites in the McMurdo Sound region except as rare pseudomorphs enclosed in hypersthene in the Harmsworth Dike. Hypersthene has been reported in amounts not exceeding 7% in the Tasmanian Dolerites, (Spry, 1958; McDougall, 1958) and in similar small amounts in the Hangnest and Downes Mountain sills of the Karroo Dolerites (Walker and Poldervaart, 1940, 1941) and in the Palisades Sill (Walker, 1940).

Concentrations of up to 70% of hypersthene in the Ferrar Dolerites is therefore unusual and is comparable with the accumulation of olivine in the more basic tholeiites or high-alumina basaltic bodies such as the Skaergaard intrusion (Wager and Deer, 1939, p. 117). Such a concentration increases the amount of magnesia present by a factor of four or five but does not alter the silica content of the rock as hypersthene contains approximately the same amount of silica as the undifferentiated rock (53–55%). Concentration of bytownitic plagioclase does depress the silica content a little (47% SiO_2 for An_{80}, Hess, 1960) but anorthosites are rare and minor in amount. Crystallization of the main mineral phases does not therefore increase the silica content of the residual liquid but the undifferentiated rock does contain about 10% of interstitial quartz-sanidine micropegmatite and accumulation of hypersthene has displaced the equivalent liquid upwards to give rise to upper zones of granophyric dolerite, small lenses of coarse-grained pegmatoid, and bands of granophyre with a composition roughly equivalent to that of a granite (62 to 67% SiO_2). The wide range of modal composition is illustrated by Fig. 1.

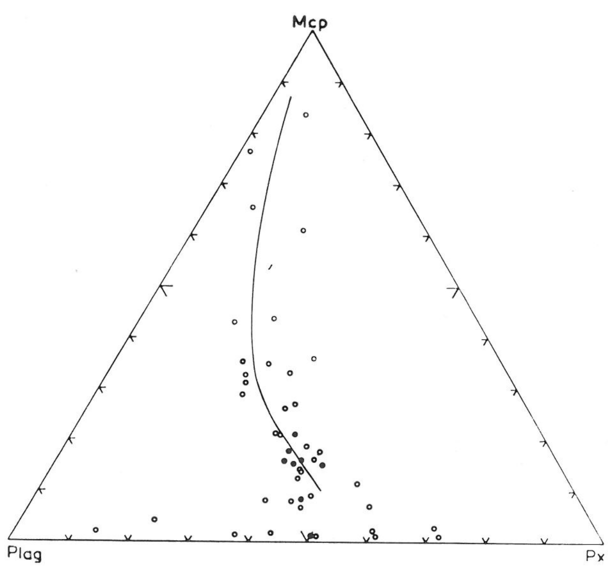

FIG. 1. Triangular diagram of modal plagioclase, pyroxene and micropegmatite plus remaining phases in 46 specimens of Ferrar Dolerite. Solid circles represent undifferentiated rocks. Plagioclase and hypersthene cumulates are at the base and granophyres and pegmatoids near the upper apex.

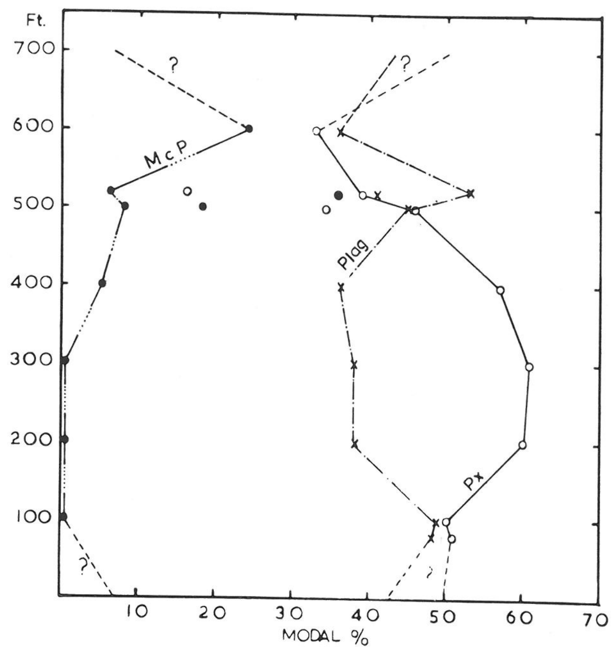

FIG. 2. Distribution of modal % of total pyroxene, plagioclase and micropegmatite with height in Basement Sill at Kukuri Hills with upper and lower margins conjectured from bulk averages. Composition of pegmatoids at 500 feet and 540 feet are shown. Hypersthene is found only at 200 and 300 feet where it constitutes 20% and 26% of the rock.

Typically then a sill of hypersthene-bearing Ferrar Dolerite about 800 feet in thickness displays the following layered structure:

(a) A glassy margin containing a few plagioclase phenocrysts and rarely, hypersthene, passing inwards to augite-pigeonite-plagioclase-mesostasis dolerite.

(b) A lower zone of augite-pigeonite-plagioclase dolerite in which the amount of interstitial micropegmatite is sometimes rather less than near the margins.

(c) A zone of hypersthene dolerite extending from about 150 to about 350 to 500 feet above the base.

(d) Lenses not more than a few inches thick of anorthosite within the hypersthene zone formed of bytownitic plagioclase.

(e) An upper zone of granophyric pigeonite dolerite extending from the top of the hypersthene zone to the upper chilled margin, and containing schlieren of coarse-grained pegmatoid.

(f) Lenses of fine-grained granophyre which occur within the granophyric dolerites are found only rarely in the sills but form bands up to 200 feet in thickness in the dike-like bodies.

A typical range of modal distribution with height in a sill is shown in Fig. 2. compiled from data from the Basement sill near Ferrar Glacier. Hypersthene occurs only at 200 and 300 feet, the pyroxene at 400 feet being augite with some pigeonite.

Dolerite bosses and dike-like bodies more than 1500 feet in thickness often show a regular layering at about 10 feet intervals. The layers are slightly concave upwards and are accentuated by weathering but petrographic study of the layers in a boss in the Lashly Mountains failed to show any marked differences in mineral composition. Rhythmic layers have been described from elsewhere in the Ferrar Dolerites by Gunn and Warren (1962).

Cryptic Layering

Optical determinations of mineral composition as well as whole-rock chemical analyses show that the early-formed ferromagnesian minerals now found near the base of the hypersthene zones consist of highly magnesian hypersthene (Mg_{83-70}) and augite (Ca_{45} Mg_{46} Fe_{9}) in contrast to the iron-rich ferroaugites (Ca_{39} Mg_{11} Fe_{50}) which have crystallized from the last fractions of the melt in the granophyres and pegmatoids. In the same way the early-formed plagioclases are highly calcic (An_{82-78}) while the last to crystallize are more sodic (An_{45-10}).

This process has been thoroughly described for other differentiated basic bodies, eg. the sills of Tasmania (Edwards 1942; McDougall 1961) and the regularity of the variation in the Ferrar sills supports the contention of original homogeneity.

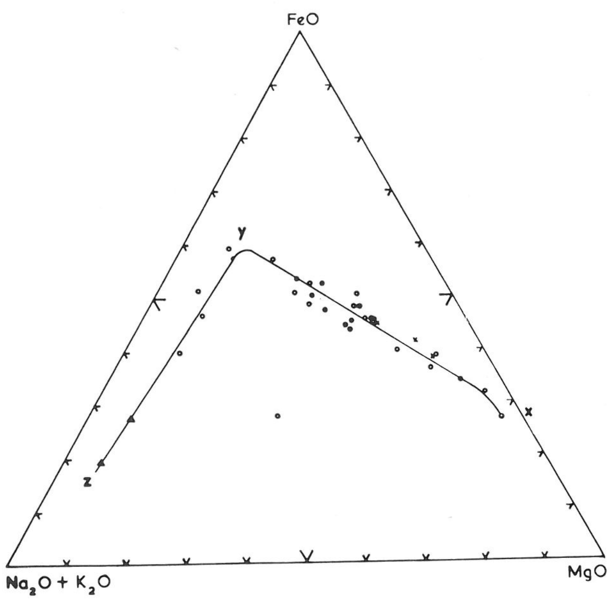

FIG. 3. F M A diagram (ferrous iron, magnesia, and total alkalis) of Ferrar Dolerites. Solid circles represent undifferentiated dolerites, circles differentiated doleites, (analyst B. Gunn), crosses three analyses of Ferrar Dolerites quoted by Benson (1916), triangles two Ferrar Dolerite granophyres kindly supplied by Dr. W. Hamilton, (U.S.G.S. unpublished analyses, Nos. F208 and 154597; analysts: Smith, and Elmore, Barlow, Botts and Chloe). Hypersthene cumulates fall near X, granophyric dolerites near Y and granophyres and pegmatoids near Z. The single isolated rock is an anorthosite.

Variation in normative plagioclase is different in sills of different marginal composition but the composition alters regularly from the margins (An_{60-70}) to the hypersthene zones (An_{75-83}) and to the granophyres and pegmatoids (An_{31-56}). The range of chemical composition is shown in Fig. 3.

Examples of Layered Bodies of Ferrar Dolerite

Due to the reconnaissance nature of Antarctic fieldwork only limited amounts of material are available from each sill and this was usually obtained in the course of a single traverse across an exposure. There is no case in which good examples of all the features described above have been found in one locality in one sill. Detailed descriptions of one sill and one dike are given which illustrate most but not all of the features which appear to be typical of the Ferrar Dolerites. Similar detailed descriptions of other differentiated sills have been published separately (Gunn, 1962).

Mt. Egerton sill. A series of samples of dolerite were collected by Mr. D. Skinner of the New Zealand Antarctic Division, from a sill 800 feet thick exposed on the slopes of Mt. Egerton, 250 miles south of McMurdo Sound. The sill is in part intruded between the Kukri Peneplain surface and Beacon Sandstone and in part into basement limestones.

Field relationships have shown that there were at least three phases of intrusion of the Ferrar Dolerites and that there are several distinct magma types (Table 1). The Egerton sill belongs to the type low in silica and high in magnesia. The hypersthene zone in this sill extends from about 150 to possibly 500 feet above the base and within it are bands of contrasting mineralogy. At 400 feet there are numerous lenses of anorthosite about 18 inches long and $1\frac{1}{2}$ inches thick while at 440 feet there is a continuous band of unusually coarse-grained augite pigeonite-plagioclase rock about 4 feet in thickness. Small pods of pegmatoid up to $3 \times 6 \times 10$ inches are found between 600 and 770 feet above the base and tend to occur subhorizontally. These show only slight quartz enrichment and no bands of granophyre were found though a dike-like body at Detour Nunatak with a similar margin composition to the Egerton sill contains an upper band of granophyre more than 200 feet thick.

(a) Petrography

The chilled rock near the lower margin is unremarkable (16793)[1] consisting of sub-ophitic intergrowths of

[1] Numbers are those of the collection of the Geology Department, University of Otago.

TABLE 1. MAGMA TYPES OF FERRAR DOLERITES AND OTHERS

	A	B	C	D	E	F
SiO_2	55.68	55.14	53.57	53.05	52.65	51.59
Al_2O_3	15.98	14.62	15.71	16.95	16.23	15.95
TiO_2	0.80	0.71	0.67	0.65	0.58	0.89
Fe_2O_3	1.81	1.76	1.25	0.79	0.51	1.38
FeO	8.01	7.78	7.87	6.69	8.21	7.52
MnO	0.17	0.18	0.17	0.07	0.15	0.14
MgO	4.17	5.82	6.36	6.91	6.64	7.56
CaO	8.42	10.07	10.63	11.56	11.34	9.52
Na_2O	2.34	2.19	1.85	2.05	1.58	2.04
K_2O	1.12	0.81	0.82	0.97	0.90	0.65
P_2O_5	0.10	0.09	0.08	tr.	0.01	0.19
H_2O^+	0.93	0.48	0.74	0.49	0.48	1.77
H_2O^-	0.62	0.23	0.36	0.43	0.85	0.57
CO_2	n.d.	0.06	n.d.	n.d.	n.d.	0.44
Total	100.15	99.94	100.08	100.61	100.13	100.21

A = Average margin of Peneplain Sill (23092, 23093).
B = Average upper and lower margins of Basement Sill, unpublished U.S.G.S. analyses (F2502, F2509), V. C. Smith analyst.
C = Average chilled margins of Detour Nunatak dike, Carapace Nunatak lava, and Mt Egerton Sill (21841, 21846, 16793).
D = Horn Bluff Dolerite (Browne, 1923).
E = Tasmanian Dolerite (average of six undifferentiated samples, Edwards, 1942).
F = Theron Dolerite (average of two chilled margins (350/6, 351/7), J. Stephenson, unpublished analyses.

augite-pigeonite with 0.2 mm plagioclase (An_{70}), very fine-grained intergrowths of quartz and orthoclase, apatite needles and iron ores. A hundred feet above the base (16794) there is also a little hypersthene present both as separate coroded crystals and as cores mantled by zones containing copious blebs of augite which is interpreted as having exsolved on inversion from pigeonite which is in turn mantled by uninverted pigeonite. The exsolution lamellae are parallel to (001) of the original pigeonite, the *b* and *c* axes of which have sometimes been retained on inversion. Pigeonite is also present as corroded separate grains and intergrown with augite. At 200 feet (16795) hypersthene is present to the extent of 40% of the rock. Euhedral 4 mm cumulus crystals (Mg_{83-71}) are closely packed and fine-grained plagioclase is interstitial. Augite is coarser in grain than the plagioclase (1 mm) but is anhedral and there is a complete lack of pigeonite either marginal to the hypersthene or as separate grains. Fine-grained, almost glassy micropegmatite and iron ores are present only in very minor amounts and the rock has the characteristic porphyritic texture of al hypersthene dolerites. Similar hypersthene dolerite is found at 400 feet (16796) but the texture is glomeroporphyritic with, in an average of three sections, considerably less hypersthene. The separation of hypersthene in such large quantity must have greatly enriched the liquid fraction in lime and alumina.

The thin lenses of anorthosite (16797) consist of about 85% of bytownitic plagioclase (An_{83}) together with a little interstitial and ophitic augite some of which is much altered and may be pigeonite (Fig. 4). A few of the larger plagioclase crystals (0.6 mm) show weak oscillatory zoning but the majority of the crystals are unzoned and are less than 0.3 mm long. A strong horizontal banding is caused by parallelism of feldspars and differences in concentration of pyroxene. The coarse-grained 4 foot band at 440 feet is similar to the anorthosites but here coarse (6 mm) poikilitic augites and inverted pigeonites are surrounded by fine-grained plagioclase, and iron ores are present. Unfortunately there is no sample of normal rock from this level but at 600 feet (16799) a little hypersthene is still present as cores mantled by inverted pigeonite. Some of these composite crystals are coarse in grain (3 mm) but there is a complete lack of euhedral outlines, the texture is granular to subophitic and uninverted pigeonite occurs as separate crystals and intergrown with augite. Rods of magnetite-ilmenite and some interstitial micropegmatite are present.

The pegmatoid lenses at 600 feet (16800) are coarse-

FIG. 4. Photomicrograph, of anorthosite, Mt. Egerton Sill (16797). A little augite is ophitically intergrown with the bytownite which shows a roughly parallel orientation. ×30.

grained with pyroxenes up to 2 cm long. Quartz-feldspar intergrowth is present to the extent of 25% but this is much less than in pegmatoids found in other sills where quartz-sanidine intergrowths may make up to 60% of the rock. The texture is granitoid or rarely ophitic with sub-hedral 2 mm plagioclase (An_{68-56}), and greenish-brown hornblende but augite, probable pigeonite and fine biotite are secondarily altered to chlorite. Titano-magnetite and ilmenite form coarse 2 mm grains. The pegmatoid from 770 feet is similar with coarse pyroxenes and plagioclase, abundant iron ores and micropegmatite and a little hornblende. The normal rock at 770 feet is a fine grained (0.2–1 mm) augite-inverted pigeonite-plagioclase-micropegmatite rock. Thirty feet above, the chilled marginal rock contains rare phenocrysts of hypersthene.

(b) Modal variation

In this sill the lower pigeonite zone which contains roughly equal amounts of augite and pigeonite extends not more than about 150 feet above the base while the zone of hypersthene accumulation is difficult to define because of the spread of sampling. At 200 feet augite is present in about the same amount as in an undifferentiated rock, (Table 2) plagioclase and micropegmatite are greatly reduced and 50% of hypersthene has been added while pigeonite is entirely absent. At 400 feet total pyroxene is present in normal amount except that hypersthene has taken the place of pigeonite. Probably the residual liquid more ferriferous than about $Mg/Mg+Fe=45$ (mol %) was expelled by the accumulating pyroxene and plagioclase. Pyroxene is still slightly in excess over its concentration in the margins at 600 feet though this could be a mafic band complementary to the anorthsite lenses below. In the upper 200 feet of the sill there is a general increase in micropegmatite especially in the pegmatoids.

(c) Mineral composition and variation

Progressive variations in normative plagioclase and pyroxene can be seen in Table 3. Optical determinations of plagioclase give consistent results but clinopyroxenes are unusually magnesian and optically variable in this sill, in the main due to exsolution of fine lamellae of hypersthene and pigeonite, the host augites therefore appearing to be more calcic than is usually the case. The lowest values of 2V have accordingly been used in determining composition (Table 4). Determinative data used are those of Hess (1960), for orthopyroxene, Tröger (1956) for plagioclase, Brown (1957) for augites and Muir (1951) for pigeonites and ferro-augites.

Mt. Harmsworth dike. A poorly exposed dike-like body of dolerite extends eastward from Mt. Harms- (9080 feet) for about three miles and descends to the Delta Glacier, a tributary of the Skelton Glacier, at about 4800 feet. Several sheets of dolerite are exposed in nearby granites and may branch from the dike, the width of which is unknown but is not less than about 600 feet. Some 200 feet of rock is exposed at the summit of Mt Harmsworth and this is all a fine-grained, light grey granophyre. At about 8000 feet the rock is a pigeonite dolerite while at the visible base the rock is a hypersthenite and is streaked with curved anorthositic bands which are usually less than 1 cm thick.

(a) Petrography

The hypersthenite rock at the base is an extreme example of an accumulative rock in which euhedral weakly pleochroic hypersthenes up to 6 mm long are closely packed and show a strong tendency to a parallel orientation (Fig. 5). A few pseudomorphs after

TABLE 2. MODES OF MT. EGERTON SILL.

No.	Height above base (ft)	Total Px.	Hypers.	Augite	Pigeon.	Plag.	Micropeg.	Hornbl. Biotite Chlorite	Opaques
16801 (a)	770 (peg.)	21.1		10.9	10.2	43.7	27.8	3.6	3.8
16801	770 (Norm.)	41.8		19.3	22.5	44.1	10.8	1.9	1.4
16800	600 (peg.)	23.0		n.d.	n.d.	44.1	25.6	2.6	4.7
16799	600	52.7	8.0	21.7	23.0	36.0	10.0	0.6	0.7
16798	440	22.2		12.1	10.1	73.5	2.8	0.3	1.2
16797	400	13.5		10.7	2.8	84.5	1.2	0.3	0.5
16796	400	43.0	19.5	21.6	1.9	55.3	1.4	—	0.3
16795	200	70.0	50.0	20.0		27.3	2.3	—	0.4
16794	100	43.4	1.5	24.5	17.4	48.8	6.4	0.4	1.0
16793	base	45.0		n.d.	n.d.	40.0	10.8	1.5	2.7

TABLE 3

	Analyses of Mt Egerton Sill				Analyses of Mt Harmsworth Dike	
No.	16793	16795	16797	16800	16790	16792
Feet above base	0	200	400	600	50	4,300
S.G.	2.94	3.08	2.76	2.84	3.12	2.78
SiO_2	53.41	53.05	47.34	56.64	53.18	63.02
Al_2O_3	16.53	11.10	30.65	15.33	9.29	13.70
TiO_2	0.67	0.30	0.18	1.20	0.30	1.17
Fe_2O_3	0.88	0.62	0.61	2.60	0.42	5.37
FeO	7.73	8.54	1.44	7.64	8.17	4.83
MnO	0.18	0.19	0.02	0.18	0.18	0.19
MgO	6.61	17.26	1.66	3.19	21.27	1.02
CaO	10.90	7.63	15.85	7.86	6.18	4.80
Na_2O	1.78	0.72	1.84	2.60	0.60	2.41
K_2O	0.81	0.32	0.29	0.91	0.30	2.07
P_2O_5	0.09	n.p.	n.p.	n.d.	n.p.	0.23
H_2O^+	0.27	0.45	0.21	1.46	0.35	0.83
H_2O^-	0.32	0.29	0.25	0.24	0.10	0.12
Total	100.18	100.47	100.34	99.85	100.34	99.76
Norm. wt. %						
ap	0.19	n.p.	n.p.	n.d.	—	0.50
il	1.27	0.58	0.35	2.28	0.58	2.22
mt	1.27	0.90	0.88	3.77	0.60	7.78
or	4.79	1.89	1.73	5.40	1.78	12.25
ab	15.05	6.08	15.58	21.98	5.09	20.40
an	34.72	26.12	74.51	27.49	21.76	20.45
di wo	7.87	4.90	1.72	4.81	3.72	0.85
di en	4.29	3.34	1.10	2.12	2.66	0.39
di fs	3.31	1.17	0.50	2.68	0.73	0.45
hy en	12.17	39.64	0.81	5.82	47.31	2.15
hy fs	9.38	13.85	0.38	7.48	12.92	2.41
ol fo			1.55		2.11	—
ol fa			0.77		0.63	—
Q	5.26	1.25		14.30	—	28.97
H_2O	0.59	0.74	0.46	1.70	0.45	0.95
Total	100.16	100.46	100.34	99.83	100.34	99.77
Norm. Plag.	An_{70}	An_{81}	An_{83}	An_{56}	An_{81}	An_{50}
Norm. pyrox.	Mg_{63}	Mg_{79}	Mg_{74}	Mg_{51}	Mg_{83}	Mg_{54}

olivine are enclosed by the hypersthene, but there are few plagioclase inclusions and crystal margins are entire and uncorroded. Plagioclase tablets are rarely as much as 1 mm in length and fit in the interstices between the hypersthene phenocrysts whereas augite tends to be moulded between orthopyroxene. There is no micropegmatite and traces of iron-ores and biotite are the only other minerals.

The rock at 800 feet appears to be a normal pigeonite dolerite with intergrowths of augite and partly inverted pigeonite with plagioclase and with interstitial micropegmatite.

At the summit the granophyre contains isolated plagioclase (An_{55-51}) which are surrounded by quartz sometimes intergrown with extensions of the plagioclase with a composition of about An_{15-10} but more often with potash feldspar (Fig. 6). Interstices between the intergrowths tend to be filled by coarser

TABLE 4. (a) EGERTON SILL

16801	770 ft	
	Augite	$2V_\gamma$ 49–56°, β 1.706, $Ca_{42}\ Mg_{33}\ Fe_{25}$
	Plagioclase	Min. α' 1.562, max. γ' 1.572, An_{69-67}
16801	(pegmatoid) 770 ft	
	Augite	$2V_\gamma$ 55°, β n.d.
	Pigeonite	n.d.
	Plagioclase	Min. α' 1.561, max. γ' 1.571, An_{67-64}
16800	(pegmatoid) 600 ft	
	Augite	$2V_\gamma$ 56±2°, β n.d.
	Plagioclase	Min. α' 1.557, max. γ' 1.572, An_{68-56}
16799	600 ft	
	Augite	$2V_\gamma$ 47–53° (variable), β 1.688±.004 (variable)
	Hypersthene	$2V_\gamma$ 62–80°, Mg_{82-70}*; $2V_\gamma$ 49–62°, Mg_{70-56}*
	Pigeonite	$2V_\gamma$ 15°, 1.682, $Ca_8\ Mg_{65}\ Fe_{27}$
	Plagioclase	Min. α' 1.563, max. γ' 1.578, An_{79-68}
16798	(pigeonite band) 440 ft	
	Augite	$2V_\gamma$ 47–51°, β 1.691, $Ca_{43}\ Mg_{46}\ Fe_{11}$
	Pigeonite	$2V_\gamma$ 17°, α 1.687, $Ca_8\ Mg_{61}\ Fe_{31}$
	Plagioclase	Min. α' 1.565, max. γ' 1.581, An_{84-73}
16797	(anorthosite lens) 400 ft	
	Augite	$2V_\gamma$ 55°, β 1.698±.003, $Ca_{49}\ Mg_{36}\ Fe_{15}$
	Plagioclase	α' 1.569, γ' 1.580, An_{83}
16796	400 ft	
	Augite	$2V_\gamma$ 51–57° (variable), γ 1.680±.003, $Ca_{45}\ Mg_{50}\ Fe_5$
	Hypersthene	$2V_\gamma$ 62–81°, Mg_{82-69}
	Plagioclase	Min. α' 1.570, max. γ' 1.582, An_{85}
16795	200 ft	
	Augite	$2V_\gamma$ 49–53°, β 1.688±.002, $Ca_{45}\ Mg_{46}\ Fe_9$
	Hypersthene	$2V_\alpha$ 64–82°, Mg_{83-71}
	Plagioclase	Min. α' 1.568, max. γ' 1.581, An_{81-80}
16794	100 ft	
	Augite	$2V_\gamma$ 48–56°, β 1.688, $Ca_{44}\ Mg_{47}\ Fe_9$
	Pigeonite	$2V_\gamma$ 15°, α 1.704, $Ca_7\ Mg_{48}\ Fe_{45}$
	Hypersthene	$2V_\alpha$ 64–76°, Mg_{79-71}; $2V_\alpha$ 55–58*, Mg_{67-63}I
16793	*Plagioclase*	α' 1.564, γ' 1.573, An_{70}

* Inverted pigeonite.

granular quartz and orthoclase but even here the grainsize does not exceed 0.5 mm. Altered and corroded pyroxene, dark green hornblende (γ=1.698) and primary and secondary biotite are intergrown with granular magnetite-ilmenite. Apatite needles are plentiful and sphene is an accessory.

(b) Modes

The modal analyses (Table 5) show the hypersthene rock at the base to be a similar though more extreme form of cumulate rock to that found in the Egerton Sill. The bulk of the rock contains up to 72% pyroxene but in the thin anorthosite streaks pyroxene is almost absent. As in the Egerton Sill pigeonite is entirely absent but here plagioclase greatly exceeds the amount of augite. The granophyre shows the characteristic features of abundant quartz, orthoclase, hornblende and iron ores and only minor pyroxene.

(c) Mineral composition

The pyroxene from the Harmsworth granophyre is too altered for optical determination but pyroxene from a similar granophyre at Detour Nunatak has

$$2V\gamma\ 47°, \quad \beta\ 1.737, \quad Ca_{34}Mg_{13}Fe_{53}$$

The difference in normative pyroxene between base and summit, (Mg_{81-54}) and in normative plagioclase (An_{81-50}) is extreme and optical determinations (Table 6) show a greater range.

The amounts of magnesia in the basal rock (Table 3) is comparable with that of picrites and is the most extreme example of hypersthene accumulation yet found in the Ferrar Dolerites.

CRYSTALLIZATION OF HYPERSTHENE

The asymmetric distribution of pyroxenes as a whole with height in the sills coupled with the markedly higher specific gravities of the hypersthene rocks points strongly to gravitative settling (Fig. 2). However the existence of hypersthene in such large quantity in sills, the marginal phases of which contain little or none, clearly demands explanation. Work done to date has not been detailed enough to answer this problem decisively but the following tentative suggestions are offered:

FIG. 5. Close packed hypersthenes with interstitial bytownite, Mt. Harmsworth Dike, (16790) ×30.

TABLE 5. MODES OF MT HARMSWORTH DIKE.

No.	Height above S.L. (ft)	Total Px.	Hypers.	Augite	Plag.	Micropeg.	Hornbl. Biotite	Opaques	Apatite
16792	9,050	7.6			27.1	52.5	8.5	3.8	0.5
16791	8,000	43.1			49.3	5.9	0.8	0.8	0.1
16790	4,800	71.7	67.3	4.4	27.6	0.3	0.1	0.3	

(1) Either the hypersthene dolerites have crystallized from a magma of the same composition as the margin or from one more magnesian. As single sills have been traced over areas of more than 10,000 sq. mi. volumes of more than 2000 cubic miles of magma have been injected in a single phase of intrusion. Considering the variability shown in sequences of lava flows (Tilley, 1960), it is unlikely the magmas were completely homogenous, indeed lateral variations have been found in single sills, but it is unlikely that several sills being filled from many different conduits could all have central zones more magnesian than the margins. Moreover, no highly magnesian glassy rocks, lavas or dikes have been found, the textures of the hypersthene dolerites is always porphyritic and the hypersthenes are enclosed in a groundmass which often has a composition of a normal dolerite minus the more refractory components.

(2) Assuming the magma to have been initially homogenous it does not seem likely that more than about 7% of hypersthene could crystallize even under conditions of perfect fractionation. Up to 21% of normative hypersthene is present in marginal rocks but in the mode this contains a little augite in solid solution and appears as pigeonite. Normative pyroxene in the Egerton Sill has a composition of Mg_{63} and hypersthene began to crystallize at Mg_{83}. Under conditions of perfect fractionation about a third of the normative pigeonite would have crystallized as hypersthene before the inversion composition at Mg_{70} was reached. Work has not yet been done in sufficient detail on any of the Ferrar sills to show whether this

TABLE 6. (b) MT. HARMSWORTH DIKE

Hypersthene zone
16790
Hypersthene $2V_\alpha$ 65–81°, Mg_{82-72}, γ 1.679–1.686, Mg_{83-74}
Augite $2V_\gamma$ $50\pm2°$, β 1.690, $Ca_{45}\,Mg_{46}\,Fe_9$
Plagioclase Min. α' 1.565, max. γ' 1.581, An_{84-73}
Granophyre zone
16792
Plagioclase Min. α' 1.554, max. γ' 1.564, An_{55-51}
Plagioclase intergrown with quartz has α' 1.535 An_{15}

FIG. 6. Granophyric intergrowths of quartz-orthoclase and quartz-albite grouped about plagioclase. Iron ores and hornblendes also present. Granophyre, summit, Mt. Harmsworth. (16792) ×70.

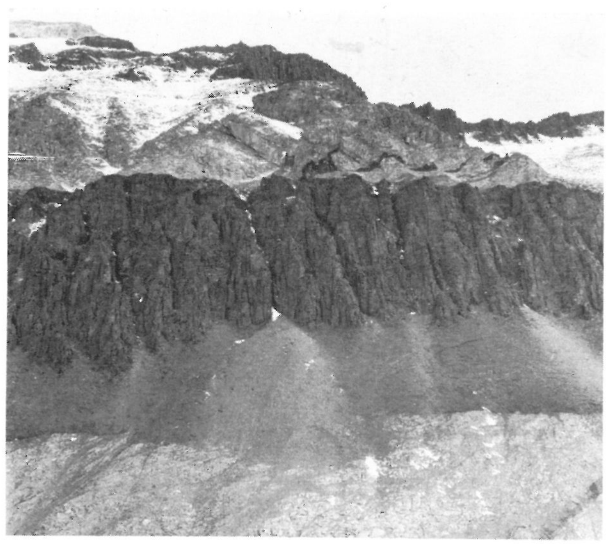

FIG. 7. Basement Sill, Kukri Hills, intruded into granodiorite, with Peneplain Sill above overlain by Beacon Sandstone. Lower sill is here 800 feet thick, hypersthene zone begins 150 feet above base.

amount is sufficient to account for the concentrations found.

(3) The non-appearance of hypersthene in marginal rocks appears to be in part due to the pyroxenes of a rapidly chilled magma crystallizing with compositions close to that of the norm. Only in the central part of sills where crystallization must have been exceedingly slow are pyroxenes found with compositions markedly more magnesian.

(4) Recent experimental work on the stability fields of ortho- and protoenstatite by Boyd and England (1961) coupled with a consideration of the unit cell dimensions of the three polymorphs of enstatite and of pigeonite (Morimoto *et al.*, 1959) suggests that high pressures favour the crystallization of magnesian orthopyroxene as the stable phase. A column of magma rising from below the Mohorovičič Discontinuity in the manner postulated by Kuno (1959) might well crystallize pigeonite under low pressure near the surface and magnesian hypersthene at depth.

(5) No hypersthene was found in the 1300 foot Peneplain Sill at Solitary Rocks in the Taylor Valley. However the margin of this sill (Table 1) is considerably less magnesian than the hypersthene-bearing sills. Comparison of the ratio

$$\frac{MgO \times 100}{MgO + FeO + MnO}$$

(mol %) of margins with that of the most magnesian hypersthene to form shows that in four sills hypersthene began to crystallize with 25–30% more MgO than the magma. This separation of solidus and liquidus is rather greater than that deduced by Kuno (1959) and by Brown (1957) from analysed phenocryst and groundmass pyroxenes but using the lower

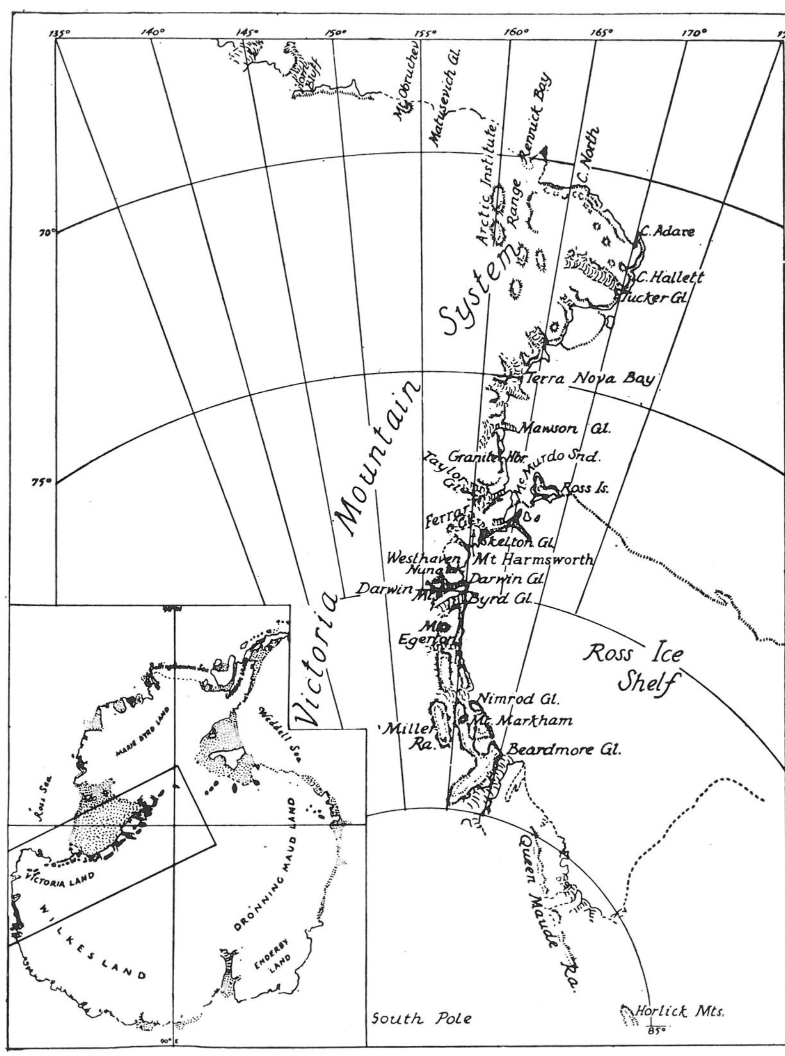

FIG. 8. Distribution of Ferrar Dolerites Group, Antarctica.

figure it is not likely that a magma in which the ferromagnesian ratio is less than about 45 could crystallize hypersthene. In the Peneplain Sill this ratio is 47 compared with 60 for the Egerton Sill, a difference which is probably significant.

Convective circulation appears to have been minimal during crystallization of the sills and the anorthositic lenses of the Egerton Sill are difficult to account for, though convective currents probably account for the rhythmic layers seen in the dike-like bodies. The presence of hydrated minerals in the pegmatoids suggests that these have formed during the last stages of crystallization in localities where the water vapour pressure has exceeded the confining pressure and water has appeared as a separate phase, whereas the granophyres are merely accumulations of residual liquids.

Phase layering is usually inconspicuous in the Ferrar Dolerites even in strongly differentiated sills (Fig. 7).

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