small irregular intrusive sheets. The upper thick intrusive sheet has a maximum thickness of more than 40m. and its upper surface, which appears chilled, is probably close to the original top of the intrusion. The base of this sheet is generally obscured by scree although a basal contact with agglomerate is visible in the north-west. The columnar jointing is mainly vertical around the margins of the sheet but curves outwards near the base, showing that the bottom of the intrusion is probably saucer-shaped. The two lower intrusive tongues have an exposed thickness of some 30m. and their pod-like form is indicated by the attitudes of their columnar jointing. In the north these lower intrusions are in contact with underlying agglomerates, while interbedded lavas and tuffs occur to the south-west below a mantle of scree. A roof contact of the eastern tongue is exposed at 430m., just west of a small tarn, where a small patch of agglomerate occurs above the intrusive tholeiite. Thin columnar-jointed sheets intrude the agglomerate for a short distance to the north of both intrusive tongues.

North-west of Svarthamrar, on the west side of Kyrfugil, four columnar-jointed intrusions occur at different levels within interbedded lavas and pyroclastics. The most northerly of these outcrops at 238m. on the east side of Vidartungur. A somewhat larger intrusion occurs on the west side of Vidartungur where it is overlain by andesitic lavas. This intrusion, which has a steep-sided contact on the south-west side with lavas and tuffs, appears to be made up of a group of northward dipping sheets. A further, steep-sided intrusion, with particularly prominent columnar jointing, occurs just to the west, again cutting lavas and tuffs.

North of Vidartungur, on the other side of the Sela river, there are a large number of columnar-jointed intrusions, the tholeiite of which sometimes contains up to 2% feldspar phenocrysts. South of Seldalur the intrusions cut lavas and pyroclastics (fig. 16b.) and to the north they intrude the bedded sub-aerial tuffs on the western flank of the Alftafjordur volcano. Many of the intrusions are undulating

Fig. 16a. Svarthamrar from the north-east, showing the upper columnar-jointed tholeiite intrusion, 40m. thick, capping the hill and one of the lower tongue-like intrusions forming a prominent cliff below. Rhyolite and agglomerate occur in the foreground.

Fig. 16b. The contact between acid agglomerate and the columnar-jointed tholeiite intrusion on the south side of Vatnshlid.

sheets floored by agglomerate, while others form prominent steep-sided knolls, and are probably "pod-like". The intrusion at Thangbrandsbryggia forms a horizontal sheet, at least 10m. thick, with only poor columnar jointing, which on its west side is in contact with a porphyritic dacite; no other contacts are exposed.

(c) Petrography

The tholeiitic rock forming the columnar-jointed intrusions is generally very fine-grained, with sparse phenocrysts. The phenocrysts, chiefly of plagioclase but with rare augite, occur in a groundmass composed of plagioclase, pyroxene and iron ore, with calcite always, and olivine and basalt glass sometimes, also present. The groundmass does not show any fluxion-banding.

The plagioclase phenocrysts commonly occur in small clusters up to 1cm. in diameter. The individual crystals, some 2.5mm. long, are of very weakly zoned bytownite (average An87) and are euhedral to sub-hedral, with a tabular habit. They are mantled by a narrow zone of labradorite (average An65), corresponding to the plagioclase of the groundmass, which poikilitically encloses very small pyroxene and iron ore granules. The phenocrysts show varying degrees of alteration to calcite and are also veined by almost colourless chlorite. The rare augite phenocrysts form pale brown euhedral crystals with slightly darker marginal zones ophitically enclosing small plagioclase laths.

The groundmass plagioclase, pyroxene (a very pale augite), iron ore and olivine (when present) occur as both sub-hedral micro-phenocrysts and, except for plagioclase, as small anhedral granules; the plagioclase is a labradorite (average An65), and always has a lath-like habit. Olivine, showing partial alteration to green "bowlingite", is an important constituent of the Nonbotn tholeiite (specimen H534), but does not occur in the analysed specimen (H566) from Svarthamrar. Pale brownish basalt glass (in specimen (H566) and colourless calcite occur in the groundmass as small irregular patches, those of calcite often being angular and "ophitically" enclosing plagioclase laths.

Chemical analysis and norm of specimen H566 are as follows:-

			Norm
S_iO_2	52.9	Qz	3.72
Al_2O_3	14.9	Or	5.56
FeO	7.5	Ab	38.77
Fe_2O_3	4.0	An	17.24
MgO	3.5	Di	12.12
CaO	7.2	Hy	9.69
Na_2O	4.6	Mt	5.80
K_2O	0.9	Il	4.10
H_2O^+	0.7	Ap	1.34
H_2O^-	0.4	H_2O	1.1
T_1O_2	2 16	Total	99.44
P_2O_5	0.65		
MnO	0.25		
Total	99.6		

Origin

The following points are considered to be significant in explaining the origin of the columnar-jointed intrusions.

(1) The occurrence of the intrusions at different, though roughly comparable, stratigraphical levels on the flanks of the Alftafjordur volcano.

(2) The occurrence of most of the intrusions in pyroclastic rocks or in lavas interbedded with pyroclastic rocks.

(3) The intrusions are cut by, but do not themselves cut, other minor intrusions.

(4) The prevalence of columnar jointing, even in the smallest intrusions.

(5) The lack of flow-banding within the intrusions.

(6) The general uniformity of composition of the intrusions.

The evidence suggests that these bodies are very high level intrusions intruded mostly into loose pyroclastics near the upper surface of the Alftafjordur volcano during a certain phase of its volcanic activity. The apparent absence of deformation of the country rocks is probably partly due to the prevalence of the intrusions within loose and unbedded agglomerates, and partly to the erosion of the upper mantling rocks whichwere the most likely to have been deformed. Once emplaced, the intruded tholeiitic magma is thought to have crystallised in a "stagnant" condition without any further flow movement. Observations of columnar jointing in extrusive lava in Antrim, Northern Ireland; on Mull, Scotland; and in Iceland, have suggested that such jointing typically develops where there is a complete absence of any internal movement of the magma during its later crystallisation, so that once commenced the jointing, which forms during cooling, can continue to develop until solidifcation is complete, with the internal isotherm contours maintaining a constant attitude. Such conditions can occur when lava flows infill hollows in the land surface, forming stagnant "ponds". The actual jointing is due to thermal stresses produced during cooling, and the columns are generally developed perpendicular to the isotherms within the cooling magma: the isotherms themselves are roughly parallel to the external contact of the particular magma body (Spry, 1962). Any internal movement of the cooling magma could result in the columns becoming bent (Waters, 1960), or, if the isothermal surfaces no longer remained parallel to each other, destroyed.

The Krossanesfjall Gabbros

(a) General Description

During the summer of 1961 two small gabbro intrusions with some associated veining granophyre were discovered on the north side of Krossanesfjall. The larger gabbro mass is exposed along the northern lip and on the craggy side-ridges of a northward-facing corrie (fig. 17). This corrie, which is backed by the basaltic lavas of Krossanesfjall summit, is infilled with rhyolitic and agglomeratic scree and probably occupies the site of a volcanic vent or pipe. The smaller gabbro mass outcrops on the col at the head of Maelifellsdalur, where it is associated with a coarse porphyritic dolerite containing up to 50% of stumpy feldspar phenocrysts: typical vent agglomerates occur around the northern and eastern margins of this smaller gabbro intrusion. The true shape of the gabbro intrusions is not known as the contacts, particularly of the smaller intrusion, are poorly exposed. The country rocks do not appear to have been structurally disturbed by either intrusion. Both gabbro intrusions are cut by a number of acid and basic minor intrusions.

The larger gabbro mass forms an irregular steep-sided intrusion cross-cutting the gently dipping country rocks on the northern side of Krossanesfjall. The best exposures of the contact occur at its eastern margin, where it cuts basalt lavas; within 20m. of the gabbro these lavas are hornfelsed and cut by thin granophyre veins, while the marginal gabbro is markedly finer-grained within 2m. of the lavas. The contact here is welded, and is not brought out by erosion. A group of dykes, including one of coarsely porphyritic dolerite similar to that associated with the smaller gabbro intrusion, cut and tend to obscure the contact. In a small stream at 370m., just east of the contact, the basalt lavas are cut off vertically to the south by an iron-stained rhyolitic agglomerate containing occasional basalt fragments. The lava-agglomerate contact is interpreted as the

Fig. 17 The north side of Krossanesfjall, showing the main Krossanesfjall gabbro intrusion (G). The smaller gabbro intrusion (g) can be seen at the col to the west. B = basalt lavas, A = agglomerate, c = contact between gabbro and basalt.

margin of the volcanic vent or pipe into which the gabbro partly intrudes. Near-vertical gabbro contacts with green acid agglomerate are sporadically exposed on the west side of the eastern corrie ridge, and contacts with basalt lavas are occasionally seen on the west side of the western corrie ridge.

The smaller gabbro mass at the head of Maelifellsdalur is intimately associated with a coarse porphyritic dolerite, and the two rock types apparently form a multiple intrusion cutting agglomerate. The intrusion is generally poorly exposed, however, and no internal or external contacts have been found.

The gabbro forming the two intrusions is generally coarser and more distinctive in appearance than the gabbro of the Austurhorn. Plagioclase, ophitic or sub-ophitic pyroxene and iron ore, with quartz and alkali feldspar, are the chief minerals: pseudomorphs after olivine and hypersthene are frequently seen, and apatite is also sometimes visible in the hand specimen. Sometimes elongate pyroxene crystals are concentrated, with iron ore, in irregular aggregates up to 5cm. in maximum length which are commonly connected to each other: pale grey plagioclase crystals, usually mantled by white alkali feldspar, occur between these aggregates. Granophyre is much subordinate to the gabbro and occurs only as thin veins cutting the gabbro and the adjacent country rocks, as in Maelifellsdalur. These veins have diffuse contacts with the gabbro and, as both rocks are unchilled at their mutual contacts, it is considered that the veins and the gabbro are more or less contemporaneous

(b) Petrography

The gabbro is a medium to coarse-grained, sometimes pegmatitic, rock with a colour index of less than 40. The finer-grained varieties have an average grain-size of 2mm. (less in the chilled marginal gabbro), while in the coarser varieties the individual crystals are sometimes more than 1cm. in length. The essential minerals are plagioclase, augite and iron ore, with interstitial quartz and alkali feldspar. Pseudomorphs after olivine and hypersthene are commonly present, and apatite, the main accessory mineral, occasionally makes up more than one per cent of the rock. Amphibole, chlorite, serpentine, biotite, calcite and epidote occur as secondary minerals. Typically the gabbro has a granular texture, although the augite is often sub-ophitic. The quartz and alkali feldspar sometimes occur in granophyric intergrowths. Chemical and modal analyses of a typical gabbro specimen (H310) are given in tables 3 & 4 .

The plagioclase occurs as anhedral to subhedral elongate tabular crystals. The crystals show marked normal zoning and are sometimes mantled by turbid alkali feldspar. In different specimens the cores of the crystals vary from bytownite (An80) to labradorite (An62), while the margins are of andesine-labradorite (av. An50), with a very thin more sodic outermost zone (An40 - 20). The most sodic zones and also the mantling alkali feldspar are lacking in the ophitic and sub-ophitic plagioclase crystals. This zoning, being euhedral, is almost certainly a primary feature (Vance, 1961 p. 1099), in contrast to secondary irregular and patchy zoning which is sometimes present; such patches are always more sodic than the surrounding plagioclase of the host crystal. The plagioclase crystals are commonly veined by calcite, albite and/or pale green chlorite: when the alteration is more intense the crystals become flecked with calcite and epidote crystals. In the gabbro close to the thicker granophyric veins (H374, H376) the plagioclase shows a different type of alteration, the calcic cores of the crystals becoming cloudy (as also do the augite crystals) due to the inclusion of minute specks of opaque dust, while the more sodic margins remain clear. This cloudiness is different from the turbid hydrothermal alteration of the alkali feldspar, and is probably due to thermal metamorphism effects (MacGregor, 1931, Poldervaart and Gilkey, 1954), the cause of which is uncertain.

The augite, which is often sub-ophitic, occurs as sub-hedral or anhedral crystals which are pale or very pale pinkish-brown with $\beta = 1.696 - 1.70$, $2V(+) = 44^\circ - 50^\circ$. The crystals are usually twinned, the twinning occasionally being lamellar, and a weak, patchy zoning is indicated by small variations of 2V within a single crystal. The augite almost always contains small specks of brown biotite, and in the more altered gabbro specimens (H312, H337) it becomes altered to calcite along irregular veins. When still more altered, calcite also develops around the margins of the augite crystals, and uralitic hornblende may occur outside the calcite, often in turn being mantled by pale green chlorite. In one specimen (H382), the augite is completely altered to calcite and chlorite.

Pseudomorphs after both hypersthene and olivine occur in most gabbro specimens. The hypersthene crystals are usually replaced by single crystals of chlorite, sometimes with associated pale green amphibole and green biotite. The pseudomorphs after olivine are either of chlorite, or less commonly, serpentine; they are easily distinguished by the concentration of iron ore in veins and around their margins. The chlorite of the phenocrysts is pleochroic from green to very pale greenish brown and is optically negative, with a small 2V: the birefringence varies from more than 0.01 to zero. The serpentine, which occurs as scaly aggregates, is paler green than the chlorite and is non-pleochroic, with a very low birefringence.

Quartz and alkali feldspar occur throughout the gabbro, sometimes in granophyric intergrowths but usually as discrete grains with rectangular mutual contacts. Pale green chlorite aggregates are very commonly associated with the quartz and alkali feldspar, as also is epidote in the more altered gabbros. The main and almost the only accessory mineral is apatite, which occurs as euhedral prisms up to a centimetre or more in length.

The typical granophyre associated with the gabbro consists of plagioclase, almost completely altered to calcite; alkali feldspar; quartz; and iron ore, with chlorite pseudomorphs and accessory apatite. The colour index of the rock as a whole is usually less than 10. Both the plagioclase, which is mantled by turbid alkali feldspar, and the chlorite pseudomorphs form euhedral elongate prismatic crystals, sometimes more than 1cm. long, lying in a partly granophyric groundmass of quartz and alkali feldspar.

Occasionally granophyric "hybrids" occur as veins cutting the gabbro. One such rock (H375) has been analysed (table 3): it consists of plagioclase, alkali feldspar, quartz, augite and iron ore, with occasional pseudomorphs after hypersthene and olivine: apatite and zircon both occur as accessory minerals, and alteration products include chlorite, amphibole, biotite and calcite. The plagioclase occurs as euhedral tabular crystals, usually less than 2mm. long, which frequently enclose many minute irregularly oriented apatite needles; they are zoned from labradorite cores (average An65) to margins of oligoclase-andesine (average An30), and are mantled by turbid alkali feldspar. The augite ia usually almost colourless, though sometimes patchily pale purplish-brown, and occurs as subhedral to anhedral, occasionally sub-ophitic, crystals: these crystals are charged with iron ore granules, and show marginal alteration to calcite. The pseudomorphs after olivine and hypersthene are similar to those in the gabbro. Interstitial quartz and alkali feldspar usually occur in micrographic intergrowths.

Key to tables 3 and 4

H310 Gabbro, 700m. north-north-east of main summit, Krossanesfjall.
H376 Ophitic gabbro, 650 m. north of main summit, Krossanesfjall.
H375 Granophyric hybrid, 750m. north-east of main summit, Krossanesfjall.

Table 3

	Chemical Analyses			Norms	
	H310	H375		H310	H375
SiO_2	47.8	56.2	Qz		2.40
Al_2O_3	18.1	14.9	Or	5.00	12.23
Fe_2O_3	3.6	3.2	Ab	27.77	47.16
FeO	7.1	6.0	An	31.97	9.45
MgO	4.2	2.4	Di	11.99	12.15
CaO	9.8	5.6	Hy	8.57	5.80
Ma_2O	2.3	5.6	Ol	1.76	
K_2O	0.85	2.1	Mt	5.34	4.64
H_2O^+	2.1	0.8	Il	4.71	3.34
H_2O^-	0.1	0.1	Ap	0.67	1.34
TiO_2	2.45	1.74	H_2O	2.2	0.9
P_2O_5	0.28	0.60	Total	100.08	99.41
MnO	0.19	0.19			
Total	100.0	99.5			
Sp. Gr.	2.92	2.78			

Analyst D.H.Blake

Table 4 Modal Analyses (vol %)

	H310	H376	H375
Plagioclase	60(An77-32)	73(An 75-40)	40(An65-30)
Augite	16	14	99
Pseudomorphs after olivine	6	(5)	-
Pseudomorphs after hypersthene	4		-
Opaque ore	7	5	6
Interstitial quartz	(5)	1.5	4
Interstitial alkali feldspar		1.5	8
Micrographic quartz and alkali feldspar	-	-	24
Accessories	2	-	-
Chlorite, hornblende, biotite	-	-	9

The Differentiated Sheets

Introduction

A number of thin basic intrusive sheets within the Austurhorn area are characterised by a richly porphyritic central portion rimmed by non-porphyritic chilled margins: further, olivine and pyroxene phenocrysts are concentrated near the base of this central portion, while feldspar phenocrysts are concentrated above, as though by gravitational differentiation. Porphyritic sheets of this type were first noted by Dr. Walker in 1958 and they have been found at shore exposures between Vik and Hvalnes farms and at cliff exposures between 300m. and 350m. on western Vikurfjall (fig. 13). These sheets intrude flat-lying basaltic lavas and associated rocks and the majority occur within the metamorphic aureole of the Austurhorn intrusion.

Field Description

The differentiated sheets are thin, never more than 2m. and usually less than 1m. thick, and they typically have an undulating form, with an average dip of 5^{o}-18^{o} to the north or north-east. Local steepening of the dip and irregularities in the strike are common. Sometimes closely spaced sheets cut across each other or are joined to each other by thin connecting sheets (fig. 18), while occasionally they form multiple intrusions, with internal chilled margins. In cross-section the sheets consist of a central porphyritic zone bounded by non-porphyritic margins and the transition between the porphyritic and non-porphyritic part is often abrupt. Inclusions of gabbro, granophyre, porphyritic rhyolite and pegmatitic basalt are frequently found within the porphyritic central zone.

The non-porphyritic margins are from 2mm. to 10cm. thick. They are normally drastically chilled at their contacts with the country rock and the actual contact is usually irregular in detail, often *with small vein offshoots. The fine-grained contact basalt passes* inwards into coarser basalt which is usually banded parallel to the main outline of the sheets but not to the minor irregularities of the

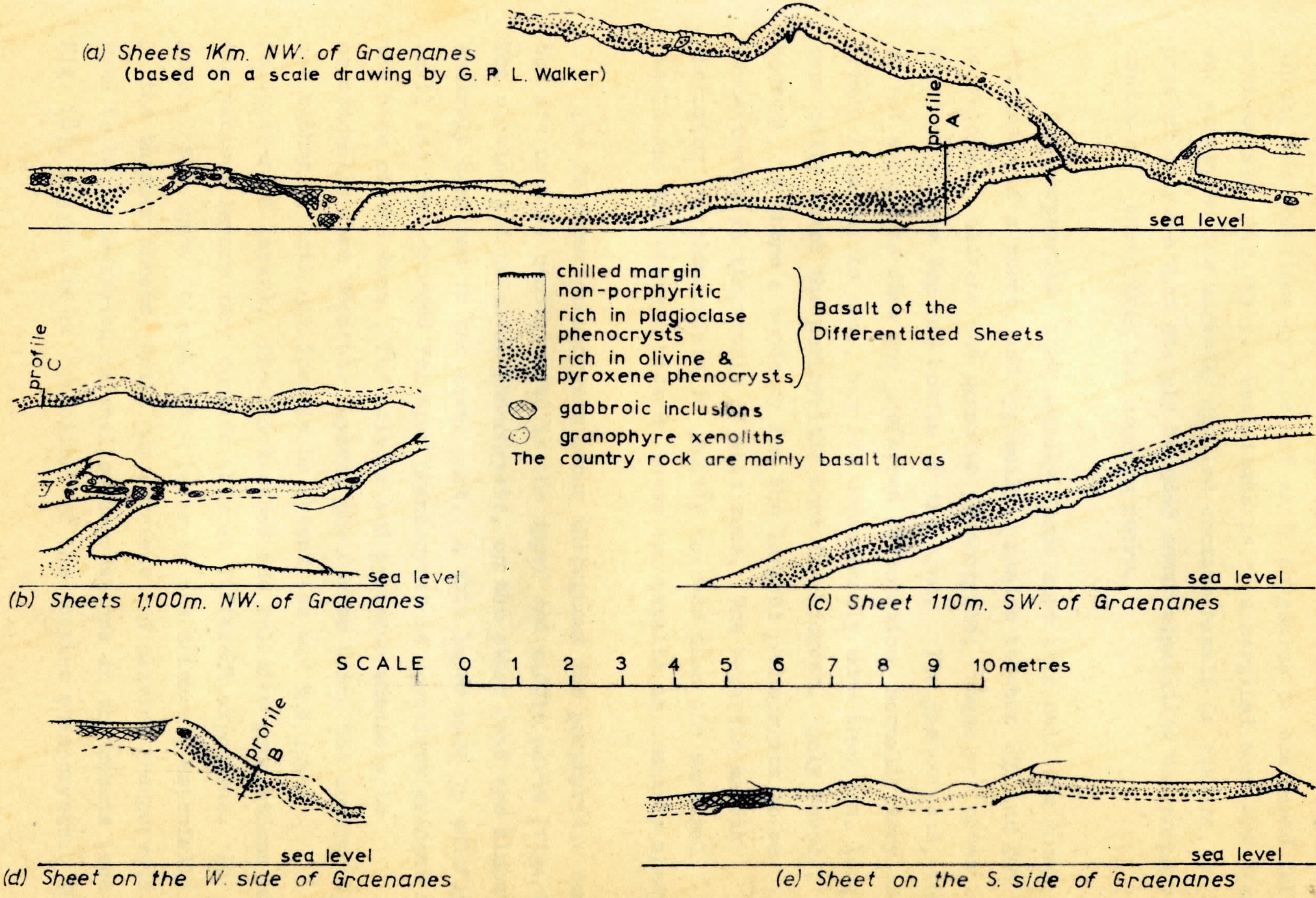
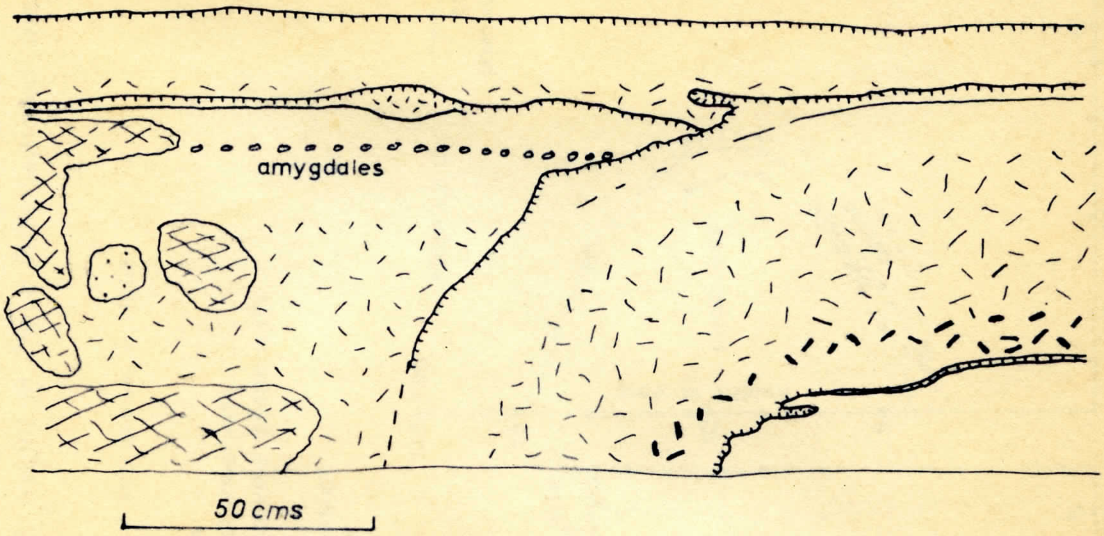
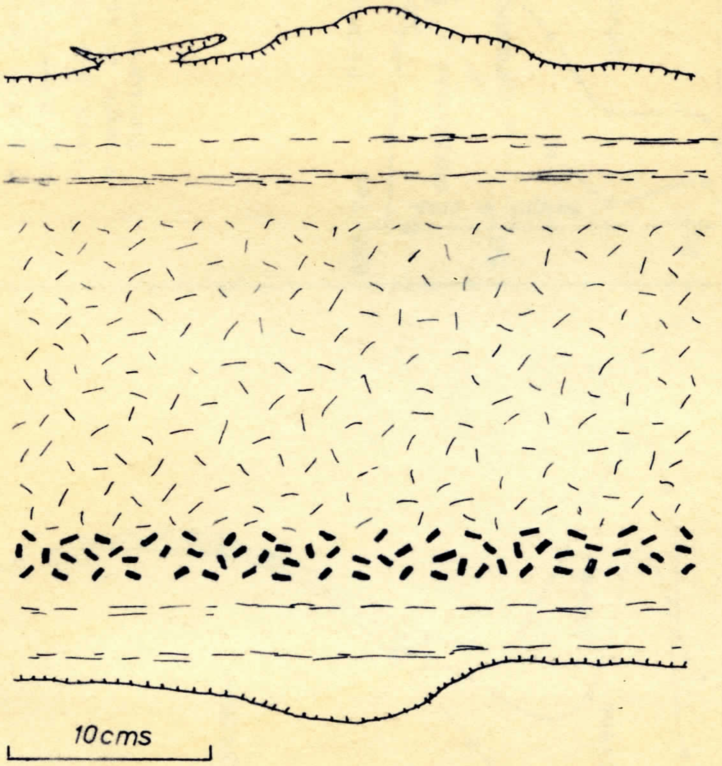


Fig. 18 Sections of some of the differentiated sheets exposed on the shore between Hvalnes and Vik Farms

Fig. 19



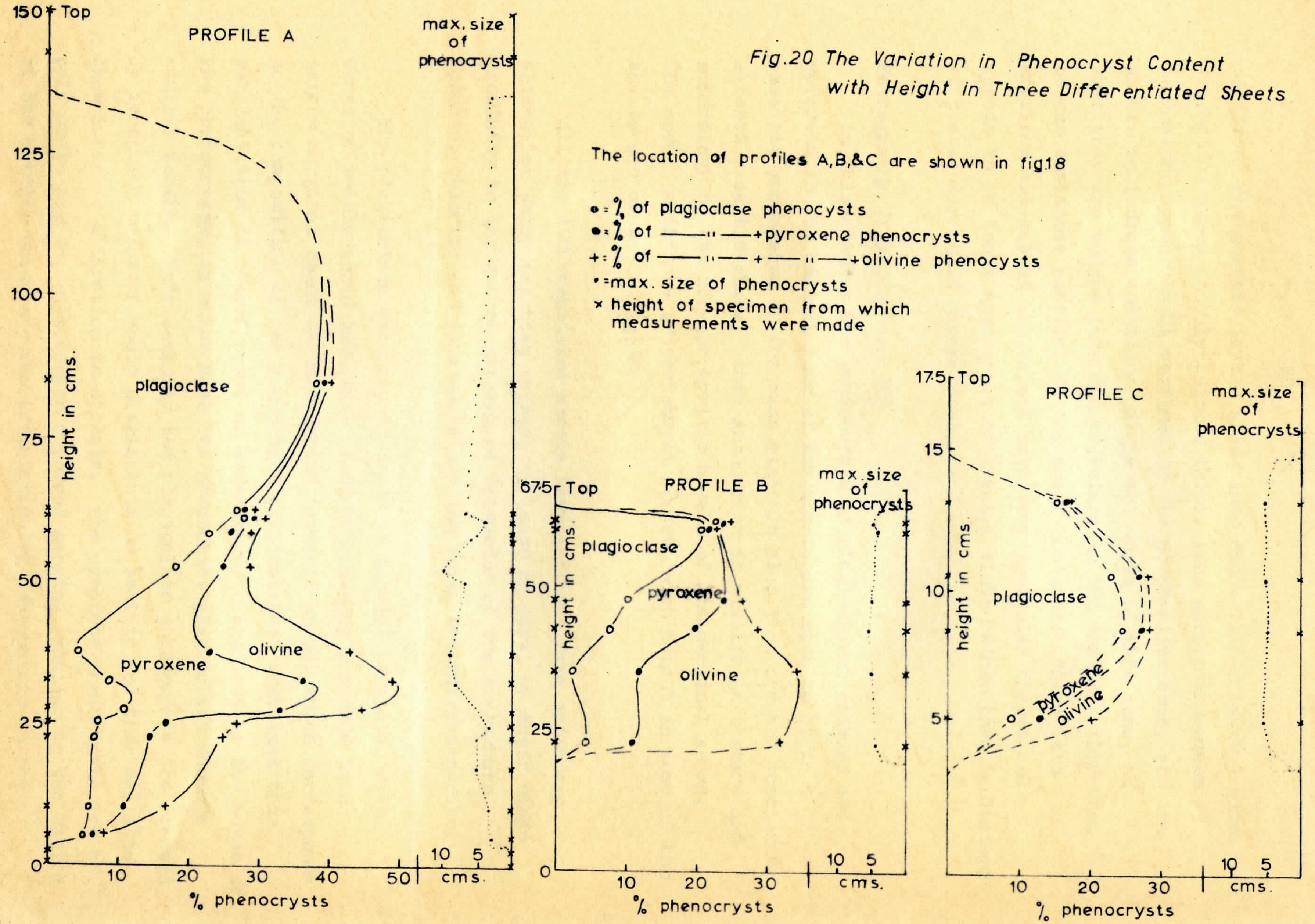
Multiple differentiated sheet 1,100 metres north-west of Graenanes.



Differentiated sheet 1,200 metres north-west of Graenanes.

Symbols as in fig.18

Fig.20 The Variation in Phenocryst Content with Height in Three Differentiated Sheets



different phenocrysts layers grade into each other (fig. 20) with transition zones usually 2-3cms. thick. The gabbro and other inclusions appear to be confined to the porphyritic zone, and the gabbro inclusions sometimes occupy the whole of this zone, as when they are wedged into constrictions in the sheets; they then become schistose parallel to the sheet contacts. Where less confined the gabbro inclusions have very irregular shapes and appear to be loose aggregates or crystal clots rather than inclusions of previously solid gabbro rock.

Petrography (figs. 21 and 22)

In thin-section the phenocrysts of plagioclase, olivine and pyroxene in the central zone of the sheets are seen to be in a basaltic groundmass of the same minerals plus iron ore and sometimes altered basaltic glass; this groundmass is similar in texture and mineralogy to the non-porphyritic basalt of the marginal zones. The modal variations of phenocryst content with height in some of the sheets are shown in fig. 20 .

All the differentiated sheets have suffered from secondary alteration which has been caused, at least in part, by their close proximity to the gabbro-granophyre intrusion of the Austurhorn. Epidote, chlorite and actinolite are the chief secondary minerals.

The plagioclase phenocrysts occur as tabular crystals, with cores of weakly zoned bytownite (An85-90) passing outwards into narrow marginal zones of labradorite (average An 65) which corresponds to the composition of the groundmass plagioclase: sometimes this marginal zone is itself zoned to andesine or oligoclase at the edges of the phenocrysts, in which case the groundmass plagioclase shows a similar zoning. Very commonly the plagioclase phenocrysts are crossed by irregular veins of sodic plagioclase or zeolite and they may also show internal alteration to epidote. The pyroxene phenocrysts are of pale brown augite, with deeper coloured margins (similar to the augite of the matrix) which are characteristically sub-ophitic to the

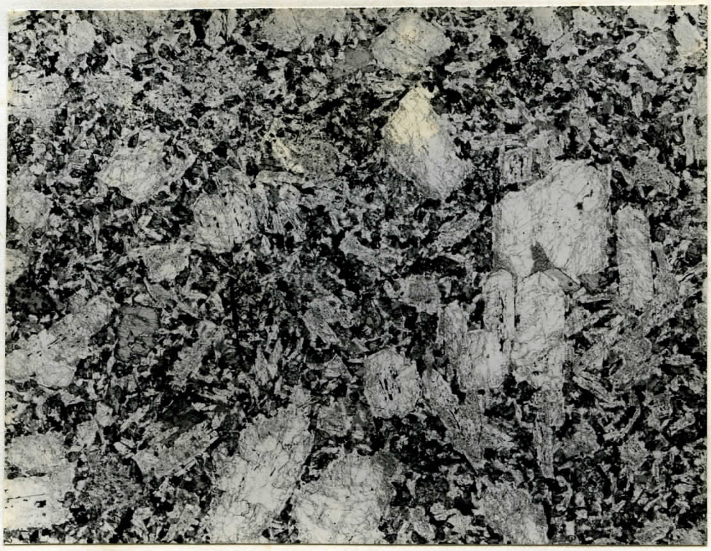


Fig.21a. **Photomicrograph** of a differentiated sheet, showing the feldspar-rich upper part of the porphyritic zone. X5.5. Ordinary light (019, profile B)

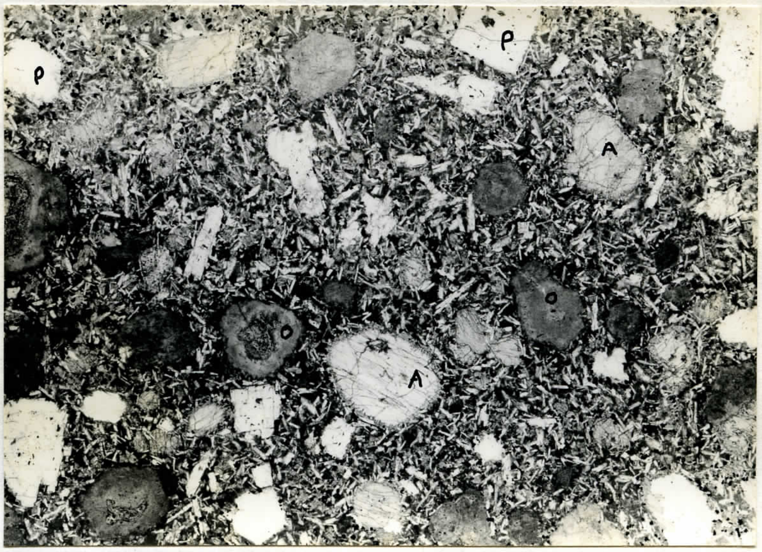


Fig.21b. Photomicrograph of the same differentiated sheet as above, showing the ferromagnesian-rich lower part of the porphyritic zone, with phenocrysts of olivine (O, mostly pseudomorphed), augite (A) and plagioclase (P). X5. Ordinary light (021, profile B).

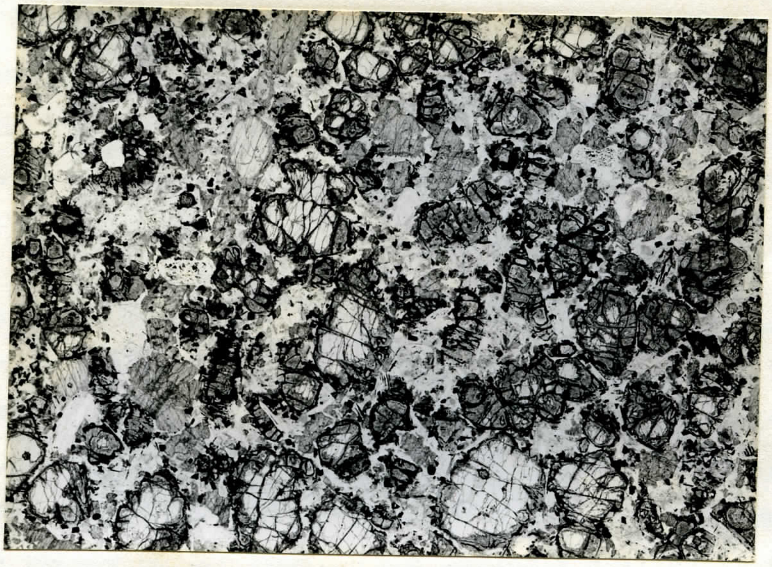


Fig.22a. Photomicrograph of a differentiated sheet, showing the richly porphyritic lower part of the porphyritic zone made up mainly of olivine phenocrysts (partly pseudomorphed), with less pyroxene and plagioclase. X4.5. Ordinary light. (E.712)

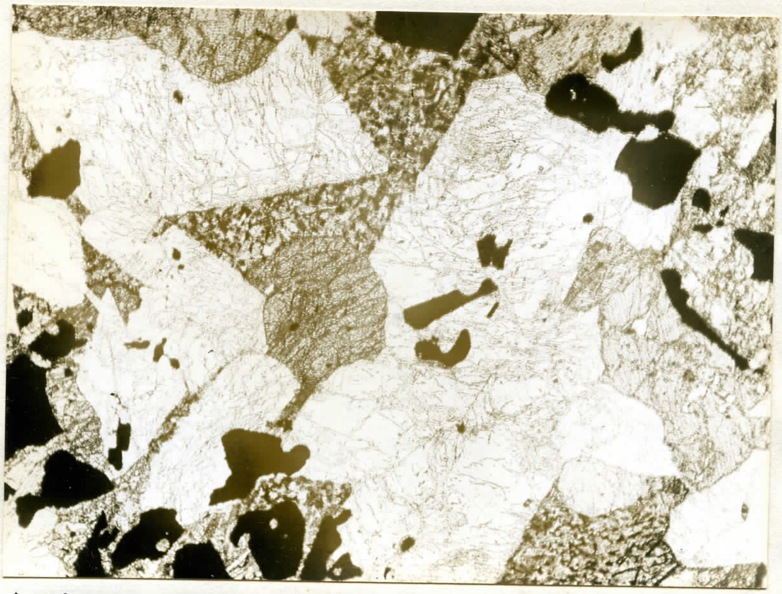


Fig.22b. Photomicrograph of a gabbroic xenolith from a differentiated sheet, showing angular patches of fine-grained basalt between the large plagioclase, augite and iron ore crystals. X15. Ordinary light. (E735).