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THE NET-VEINED COMPLEX OF THE AUSTURHORN INTRUSION, SOUTHEASTERN ICELAND¹

D. H. BLAKE²

ABSTRACT

The Austurhorn intrusion, one of a number of larger gabbro and granophyre intrusions that occur within the Tertiary lava pile of southeastern Iceland, is a composite, stocklike body cropping out over about 11 km.². The eastern part of this intrusion consists of a net-veined complex, in which acid, basic, and hybrid intermediate rocks are intimately associated.

Within the net-veined complex the basic and hybrid rocks occur as rounded to angular masses enclosed in and veined by granophyre. Many of these inclusions have pillow-like forms, with finer-grained margins and highly regular contacts, and most other inclusions appear to be pieces of fragmented pillows. Commonly the pillows occur in groups in which the individual pillows, all of the same composition, are separated from one another by thin layers of granophyre. There are, however, many examples of pillows of different compositions occurring alongside one another.

Evidence concerning the formation of the net-veined complex is discussed, and it is concluded that the pillows represent intrusions of basic and hybrid magmas into acid magma. The complex is considered to have been formed in situ shortly after the emplacement of, first, the granophyre magma, which displaced the country rocks by stoping, and, second, the gabbro magma, which was intruded into the granophyre magma before the latter had completely solidified.

I. INTRODUCTION

The Austurhorn intrusion is one of a number of larger gabbro and granophyre intrusions that have been emplaced within the Tertiary lavas of southeastern Iceland (fig. 1). Part of this intrusion consists of a "net-veined complex," in which basic and hybrid rocks are intimately associated with granophyre.

The occurrence of gabbro and granophyre in southeastern Iceland has long been known (Thoroddsen, 1896; Cargill, Hawkes, and Ledebøer, 1928; Anderson, 1949; Jonsson, 1954; Walker, 1964). Thoroddsen recorded both rock types at Austurhorn, and suggested that they formed a laccolithic intrusion. Hawkes (in Cargill *et al.*, 1928) later gave a more detailed description of the Austurhorn intrusion and interpreted it, as does the author, as an irregular composite stock. Some of the features of the net-veined complex were described briefly in a recent paper by Blake, Elwell, Gibson, Skelhorn, and Walker (1965).

The intrusion forms the eastern part of the Austurhorn ridge (fig. 2), including

Hvalnesfjall and eastern Víkurfjall. Here the gabbro and granophyre form a rugged, steep-sided mass which contrasts strongly with the stepped landscape of the generally flat-lying basalt lavas to the north and west. The intrusion also crops out on the southeastern side of Krossanesfjall and along the adjacent coast, and it extends for an unknown distance eastward beneath the sea. Extensive scree are developed below the steep granophyre exposures of the Austurhorn ridge and Krossanesfjall.

The country rocks surrounding the Austurhorn intrusion consist of gently dipping Tertiary lavas (chiefly basalts), tuffs, and numerous minor intrusions. Most of the extrusions and minor intrusions are probably the products of a Tertiary volcanic center, the Alftafjörður Volcano (Walker, 1963, fig. 1), situated about 10 km. to the north. There are also some younger minor intrusions that cut the Austurhorn intrusion as well as the country rocks.

II. GENERAL FEATURES OF THE AUSTURHORN INTRUSION

A. FORM OF THE INTRUSION

The Austurhorn intrusion crops out over an area of 11 km.². It is made up mostly of granophyre and its associated net-veined

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complex, and gabbro is almost entirely restricted to Hvalnesfjall (fig. 2), where it occurs as a large body that appears to be completely encircled by granophyre. The main exposures of the net-veined complex occur mainly to the east of Hvalnesfjall.

Roof and side contacts of the intrusion are well exposed on Vikurfjall and Krossanesfjall and at Krossanes, where pale grano-

banding has been found at two localities, one on either side of Hvalnesfjall (fig. 2); it consists of alternating pale feldspathic and dark ferromagnesian bands, mostly less than 1 cm. thick, which dip inward toward the center of the gabbro mass.

The contacts between the gabbro and granophyre are generally well exposed. On the eastern side of Hvalnesfjall, where the

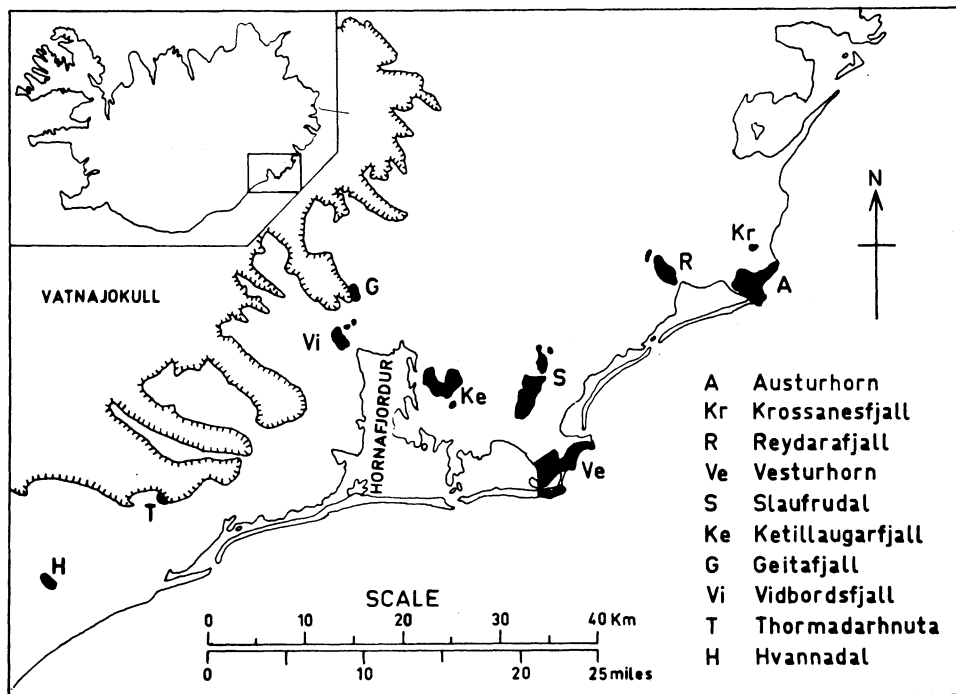


FIG. 1.—Index map of southeastern Iceland showing location of gabbro and granophyre intrusions (solid black).

phyre is in contact with dark country rocks, and from these contacts the stocklike, transgressive nature of the intrusion is readily apparent. The contacts are sharp and irregular, both on a large scale and in detail, and many veins and apophyses of granophyre penetrate the country rocks. The contact granophyre is not noticeably chilled.

The gabbro body of Hvalnesfjall shows both large-scale layering and small-scale mineral banding. The layering is visible from a distance, each layer being about 10 m. thick, but is not apparent close up. Mineral

gabbro overlies the granophyre, the contact is sharp and irregular, and veins and apophyses of granophyre penetrate the overlying gabbro. Neither the gabbro nor the granophyre is chilled against the other. In contrast, on the northwestern side of Hvalnesfjall, where the gabbro/granophyre contact is nearly vertical, the lower exposures of the contact show a transition zone of hybrid rock, a meter or more wide, separating normal coarse-grained gabbro from granophyre. Above a height of 300 m. this hybrid zone gives way to a breccia zone of similar

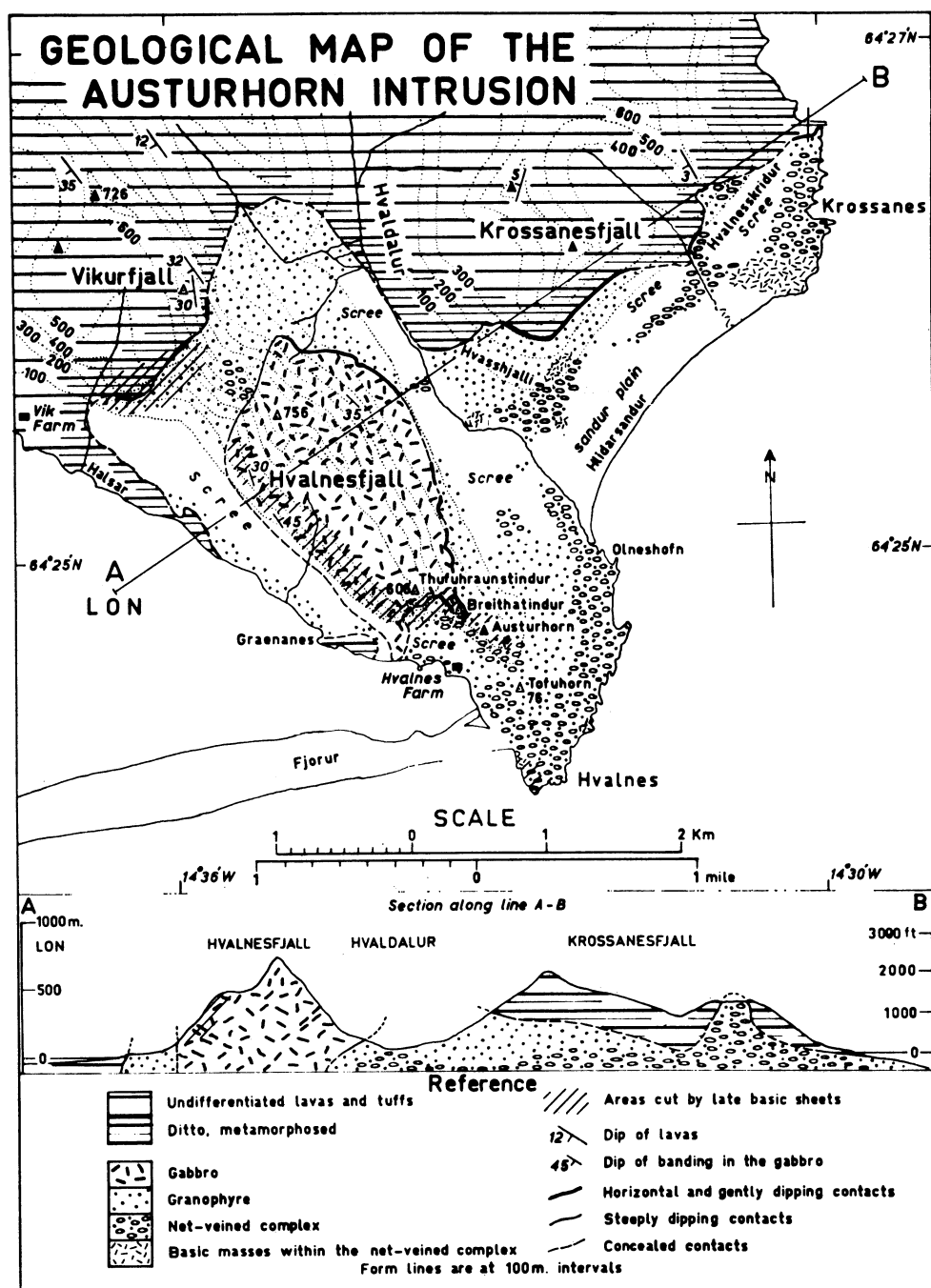


FIG. 2.—Geological map of the Austurhorn intrusion, southeastern Iceland

thickness in which angular gabbro fragments lie in a matrix of granophyre.

Certain parts of the Austurhorn intrusion have been intruded by numerous cross-cutting dykes and sheets of tholeiitic basalt. These minor intrusions are especially abundant along the Austurhorn ridge, where they cut gabbro, granophyre, and country rocks, but they are almost completely absent from the net-veined complex. They have chilled margins, and are generally less than 1 m. thick; a few have intricate crenulate contacts where they cut granophyre.

B. METAMORPHISM OF THE COUNTRY ROCKS

A well-defined metamorphic aureole, up to 1 km. wide, surrounds the Austurhorn intrusion, and the basalt lavas within the aureole contain a distinctive suite of amygdale minerals. The most abundant of these minerals are epidote, chlorite, calcite, quartz, and alkali feldspar; less common are garnet, prehnite, scolecite, mesolite, actinolite, pyroxene, plagioclase, and pyrite. This suite of amygdale minerals is closely comparable to that in Scottish Tertiary basalt lavas which have been similarly metamorphosed, as, for example, on the Isles of Mull (M'lintock, 1915) and Skye (Harker, 1904).

C. MODE OF EMPLACEMENT

The basalt lavas around the Austurhorn intrusion show evidence of slight updoming on Vikurfjall and also possibly at Krossanes. The volume of the intrusion, however, is much larger than the space provided by this updoming, and the intrusion is thought to have been emplaced mainly by stoping.

D. DEPTH OF EMPLACEMENT

An estimate of the depth at which the Austurhorn intrusion was emplaced can be obtained from a study of the zeolite minerals occurring in the basalt lavas outside the Austurhorn metamorphic aureole. Walker (1960) showed that the different zeolites found in the amygdalae of basalt lavas in eastern Iceland occur in flat-lying zones that cut across the stratigraphic layering of the lavas, and that these zones are related to

the maximum depth at which the lavas were buried. In olivine tholeiite lavas Walker recognized three zones; these are (i) an upper Chabazite and Thomsonite Zone; (ii) a middle Analcite Zone; and (iii) a lower Mesolite and Scolecite Zone. In the lower part of the Mesolite and Scolecite Zone, Walker has since recognized a separate Laumontite Zone, the top of which lies at an estimated 1,700 m. below the original top of the lava pile (G. P. L. Walker, personal communication). In olivine tholeiite lavas on Vikurfjall, just outside the Austurhorn thermal aureole, the top of the Laumontite Zone occurs at a height of about 750 m., the same height as the highest exposures of the Austurhorn intrusion, thus indicating that that part of the intrusion now exposed was emplaced at a depth of about 1,700 m.

E. PETROGRAPHY OF MAIN ROCK TYPES

Granophyre.—The acid rocks of the Austurhorn intrusion vary widely both in texture and in composition, and although generally referred to as granophyre they also include some with granitic textures. The most abundant acid rock is a pale-pink porphyritic granophyre containing white phenocrysts of feldspar, up to 3 mm. long, in a fine-grained leucocratic groundmass; dark minerals make up less than 5 per cent of the rock and consist mainly of acicular ferromagnesian phenocrysts usually less than 5 mm. long. Granophyre with between 5 and 10 per cent of dark minerals is also common, and a darker granophyre occurs locally. Small crystal-lined cavities and partly digested inclusions are common throughout; the cavities contain euhedral crystals of quartz, alkali feldspar, epidote, and, less commonly, magnetite, amphibole, calcite, laumontite, and garnet.

Under the microscope the granophyre is seen to consist dominantly of quartz, alkali feldspar, and (in most specimens) plagioclase, with one or more of the following minerals: diopsidic augite, ferroaugite, aegirine-augite, fayalite, and hornblende. Minor constituents are allanite, apatite, biotite, calcite, chlorite, epidote, fluorite, iddingsite

(after fayalite), magnetite, secondary amphibole, sericite, sphene, and zircon. The granophyre is normally porphyritic, the phenocrysts lying in a fine-grained groundmass of quartz and alkali feldspar: this groundmass is usually micrographic but may be granitic. The phenocrysts in the pink granophyre consist of either (i) plagioclase, ferroaugite, and sometimes fayalite, or (ii) alkali feldspar and aegirine-augite. In the darker granophyre the phenocrysts consist of plagioclase, hornblende, and diopside augite. The ferromagnesian pheno-

Fayalite is honey-colored, with $\beta = 1.848 \pm 0.005$, $2V = 49^\circ - 52^\circ$. Greenish-brown hornblende occurs both as a primary mineral, commonly associated with diopsidic augite, and as an alteration product of pyroxene.

The variation in mineralogy and chemistry of the Austurhorn acid rocks is shown in tables 1 and 2. Chemically the rocks are closely comparable to the pitchstones of eastern Iceland (table 2).

Gabbro.—The gabbro has an average grain size of 3 mm., and contains about 30

TABLE 1

MODAL ANALYSES (VOL. PER CENT OF ACID ROCKS FROM THE AUSTURHORN INTRUSION)

(For Key to Analyses See Notes to Tables 1-3)

	1	2	3	4	5	6	7	8
Plagioclase phenocrysts.....	.....	14	20	23	32	36	42	46
Alkali feldspar phenocrysts.....	39*	.....	.....	.....	.....	.....	.....	.....
Augite.....	.....	.....	.....	.....	4	.....	0.5	6
Ferroaugite.....	.....	1	.....	3	.....	2	.....	.....
Aegirine-augite.....	5	.....	.....	.....	.....	.....	.....	.....
Fayalite.....	.....	.....	.....	1	.....	1	.....	.....
Hornblende, etc.....	1	3	4	4	4	2	8.5	21
Groundmass:								
Micrographic intergrowth.....	52	70	.....	49	31	48	39	14
Non-micrographic quartz.....	3	3	22	3	13	4	4	6
Non-micrographic alkali feldspar.....	.....	9	54	17	16	7	6	7
Specific gravity.....	2.65	2.54	2.58	2.67	2.53	.....	2.65	2.80

* Includes a small amount of interstitial alkali feldspar.

crysts tend to be subhedral, whereas the feldspar phenocrysts are commonly euhedral.

The alkali feldspar, whether as phenocrysts or in the groundmass, is usually turbid: it ranges from orthoclase to anorthoclase in composition, and X-ray studies show it to be cryptoperthitic. The plagioclase is present only as euhedral phenocrysts: these are zoned from cores of andesine or labradorite to margins of albite, and they are rimmed with turbid alkali feldspar. Ferroaugite forms pale-green, patchily zoned phenocrysts, with $\beta = 1.735 \pm 0.01$, $2V = 53^\circ - 62^\circ$. Green aegirine-augite phenocrysts show similar patchy zoning, with $\beta = 1.740 \pm 0.005$, $2V = 66^\circ - 82^\circ$.

per cent of dark minerals. Irregular patches of pegmatitic, melanocratic, and anorthositic gabbro, however, are common throughout the mass. In thin section the gabbro is seen to consist essentially of plagioclase, augite, and iron ore, frequently with olivine and hypersthene (both commonly pseudomorphed); apatite is present as an accessory mineral, and albite, biotite, bowlingite, calcite, chlorite, epidote, hornblende, serpentine, and tremolite occur as secondary minerals. The texture of the gabbro is normally hypidiomorphic granular, although ophitic varieties are quite common. The plagioclase generally shows normal zoning from cores of bytownite or calcic labradorite (An 85-70) to margins of sodic labradorite or andesine

TABLE 2
CHEMICAL ANALYSES*
(For Key to Analyses See Notes to Tables 1-3)

	AUSTURHORN ROCKS									AVERAGE PITCHSTONE, E. ICELAND (Walker, 1962)
	Granophyre				Gabbro			Basic Pillow		
	2†	3†	7†	9‡	10†	15†	18‡	19†	20†	
SiO ₂	72.1	70.9	66.5	66.66	40.4	45.4	47.30	54.3	54.1	70.5
TiO ₂	0.35	0.34	0.59	0.25	6.10	2.30	0.58	2.10	2.19	0.3
Al ₂ O ₃	12.7	14.3	15.2	14.89	12.4	19.6	25.04	14.7	14.8	12.4
Fe ₂ O ₃	2.4	2.1	2.1	2.74	7.1	5.6	0.93	2.6	2.7	1.1
FeO	1.6	1.5	3.1	3.22	11.0	6.1	3.41	7.8	7.9	1.9
MnO	0.16	0.04	0.13	tr	0.22	0.12	.....	0.21	0.15	0.1
MgO	0.15	0.29	0.78	1.04	7.3	4.3	4.00	3.8	3.8	0.3
CaO	1.26	1.21	2.63	3.22	12.4	12.3	15.92	7.2	7.2	1.4
Na ₂ O	5.1	5.7	5.7	4.44	1.8	2.7	1.56	5.2	4.1	4.6
K ₂ O	3.6	3.2	2.7	2.72	0.3	0.4	0.42	1.0	1.4	2.8
P ₂ O ₅	0.12	0.06	0.38	0.18	0.10	0.17	0.10	0.53	0.48	0.05
H ₂ O+	0.8	0.3	0.4	0.37	1.3	0.9	0.54	1.2	1.2	3.8
H ₂ O-	0.05	0.1	0.05	0.16	0.2	0.1	0.12	0.1	0.1	0.8
Total	100.4	100.0	100.3	99.89	100.6	100.0	99.92	100.7	100.1	

* Rock analyses performed by Blake using rapid methods modified from Shapiro and Brannock (1952).

† Analyst, D. H. Blake.

‡ Analyst, W. H. Herdsman.

TABLE 3
MODAL ANALYSES (VOL. PER CENT) OF GABBRO
FROM THE AUSTURHORN INTRUSION
(For Key to Analyses See Notes to Tables 1-3)

	SPECIMEN								
	10	11	12	13	14	15	16	17	18
Plagioclase.....	53	67	70	60	27	61	35	35	77
Augite.....	27	23	20	36	41	24	48	43	22
Hypersthene.....	(6)*	(2)	(2)	(1)	3	(5)	.....	7	.....
Olivine.....	.....	(1)	(1)	.....	20	.....	.....	9	.....
Iron ore.....	12	6	6	3	4	9	16	4	1
Accessories.....	2	1	1	.....	5	1	1	2	.....

* Nos. in parentheses are pseudomorphs.

NOTES TO TABLES 1-3 SPECIMENS FROM THE AUSTURHORN INTRUSION

1. Aegirine-augite granophyre, from Hvalnesskridur (specimen H.324).
2. Ferroaugite granophyre, from the southern side of Krossanesfjall (specimen H.304).
3. Granite, from the net-veined complex at Hvalnes (specimen H.416).
4. Fayalite granophyre, from Breithatindur (specimen H.217).
5. Epidotic granophyre, from Graenanes (specimen H.644).
6. Granophyre, from Krossanes (specimen H.681).
7. Hornblende granophyre, from the net-veined complex at Hvasshjalli (specimen H.313).
8. Basic granophyre, from Breithatindur (specimen H.187).
9. "Graphic hornblende granodiorite," from Vikurfjall (specimen 130(A), Cargill *et al.*, 1928).
10. Gabbro, from the shore west of Hvalnes farm (specimen H.164).
11. Gabbro, from the northeast side of Hvalnesfjall (specimen H.206).
12. Ophitic gabbro, from Thufuhraunstindur (specimen H.221).
13. Ophitic gabbro, from Thufuhraunstindur (specimen H.223).
14. Melanocratic gabbro, from northwest Hvalnesfjall (specimen H.231).
15. Banded gabbro, from west Hvalnesfjall (specimen H.232).
16. Gabbro, from granophyre contact on Breithatindur (specimen H.292).
17. Gabbro, from northwest Hvalnesfjall (specimen H.625).
18. Gabbro, from Breithatindur (specimen 82(A), Cargill *et al.*, 1928).
19. Margin of tholeiitic pillow, from the net-veined complex at Krossanes (specimen H.667).
20. Interior of the same tholeiitic pillow as 19, from the net-veined complex at Krossanes (specimen H.668).

(An 55-40): zoning is most noticeable at the crystal margins.

Chemical and modal analyses of gabbro specimens from Hvalnesfjall are shown in tables 2 and 3. The specimens chosen show the wide range in composition found within the gabbro mass.

III. THE NET-VEINED COMPLEX

The net-veined complex consists of an intimate association of acid, basic, and hy-

brid intermediate rocks in which the more basic rocks occur as angular to rounded masses enclosed in and veined by granophyre. Rock types within the complex comprise tholeiitic basalt and dolerite (tholeiite), gabbro, diorite, various hybrid rocks, granite, and granophyre. The limits of the complex are taken arbitrarily where basic and hybrid inclusions within the granophyre form less than 5 per cent of the total rock.

The main outcrop of the net-veined com-

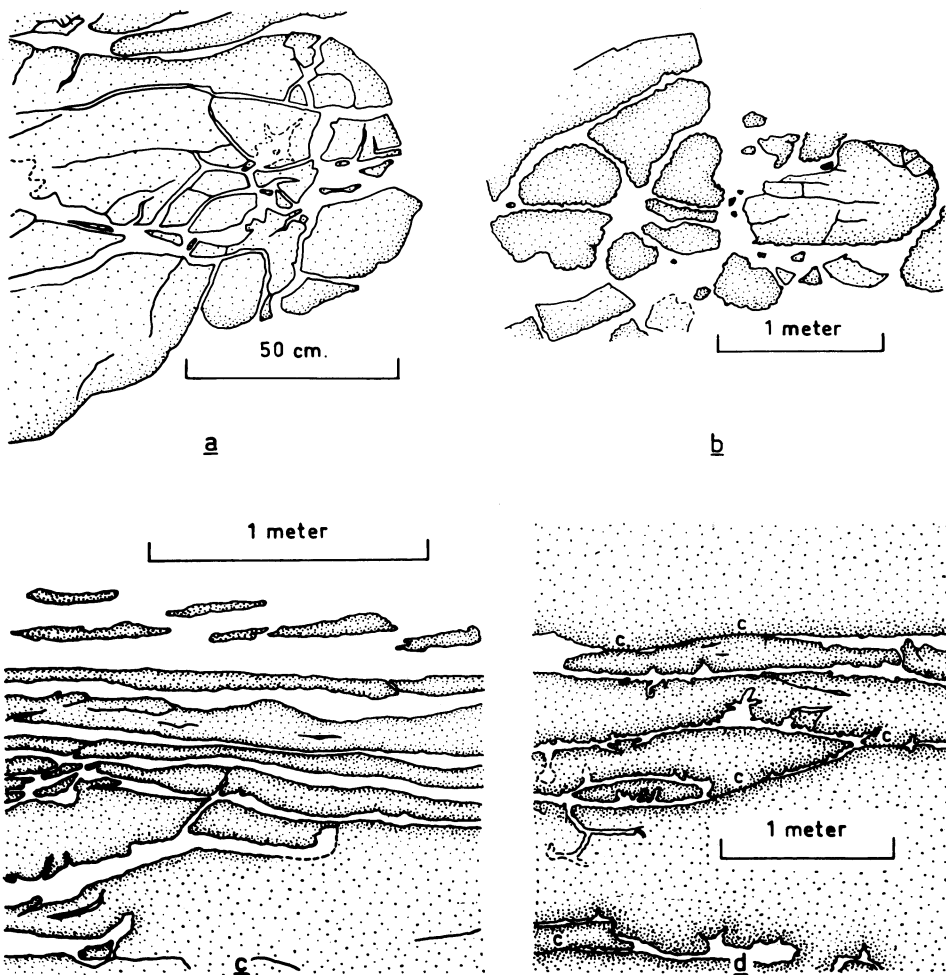


FIG. 3.—Field sketches of basic pillows (*stippled*) in granophyre; the finer grain size of the pillow margins is indicated on the sketches by the denser stippling: (a) pillow partly broken up by granophyre veins, Olnesshofn; (b) group of small pillows and pillow fragments, Olnesshofn; (c) vertical cross section of a group of mainly flat-lying tabular pillows, Olnesshofn; (d) part of a group of closely spaced pillows in which some of the pillows touch one another (at the places marked "c"), Hvasshjalli.

plex forms most of the eastern part of the Austurhorn intrusion, covering an area of more than 3 km.², and it ranges in height from sea level around the coast to over 200 m. on Austurhorn and over 300 m. on Krossanesfjall. A small outcrop also occurs on top of the Austurhorn ridge west of the gabbro of Hvalnesfjall (see fig. 2). The complex is best exposed along the coast between Hvalves and Krossanes (see pl. 2,A).

A. PILLOW-LIKE INCLUSIONS

One of the most striking features of the net-veined complex is the widespread occurrence within the granophyre of rounded, pillow-like inclusions of basic and hybrid rocks (fig. 3; pls. 1 and 2). These pillows are of various shapes, and they range in size from less than 1 to more than 10 m. in maximum diameter. Very commonly they occur in groups, and some of these groups are similar in appearance to groups of basalt pillows in pillow lavas. In the pillow groups within the net-veined complex the individual pillows are normally close together, but in almost every case are separated from one another by thin layers of granophyre: only very rarely are two pillows seen to touch (fig. 3,d). Where closely spaced, the bulges of one pillow fit into corresponding depressions in adjacent pillows (pl. 1,B).

In general the pillows appear quite haphazard in their distribution and orientation. However, a crude layering of pillows is apparent in a few places, especially where groups of tabular pillows occur (fig. 3,c): in such groups the pillows are normally flat-lying and only rarely are they inclined at angles of more than 10°.

Characteristically the pillows show a progressive decrease in grain size toward their margins, dolerite in the centers of basic pil-

lows grading into fine-grained basalt at the pillow margins (pl. 2,D). In the larger pillows this gradational increase in grain size may continue over a distance of more than 1 m. from the contact with the granophyre. The finer-grained pillow margins are also commonly appreciably darker than the pillow interiors (cf. Bishop, 1964): these dark margins range in thickness in different pillows from 0.05 to 2 cm., but they generally have a constant thickness in any one pillow (pl. 3,A) and also within a particular pillow group. The dark margins are normally most marked where the pillows have sharp contacts with the adjacent granophyre, and may be absent where the contact of the pillow and granophyre is diffuse.

The contacts of the pillows with the surrounding granophyre are highly irregular, and may vary from sharp to diffuse within a few centimeters. Typically the contacts are crenulate, with rounded protuberances of pillow rock alternating with pointed embayments of granophyre (fig. 3,d; pl. 2,A): in some examples deep embayments of granophyre pass inward into ill-defined, quartzofeldspathic patches within the pillow interior.

The pillows are formed of a variety of basic and hybrid rock types, but all pillows within a particular pillow group are usually of the same rock type. Basic pillows are the most common and are represented by three types of basalt: aphyric tholeiite, porphyritic tholeiite, and olivine tholeiite. In the porphyritic tholeiite pillows small feldspar phenocrysts, up to 5 mm. long, form about 10 per cent of the total rock; these phenocrysts tend to maintain a constant size, and so lose their prominence in the doleritic interiors of large pillows (pl. 2,D). The olivine tholeiite pillows are coarser-grained than

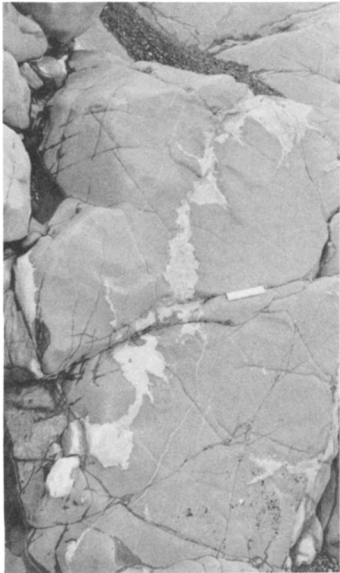
PLATE 1

THE AUSTURHORN NET-VEINED COMPLEX

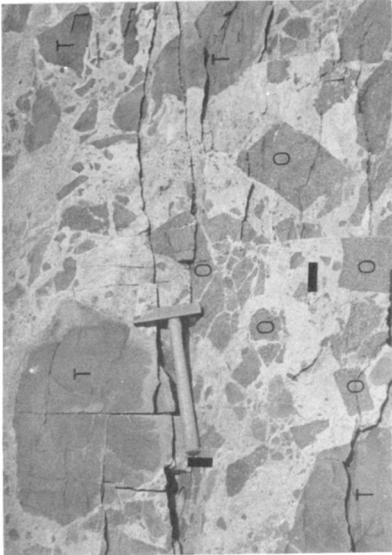
A, Exposures of the net-veined complex at Krossanes, looking northward.

B, Group of porphyritic basalt pillows separated from one another by narrow layers of granophyre. An exposure at the base of Hvalnesskridur.





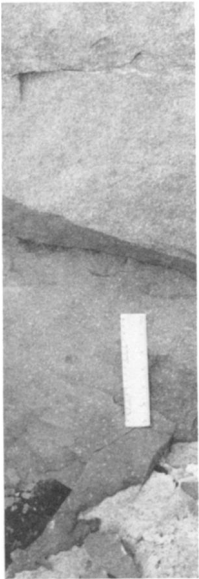
A



B



C



D

the other tholeiite pillows of comparable size, and are darker in color. The hybrid pillows are intermediate in composition between the tholeiite pillows and surrounding granophyre: they are neither as abundant nor as prominent as the tholeiite pillows.

Many of the pillows are cut by granophyre veins (fig. 3,*a*; pl. 2,*A*), most of which join up with the granophyre surrounding the pillows. The veins commonly form intricate networks. The veins are thin (mostly less than 5 cm. wide) and may be either sinuous or rectilinear, with more or less parallel, but not always matching, sides. The vein contacts are normally sharp near the pillow margins but may be diffuse in the pillow centers. Many pillows are partly or completely broken up by veins, and all stages are seen from pillows cut by a few very thin veins to completely fragmented pillows now represented by isolated, but still recognizable, pillow fragments scattered through the granophyre (pl. 2,*c*). There are also some later aplitic veins which cut right across the pillows and enclosing granophyre; these veins are parallel-sided, and have matching walls.

Not always easily distinguishable from granophyre veins cutting pillows are the thin granophyre layers that occur between closely spaced pillows. These layers may be roughly parallel-sided but, unlike the veins, they never have matching walls (fig. 3,*d*; pl. 2,*A*). This distinction is well displayed on the east side of Krossanesfjall, at the margin of the Austurhorn intrusion, where closely spaced pillows within the net-veined com-

plex lie alongside basalt lavas: the pillows here are separated from one another and from the country-rock lavas by thin granophyre layers, and both pillows and lavas are cut by granophyre veins. Some of the thin granophyre layers, especially those between tabular pillows, have finger-like apophyses projecting into the pillows (fig. 3,*d*), and are similar in appearance to the "sheet veins" of the Guernsey net-veined complex (Elwell, Skelhorn, and Drysdall, 1962). Contacts between granophyre layers and pillows may be either sharp or diffuse, and may be different on either side of a granophyre layer.

B. OTHER INCLUSIONS

Many inclusions within the net-veined complex do not have an obvious pillow-like form. Some are angular rather than rounded and others have an irregular, indeterminate shape (pl. 2,*B*).

Angular or partly angular inclusions, generally less than 10 cm. in maximum diameter, are abundant throughout the complex. Usually these inclusions have sharp boundaries, and they do not show any regular textural zoning. They include fragments of gabbro, identical in character with the gabbro of Hvalnesfjall, and numerous fragments of basalt and dolerite, many of which are probably derived from fragmented basic pillows (fig. 3,*b*; pl. 3,*C*). There are also many angular inclusions of gray granophyre and various hybrid rocks.

Inclusions which have indeterminate shapes are usually of hybrid composition. Commonly they show compositional zoning,

PLATE 2

FEATURES OF THE AUSTURHORN NET-VEINED COMPLEX

A, Deeply embayed crenulate contacts between an irregular granophyre layer and two basalt pillows, Olsheshofn. The scale is given by the 15-cm. (9-inch) rule.

B, Angular inclusions of tholeiite (*T*) and olivine tholeiite (*O*) in granophyre at Krossanes. The tholeiite inclusion above the hammer has an irregular margin of pale-gray hybrid rock. The hammer head rests on a partly fragmented olivine tholeiite inclusion.

C, Basalt inclusions, most of which are pieces of fragmented pillows, in granophyre at Hvalnes. Scale is given by the 15-cm. (9-inch) rule.

D, The outer part of a large porphyritic basalt pillow at Krossanes, showing the gradational increase in grain size from a fine-grained porphyritic basalt at the pillow margin to a coarse aphyric dolerite in the pillow interior.

with a relatively more basic interior merging outward, through a spotted or streaky transition zone of variable thickness, into the surrounding granophyre. Such inclusions are normally quite small (less than 1 m. in diameter).

There are also some much larger inclusions, tens of meters in maximum diameter, whose form is not known. These include gabbroic masses on Hvasshjalli and Breithatindur, and various doleritic and dioritic bodies on Breithatindur and at Hvalnes and Krossanes (fig. 2).

C. ENCLOSING GRANOPHYRE

The granophyre within the net-veined complex is generally similar to that found elsewhere within the Austurhorn intrusion. Xenocrysts and partly digested inclusions, however, are more abundant, especially in acid layers separating closely spaced pillows, and these give the granophyre a spotted "hybrid" appearance. Also crystal-lined cavities tend to be larger than those in the granophyre outside the net-veined complex. Epidote is locally very abundant in the granophyre and occurs in the matrix and on joint surfaces as well as in cavities.

Immediately adjacent to many basic pillows the granophyre is paler in color than away from the pillows, this pale zone usually being less than 1 cm. thick.

D. PETROGRAPHY

Tholeiite pillows.—The interiors of the larger tholeiite pillows are of fairly coarse-grained aphyric dolerite (pl. 2,*D*) and con-

sist essentially of plagioclase, augite, and opaque minerals. Plagioclase occurs as strongly zoned laths ranging from labradorite (An 60-70) in the cores to andesine or oligoclase at the margins. Augite, commonly ophitic, is the only pyroxene, and is marginally altered to brown hornblende. Opaque minerals form equant and acicular crystals. Minor constituents are apatite, rare serpentine pseudomorphs after olivine, chlorite, calcite, and interstitial quartz and alkali feldspar.

Within a few centimeters of the pillow margins the grain size decreases gradationally, and the augite is no longer ophitic but occurs instead as small granular crystals. Prominent phenocrysts of plagioclase may be present.

At the pillow margins the texture is generally subvolcanic, with the groundmass feldspar forming a matrix made up of elongate crystals arranged in radial or sheaflike patterns (pl. 3,*c*). Small skeletal plagioclase laths and plagioclase phenocrysts showing normal zoning and twinning are commonly present (pl. 3,*a*). Rare augite phenocrysts may occur, but the granular augite of the groundmass is partly or completely replaced by green hornblende. Opaque minerals occur both as skeletal crystals made up of small groups of parallel rods and as larger equant crystals lining the pillow granophyre contacts (pl. 3,*C*). Poikilitic crystals of brown hornblende and biotite, up to 2 mm. in diameter, occur in many pillow margins; those of biotite are commonly surrounded by pale feldspathic zones (pl. 3,*b*). Apatite

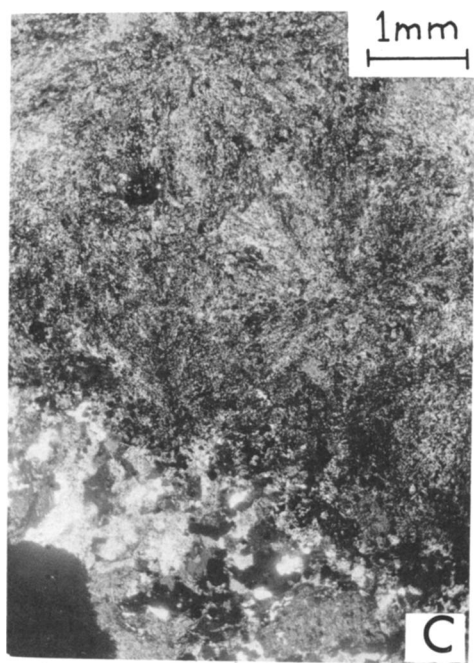
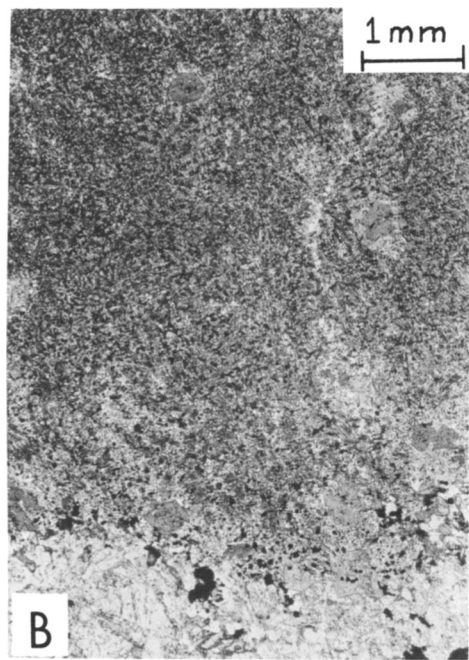
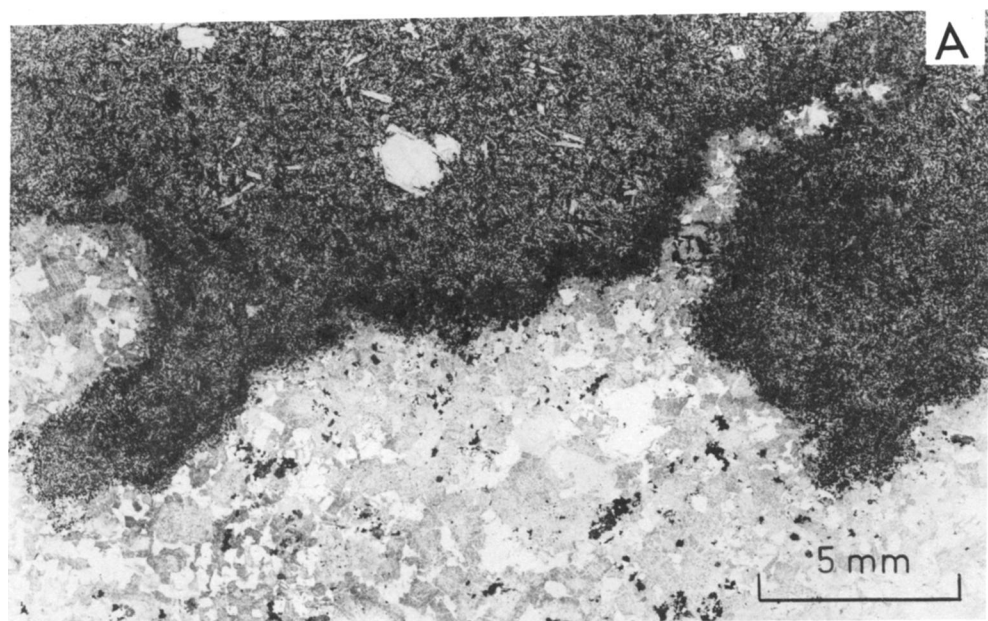
PLATE 3

PHOTOMICROGRAPHS OF THOLEIITE PILLOWS

A, Photomicrograph of an irregular contact of a porphyritic tholeiite pillow and granitic acid rock, Olsheshofn, showing a narrow marginal zone of darker pillow rock running parallel to the contact. The pillow contains both plagioclase phenocrysts and skeletal, H-shaped plagioclase laths. The acid rock is composed chiefly of quartz and turbid alkali feldspar. Ordinary light, $\times 5$.

B, Photomicrograph of the contact of a tholeiite pillow and granophyre, Krossanes, showing "megacrysts" of biotite surrounded by narrow feldspathic halos within the fine-grained pillow margin. Plane-polarized light, $\times 13$.

C, Photomicrograph of the contact of a tholeiite pillow and granitic acid rock, Olsheshofn, with nicols crossed, showing the sheaflike pattern of the groundmass feldspar at the pillow margin. There is a concentration of euhedral magnetite crystals at the edge of the pillow, $\times 13$.



is an abundant accessory mineral, forming minute rods arranged in parallel groups similar to those of the opaque minerals. Quartz and alkali feldspar can rarely be distinguished.

Chemical analyses of two specimens from a basic pillow, one from the center and the other from the margin, are given in table 2. These analyses indicate that there is little variation in composition within this particular pillow except for an apparently higher soda and lower potash content in the pillow margin than in the pillow center.

Many of the petrographic features of the tholeiitic pillows are similar to those of tholeiitic pillow-like inclusions at Slieve Gullion, Northern Ireland (Bailey and McCallien, 1956), and on Mount Desert Island, Maine, U.S.A. (Chapman, 1962).

Olivine tholeiite pillows.—These do not show as marked a textural zoning as the olivine-free tholeiite pillows. The olivine tholeiite has an ophitic texture, with plagioclase laths, up to 2 mm. long, enclosed in pale-brown augite which is partly altered to brown hornblende and biotite; also present are hypersthene, generally pseudomorphed by pale-green amphibole, pseudomorphs of talc and chlorite after olivine, and iron ore. The plagioclase laths are zoned from calcic labradorite and bytownite in the cores to andesine at the margins.

Hybrid rocks.—Petrographically the hybrid rocks show various combinations of basaltic, granophyric, and granitic features. The more basic of the hybrids have basaltic textures and consist of plagioclase, augite, iron ore, and hornblende, with interstitial and commonly micrographic quartz and alkali feldspar. Some of the other hybrid rocks also have basaltic textures but consist of laths of alkali feldspar instead of plagioclase, and hornblende, chlorite, and calcite in place of pyroxene. The more acid hybrids are typically heterogeneous, irregular clusters of hornblende and iron-ore crystals occurring in a partly micrographic and partly granitic groundmass of quartz and alkali feldspar; in such rocks plagioclase and augite are present only as corroded xenocrysts. In all the hy-

brid rocks apatite is an important accessory mineral, occurring as innumerable minute prismatic crystals.

Enclosing granophyre.—The granophyre within the net-veined complex is generally similar to that outside the complex. Differences are seen, however, close to many pillows, where the acid rock commonly has a granitic texture. In some of the thin granophyre layers between closely spaced pillows an apparent flow banding is indicated by elongate plagioclase phenocrysts which are aligned parallel to the adjacent pillow contacts.

The acid veins cutting the pillows are either micrographic or granitic, and only in the thinnest veins are phenocrysts absent.

IV. FORMATION OF THE AUSTURHORN NET-VEINED COMPLEX

Net-veined complexes similar to that described here have been recorded from many parts of the world (table 4), and each of these complexes is characterized by the presence of pillow-like masses of basic rock enclosed in and veined by acid rock. The formation of such pillows is undoubtedly closely connected with the formation of these net-veined complexes.

Summarized below are various features of the pillows within the Austurhorn net-veined complex which need to be accounted for:

1. The pillows are always more basic in composition than the rock immediately surrounding them.
2. The pillows are very variable in size and shape (although probably no more so than basalt pillows in pillow lavas, to which many of the Austurhorn pillows show a remarkable resemblance).
3. The pillows commonly occur in groups in which they usually appear to have accommodated themselves to the shapes of adjacent pillows (pl. 1, B).
4. The pillows have fine-grained margins, and become progressively coarser-grained inward away from the surrounding granophyre.
5. Many pillows have dark margins, and such margins tend to be of constant thickness for any one pillow.

6. The contacts of the pillows with the surrounding granophyre are characteristically highly irregular and crenulate, and they may be sharp or diffuse.
7. Rock types represented by the pillows include olivine tholeiite, olivine-free tholeiite, and hybrids intermediate in composition between tholeiite and granophyre.
8. Although all pillows within a particular group are usually of the same composition, there are many examples of pillows of different composition that occur adjacent to one another.
9. The pillows are cut by acid veins. Some of the pillows have been completely broken up by such veins, and fragments of pillows, still recognizable as such, are scattered throughout the granophyre of the net-veined complex.
10. Individual pillows are separated from one another by acid layers which range in thickness from less than 1 cm. to more than 1 m.
11. Under the microscope the finer-grained pillow margins show the following features: (a) sheaflike aggregates of plagioclase; (b) rare skeletal crystals of plagioclase; (c) minute needles of apatite showing a variety of parallel and skeletal growths; (d) skeletal crystals of opaque ore; (e) hornblende in place of pyroxene; (f) poikilitic crystals of biotite and hornblende.

Three main theories have been put forward to account for pillows in net-veined complexes. These are the fluidization theory, proposed by Reynolds (1954); the replacement theory, the chief advocate of which is Chapman (1955, 1962); and the commingling theory of Wager and Bailey (1953). Of these three theories the author favors the third, for reasons which are discussed below.

A. FLUIDIZATION THEORY

Reynolds (1954) applies the term "fluidization" to describe the process by which liquid and solid particles are supported and transported by gas. In applying this theory to the acid net veining of layered doleritic rocks at Slieve Gullion, Reynolds considers that an intense flow of gas containing tuff-size particles was injected along fractures within the dolerite. The gas eroded and melted the adjacent dolerite, the latter developing the characteristic highly irregular margins. The narrow fine-grained edges of dolerite adjoining the intruded acid veins are considered by Reynolds to be due to melting of the dolerite, and further, "that the melted material mainly solidified as glass which has since devitrified" (Reynolds, 1954, p. 596).

The fluidization theory has since been dis-

TABLE 4
NET-VEINED COMPLEXES

Age	Country	Location	References
Tertiary	Iceland	Austurhorn Vesturhorn	Cargill <i>et al.</i> (1928)
	Scotland	Ardnamurchan: quartz-dolerite of Sgurr nam Meann, Center 2	Richey and Thomas (1930); Wells (1954)
		Quartz-dolerite of Center 3 St. Kilda	Richey and Thomas (1930) Cockburn, (1935); Wager and Bailey (1953)
Devonian	Northern Ireland	Slieve Gullion	Reynolds (1951, 1954); Wager and Bailey (1953); Bailey and McCallien (1956); Bailey (1958, 1959); Elwell (1958, 1962)
	Eire	Carlingford	Bailey (1959)
	Channel Islands	Jersey	Wells and Wooldridge (1931); Bishop (1964)
		Guernsey	Elwell <i>et al.</i> (1960, 1962)
Late Paleozoic?	U.S.A.	Mount Desert Island, Maine	Chapman (1955, 1962)
Precambrian	Australia	Holbourne Island, Queensland	A.G.L. Paine (personal communication)
	Greenland	Julianehab	Windley (1965)

puted for the formation of pillows at Slieve Gullion by Bailey and McCallien (1956). Also, Chapman (1962) rejected this theory in accounting for the pillows in the Mount Desert Island composite dykes. For the following reasons the fluidization theory is considered untenable at Austurhorn.

1. It is considered that a crystallizing fused margin will not become *progressively* finer-grained toward the source of heat (Bailey and McCallien, 1956; Elwell, 1958; Elwell *et al.*, 1962; Chapman, 1962).

2. The fluidization theory cannot explain why finer-grained margins are absent around all gabbro and many basalt, dolerite, and hybrid inclusions within the Austurhorn net-veined complex.

3. As was pointed out by Chapman (1962, p. 560), the irregular and crenulate contacts of the pillows are not fluted or single-curved surfaces, and cannot be explained by fluidization.

4. Such a process cannot account for the many examples of acid layers between pillows which have sharp contacts on one side and diffuse contacts on the other.

5. The fact that some acid veins grade into dolerite in the centers of large pillows cannot be accounted for by the fluidization theory (cf. Elwell, 1958, p. 67).

B. REPLACEMENT THEORY

Chapman (1955, 1962) has described certain composite (net-veined) dykes from Mount Desert Island, Maine, U.S.A., where pillow-like blocks of dolerite are enclosed in a matrix of granite and granophyre. He suggests that originally the dykes were formed of dolerite which later became partly replaced metasomatically by granitic material introduced along numerous fractures in the dyke, so forming the pillows of dolerite. The finer-grained margins of the dolerite pillows are considered by Chapman to have been formed by recrystallization during metasomatic replacement, and not by chilling of the dolerite. The replacement theory for pillow formation appears to be based fundamentally on the interpretation of the finer-grained pillow margins, i.e., on whether

these are due to recrystallization, as claimed by Chapman, or to chilling, as has been claimed for similar finer-grained margins by, among others, Reynolds (1937), Wager and Bailey (1953), Bailey and McCallien (1956), Elwell (1958), Bailey (1959), Elwell *et al.* (1960, 1962), and Blake *et al.* (1965).

There are a number of objections to the replacement theory for the formation of pillows in the Austurhorn net-veined complex.

1. It seems inconceivable that the process of metasomatism can account for the difference between the granophyre/pillow and granophyre/country-rock contacts.

2. The replacement theory does not explain why some inclusions within the net-veined complex are entirely unaffected, whereas other inclusions, of similar composition and grain size, show marked textural changes at their margins.

3. It is difficult to see how skeletal crystals of iron ore and apatite and swallow-tailed, H-shaped plagioclase crystals, as found in the margins of the Austurhorn pillows, can be formed other than by chilling; such features are typically found in the margins of both minor basic intrusions and basalt pillows in pillow lavas, where chilling has clearly occurred. The author cannot accept Chapman's explanation that the skeletal plagioclases in the pillow margins have come to resemble skeletal crystals in undoubted chilled margins through recrystallization (Chapman, 1962, p. 554). Further evidence that the pillow margins are true chilled margins is provided by the work of Wyllie, Cox, and Biggar (1962), who have shown that an elongate acicular habit is characteristic of apatite which has crystallized from a liquid during quenching; such crystals are typical of extrusion and hypabyssal rocks and of some granophyres, but are unknown in metamorphic rocks, where apatite has an equant habit.

4. That the decrease in grain size in the pillow margins is primary and not due to secondary recrystallization is indicated by many of the larger Austurhorn pillows in which the ophitic texture of the pillow centers becomes progressively finer-grained,

and yet remains subophitic, toward the pillow margins. Similar evidence is shown by pillows which grade from porphyritic basalt at their margins to aphyric dolerite in their centers (pl. 2, *D*).

5. Although the granular habit of augite and hornblende in the pillow margins could be taken as evidence of recrystallization, many feldspar crystals in the pillow margins are lathlike instead of also being granular, as in undoubted examples of completely recrystallized basic rocks (Reynolds, 1937, p. 275).

C. COMMINGLING THEORY

In a short paper Wager and Bailey (1953) suggested that basic magma, on coming into contact with cooler acid magma, will become marginally chilled, and will develop a solid or semisolid skin. With physical mixing of the two magmas, pillows of basic magma could form within the acid, and the pillows so formed would be able to assume all the shapes seen in the field. According to this "commingling theory" (so called by Chapman, 1962), the finer-grained margins of the pillows are true chilled margins. This theory has been applied to account for features in the net-veined complexes at Slieve Gullion, Northern Ireland (Bailey, in Wager and Bailey, 1953; Bailey and McCallien, 1956; Elwell, 1958, 1962); Carlingford, Eire (Bailey, 1959); St. Kilda, Scotland (Wager, in Wager and Bailey, 1953); and Guernsey, Channel Islands (Elwell *et al.*, 1960, 1962). The author considers that the commingling theory can also account for the characteristic features of the Austurhorn net-veined complex.

It is significant that undoubted examples of chilling of basic magma against acid magma are found in many composite extrusions and composite minor intrusions (Bailey and McCallien, 1956; Gibson and Walker, 1964; Blake *et al.*, 1965), where metasomatism or melting of the basic rock can hardly have taken place. In many such examples the chilled basic inclusions within the acid rock are similar in shape to the Austurhorn pillows and have similar sharp crenulate contacts with the acid rock.

D. THE COMMINGLING THEORY APPLIED TO THE AUSTURHORN NET-VEINED COMPLEX

It is considered that the following interpretation of the Austurhorn net-veined complex can answer the objections to the commingling theory of pillow formation which have been put forward by Chapman (1962).

The basic pillows represent originally liquid inclusions of basic magma which were emplaced in liquid acid magma in a manner analogous to the extrusion of pillow lavas into water. The basic magma chilled against the cooler acid magma, and formed a solid or semisolid "skin" around the pillows; this skin inhibited mixing of the two magmas at the pillow contacts.

The basic pillows remained in a plastic condition for a short time after their intrusion, and during this period they were able to change their shapes when affected by external forces (cf. pillows in pillow lavas), and hence were able to accommodate themselves to the shapes of adjacent pillows (pl. 1, *B*).

The injections of basic magma heated the acid magma, especially adjacent to the basic pillows, and thereby rendered it more fluid. (Shaw [1963, 1965] and Friedman, Lond, and Smith [1963] have shown that there is a very marked decrease in the viscosity of acid magma with increase in temperature and/or H₂O content. See also Blake *et al.*, 1965.) The acid magma became less viscous than the cooling basic magma, and, where the chilled basalt skin became broken before the crystallization of the pillow interior was complete, acid veins penetrated inward, instead of basic magma flowing outward. Near the pillow margins the pillow magma chilled against the cooler vein magma, but farther into the pillow the vein magma commonly became heated until it was at a similar temperature to that of the pillow magma, and here some mixing of the two magmas took place, forming, in some instances, quartzofeldspathic patches within the pillow interior; where this happened the vein contacts are diffuse. Other acid veins cutting the pillows were formed after the pillow magma had completely crystallized, and

these veins have sharp boundaries with no bordering chilled pillow rock. In many cases the pillows were completely broken up by acid veins, and the separate pillow fragments became isolated from one another within the mobile acid magma (pl. 2,C).

The degree of chilling shown by the basic rock depended on the difference in temperature between the pillow magma and surrounding acid magma. In places the acid magma surrounding the pillows of basic magma became much hotter than normal, perhaps where there were concentrations of basic pillows, and some mixing of acid and basic magmas took place at the pillow contacts before a solid pillow "skin" had formed. Where this occurred the contacts of the pillows and surrounding acid rock are diffuse instead of sharp.

The thin acid layers between closely spaced pillows may best be explained by the gravitational settling of the pillows on top of one another and the consequent squeezing out of most of the acid magma from between the pillows. This would explain why the degree of chilling of the pillow margins has little relation to the volume of acid rock between the pillows, and why some thin acid layers have sharp contacts with pillows on one side and diffuse contacts on the opposite side. The extent of gravitational settling would depend on the viscosity of the acid magma (which may locally have started to crystallize), on the shapes and sizes of the pillows and on the presence or absence of flow and turbulence within the acid magma (Shaw, 1965).

In many chilled pillow margins some recrystallization and chemical reaction took place in addition to chilling. Partial recrystallization is indicated by poikilitic biotite and hornblende crystals and the sheaflike texture of the groundmass feldspar. Evidence of reaction caused by a chemical gradient across pillow contacts is given by the development of biotite and the replacement of augite by hornblende in many pillow margins, and a corresponding absence of ferromagnesian minerals in the granophyre immediately adjacent to such pillows.

V. SEQUENCE OF INTRUSION WITHIN THE AUSTURHORN INTRUSION

The widespread occurrence of porphyritic and aphyric tholeiite pillows and the presence of olivine tholeiite pillows at Krossanes are evidence that there were a number of separate intrusions of three different types of basic magma into the acid magma of the net-veined complex. These basic intrusions are considered to have originated outside the Austurhorn intrusion, and to have formed thin cross-cutting sheets and dykes where they were intruded into basalt lavas and solidified gabbro and granophyre, and to have formed the pillows of the net-veined complex where they were intruded into acid magma. This would account for the general absence of basic sheets and dykes within the net-veined complex and their local abundance outside the complex, and also for the occurrence within the Austurhorn intrusion of basic intrusions ranging from sheets and dykes with simple contacts, through those with intricate contacts, to thin tabular pillows. The net-veined complex is therefore considered to have been formed *in situ* after the emplacement of both the granophyre and gabbro magmas.

The likelihood of a number of basic intrusions intersecting the Austurhorn granophyre before it had completely crystallized can be gauged from the abundance of minor intrusions in the nearby country rocks, where they locally form more than 10 per cent of the total outcrop.

Intrusions of hybrid magma, unlike those of basic magma, appear to be confined to within the Austurhorn intrusion, and it seems likely that the hybrid magma which formed the hybrid pillows resulted from the mechanical mixing of acid and basic magmas at greater depths within the Austurhorn intrusion (cf. the production of marscoite and similar hybrid rocks on the Isle of Skye, described by Wager, Vincent, Brown, and Bell 1965). Most of the small hybrid inclusions within the net-veined complex are probably fragments of basic and hybrid pillows which have been partly digested by acid magma.

The age of the gabbro of Hvalnesfjall

relative to the surrounding granophyre is not certain. Although contact features of the gabbro and granophyre (see sec. II A) appear to indicate that the gabbro magma was intruded before the acid magma, the present position of the gabbro is difficult to reconcile with such a view. The large and comparatively heavy gabbro mass appears to be encircled and underlain (see fig. 2) by much lighter granophyre. If the gabbro was intruded before the granophyre, it surely should have sunk to the base of the granophyre intrusion, as did (presumably) the basalt lavas displaced by the granophyre.

If the gabbro is later than the granophyre, it is possible to account for the contact relationships of the gabbro by analogy with the contact relationships observed in the net-veined complex. Like the basic magma forming the pillows in the net-veined complex, the gabbro magma may have been intruded into previously emplaced but still hot and perhaps only partly crystalline acid magma. In this case the acid magma immediately adjacent to the gabbro magma would have been heated and thereby rendered more mobile, and, as it would remain liquid after the gabbro had solidified, it would be able to vein the gabbro. Much of the marginal gabbro may then have been broken up and incorporated, as xenoliths, within the acid magma (gabbro xenoliths are widespread throughout the net-veined complex). The gabbro magma may initially have been chilled against the cooler acid magma and formed a solid skin, although no such chilled skin has been recognized; at any rate the two magmas remained essentially

separate, except on the western side of Hvalnesfjall. Here the hybrid zone at the gabbro contact may be due to partial mixing of acid and basic magmas, possibly immediately after the gabbro intrusion.

The author considers that the gabbro was intruded into previously emplaced acid magma, and that the sequence of intrusion within the Austurhorn mass was as follows:

1. Acid magma was intruded into gently dipping lavas and tuffs to form a stock, and the country rocks were displaced mainly by stoping.

2. The gabbro was then intruded into the acid magma before the latter had completely solidified.

3. Further intrusions of basic magma then took place and these formed cross-cutting sheets and dykes where they cut solid rock, and pillow-like masses where they were intruded into the still liquid acid magma of the net-veined complex.

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REFERENCES CITED

- ANDERSON, F. J., 1949, Geological observations in south-eastern and central Iceland: *Roy. Soc. Edinburgh Trans.*, v. 61, p. 779-792.
- BAILEY, E. B., 1958, Some aspects of igneous geology: *Geol. Soc. Glasgow Trans.*, v. 23, p. 29-52.
- 1959, Mobilisation of granophyre in Eire and sinking of olivine in Greenland: *Liverpool and Manchester Geol. Jour.*, v. 2, pt. 2, p. 143-154.
- and McCALLIEN, W. J., 1956, Composite minor intrusions, and the Slieve Gullion complex, Ireland: *Liverpool and Manchester Geol. Jour.*, v. 1, pt. 6, p. 466-501.
- BISHOP, A. C., 1964, Dark margins at igneous contacts. A critical study with special reference to those in Jersey, C. I: *Geol. Assoc. Proc.*, v. 74, pt. 3 (for 1963, issued 1964), p. 289-300.
- BLAKE, D. H., ELWELL, R. W. D., GIBSON, I. L., SKELHORN, R. R., and WALKER, G. P. L., 1965, Some relationships resulting from the intimate association of acid and basic magma: *Quart. Jour. Geol. Soc. London*, v. 121, p. 31-49.
- CARGILL, H. K., HAWKES, L., and LEDEBOER, J. A., 1928, The major intrusions of south-eastern Iceland: *Quart. Jour. Geol. Soc. London*, v. 84, p. 505-539.

- CHAPMAN, C. A., 1955, Granite replacement in basic dykes, Mount Desert Island, Maine: *Ill. Acad. Sci. Trans.*, v. 47, p. 117-125.
- 1962, Diabase-granite composite dykes, with pillow-like structure, Mount Desert Island, Maine: *Jour. Geology*, v. 70, p. 539-564.
- COCKBURN, A. M., 1935, The geology of St. Kilda: *Roy. Soc. Edinburgh Trans.*, v. 58, p. 511-547.
- ELWELL, R. W. D. 1958, Granophyre and hybrid pipes in a dolerite layer of Slieve Gullion: *Jour. Geology*, v. 66, p. 57-71.
- 1962, Some relationships at Slieve Gullion, Northern Ireland; a discussion: *Jour. Geology*, v. 70, p. 121-124.
- , SKELHORN, R. R., and DRYSDALL, A. R., 1960, Inclined granite pipes in the diorites of Guernsey: *Geol. Mag.*, v. 95, p. 89-105.
- , ———, ——— 1962, Net-veining in the diorite of north-east Guernsey, Channel Islands: *Jour. Geology*, v. 70, p. 215-226.
- FRIEDMAN, I., LOND, W., and SMITH, R. C., 1963, Viscosity and water content of rhyolite glass: *Jour. Geophys. Research*, v. 68, no. 24, p. 6523-6535.
- GIBSON, I. L., and WALKER, G. P. L., 1964, Some composite rhyolite-basalt lavas and related composite dykes in eastern Iceland: *Geol. Assoc. Proc.*, v. 74, pt. 3 (for 1963, issued 1964), p. 301-318.
- HARKER, A., 1904, The Tertiary igneous rocks of Skye: *Geol. Survey Mem.*
- JONSSON, J., 1954, Outline of the geology of the Hornafjörður region: *Geografiska Ann.*, v. 36, p. 145-161.
- M'LINTOCK, W. F. P., 1915, On the zeolites and associated minerals from the Tertiary lavas around Ben More, Mull: *Roy. Soc. Edinburgh Trans.*, v. 51, p. 1-33.
- REYNOLDS, D. L., 1937, Contact phenomena indicating a Tertiary age for the gabbros of the Slieve Gullion district: *Geol. Assoc. Proc.*, v. 48, p. 247-275.
- 1951, The geology of Slieve Gullion, Foughill and Carrickcarnan; an actualistic interpretation of a Tertiary gabbro-granophyre complex: *Roy. Soc. Edinburgh Trans.*, v. 62, p. 25-143.
- 1954, Fluidisation as a geological process, and its bearing on the problem of intrusive granites: *Am. Jour. Sci.*, v. 252, p. 577-614.
- RICHEY, J. E., and THOMAS, H. H., 1930, The geology of Ardnamurchan, North-west Mull and Coll: *Geol. Survey Mem.*
- SHAPIRO, L., and BRANNOCK, W. W., 1952, Rapid analyses of silicate rocks: *U.S. Geol. Survey Circ.* 165.
- SHAW, H. R., 1963, Obsidian-H₂O viscosities at 1000 to 2000 bars in the temperature range 700° to 900°C: *Jour. Geophys. Research*, v. 68, no. 23, p. 6337-6343.
- 1965, Comments on viscosity, crystal settling, and convection in granitic magmas: *Am. Jour. Sci.*, v. 263, p. 120-151.
- THORODDSEN, TH., 1896, Fra det sydøstlige Island: *Geograf. Tidsskrift (Copenhagen)*, v. 13, p. 3-37.
- WAGER, L. R., and BAILEY, E. B. 1953, Basic magma chilled against acid magma: *Nature*, v. 172, p. 68-69.
- , VINCENT, E. A., BROWN, G. M., and BELL, J. D., 1965, Marscoite and related rocks of the western Red Hills complex, Isle of Skye: *Roy. Soc. Phil. Trans.*, A, v. 257, p. 273-307.
- WALKER, G. P. L., 1960, Zeolite zones and dike distribution in relation to the structures of the basalts of eastern Iceland: *Jour. Geology*, v. 68, p. 515-528.
- 1962, Tertiary welded tuffs in eastern Iceland. *Quant. Jour. Geol. Soc. London*, v. 118, p. 275-93.
- 1963, The Breiddalur central volcano, eastern Iceland: *Quart. Jour. Geol. Soc. London*, v. 119, p. 29-63.
- 1964, Geological investigations in eastern Iceland: *Bull. Volcanol.*, v. 27, p. 3-15.
- WELLS, A. K., and WOOLDRIDGE, S. W., 1931, The rock groups of Jersey, with special reference to intrusive phenomena: *Geol. Assoc. Proc.*, v. 42, p. 178-215.
- WELLS, M. K., 1954, The structure of the granophyric quartz-diorite intrusion of Centre 2, Ardnamurchan, and the problem of net-veining: *Geol. Mag.*, v. 91, p. 293-307.
- WINDLEY, B. F., 1965, The composite net-veined diorite intrusives of the Julianehåb district, South Greenland: *Meddel. Grønland*, v. 172, no. 8.
- WYLLIE, P. J., COX, K. G., and BIGGAR, G. M., 1962, The habit of apatite in synthetic systems and igneous rocks: *Jour. Petrology*, v. 3, p. 238-243.