# APPENDIX

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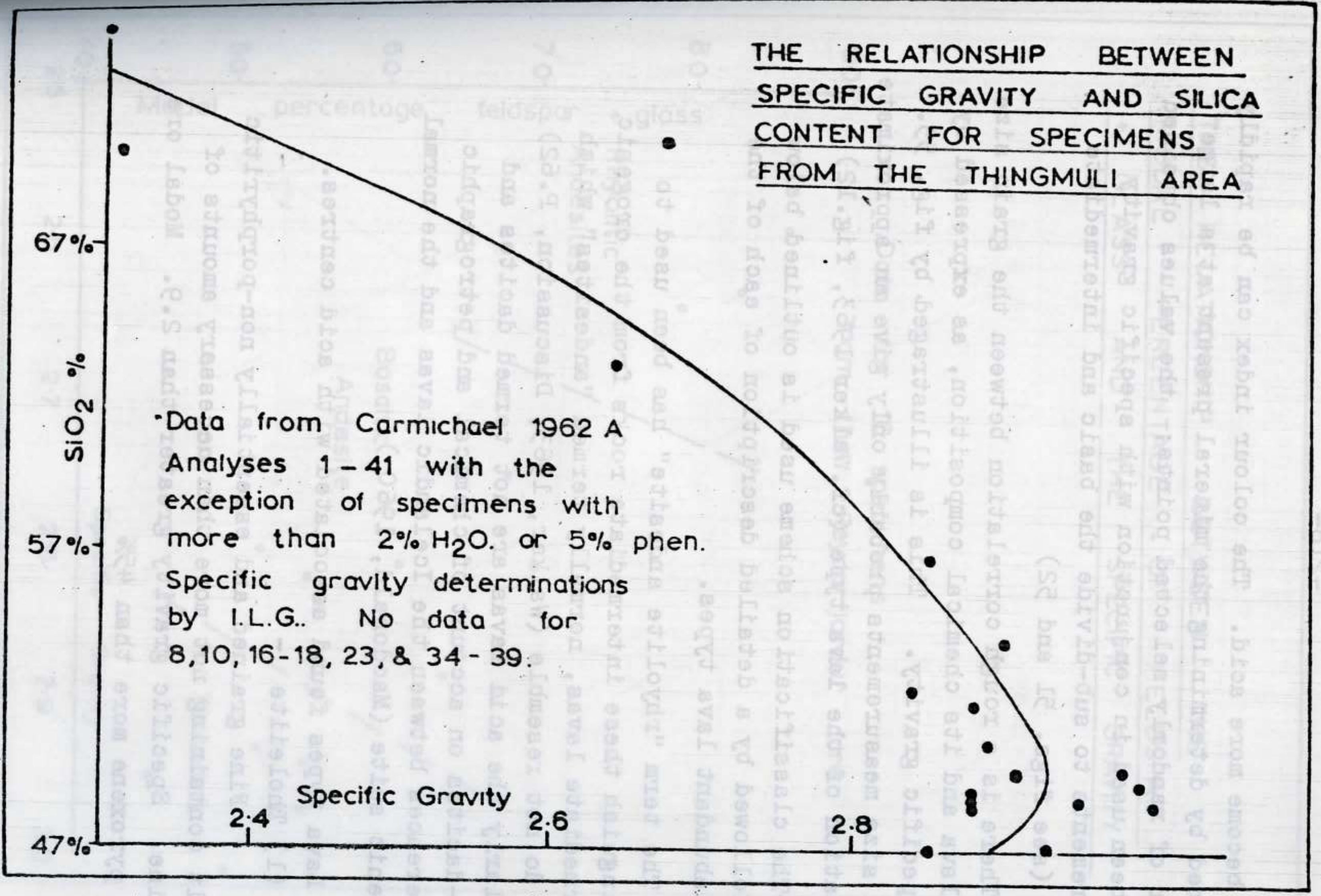
## 1. PETROLOGY

### (a) Classification of lava-types

The petrological investigation of Icelandic rocks is made difficult by the small grain size of the component rock-forming minerals. The only groundmass constituent susceptible to rapid optical determination in many rocks is the plagioclase, and even this becomes difficult to determine in the finer grained intermediate rocks. The author has therefore used other diagnostic features for classificatory purposes, particularly the specific gravity and the colour index as expressed by the modal percentage of dark minerals.

The specific gravity of small hand specimens can be readily determined both in the field and in the laboratory and the values obtained used in classifying the lava series. The success of the method depends on the rocks being (i) fresh, (ii) sensibly non-porphyritic, (iii) non-vesicular, and (iv) all members of the same magma series. All these criteria are fulfilled by the majority of the rocks from the Reydarfjordur centre. The results for a suite of analysed rocks from the Thingmuli acid centre (Carmichael 1962A) is given in fig. 50, from which it can be seen how close is the correlation between specific gravity and chemical composition as expressed by the %$SiO_2$. Rocks types from this latter area are probably directly comparable to lavas from the Reydarfjordur centre.

The majority of the basic and intermediate lavas have the same intergranular basaltic texture and are composed of pyroxene, ore, feldspar and interstitial glass. They form a continuous series in which the colour index, the modal proportion of ore plus pyroxene, decreases as the


THE RELATIONSHIP BETWEEN SPECIFIC GRAVITY AND SILICA CONTENT FOR SPECIMENS FROM THE THINGMULI AREA

·Data from Carmichael 1962 A Analyses 1 – 41 with the exception of specimens with more than 2% $H_2O$. or 5% phen. Specific gravity determinations by I.L.G.. No data for 8,10, 16-18, 23, & 34 - 39.

Fig 50

rocks become more acid. The colour index can be rapidly measured by determining the mineral present at a large number of randomly selected points; the values obtained have been used in conjunction with specific gravity measurements to sub-divide the basic and intermediate lavas (see figs. 51 and 52)

There is a rough correlation between the grain size of a lava and its chemical composition, as expressed by the specific gravity. This is illustraged by fig. 53. Grain size measurements probably only give an approximate indication of the lava type (cf.Walker 1963, fig.12)

The classification scheme used is outlined below and followed by a detailed description of each of the more abundant lava types.

The term "rhyolite andesite" has been used to distinguish these intermediate rocks from the orogenic intermediate lavas, normally termed "andesites" which they do not resemble (Walker, 1963, Discussion, P.62) Similarly the acid lavas are not termed dacites and rhyo-dacites on account of chemical and petrographic differences between the Icelandic lavas and the normal orogenic suite (Macdonald, 1960 )

### (II) Lava types found associated with acid centres.

#### (1) Tholeiite -

Fine grained and essentially non-porphyritic basalt containing not more than accessary amounts of olivine. Specific gravity greater than 2.9. Modal ore plus pyroxene more than 45%

THE RELATIONSHIP BETWEEN THE MODAL PERCENTAGE OF FELDSPAR + GLASS AND THE SPECIFIC GRAVITY

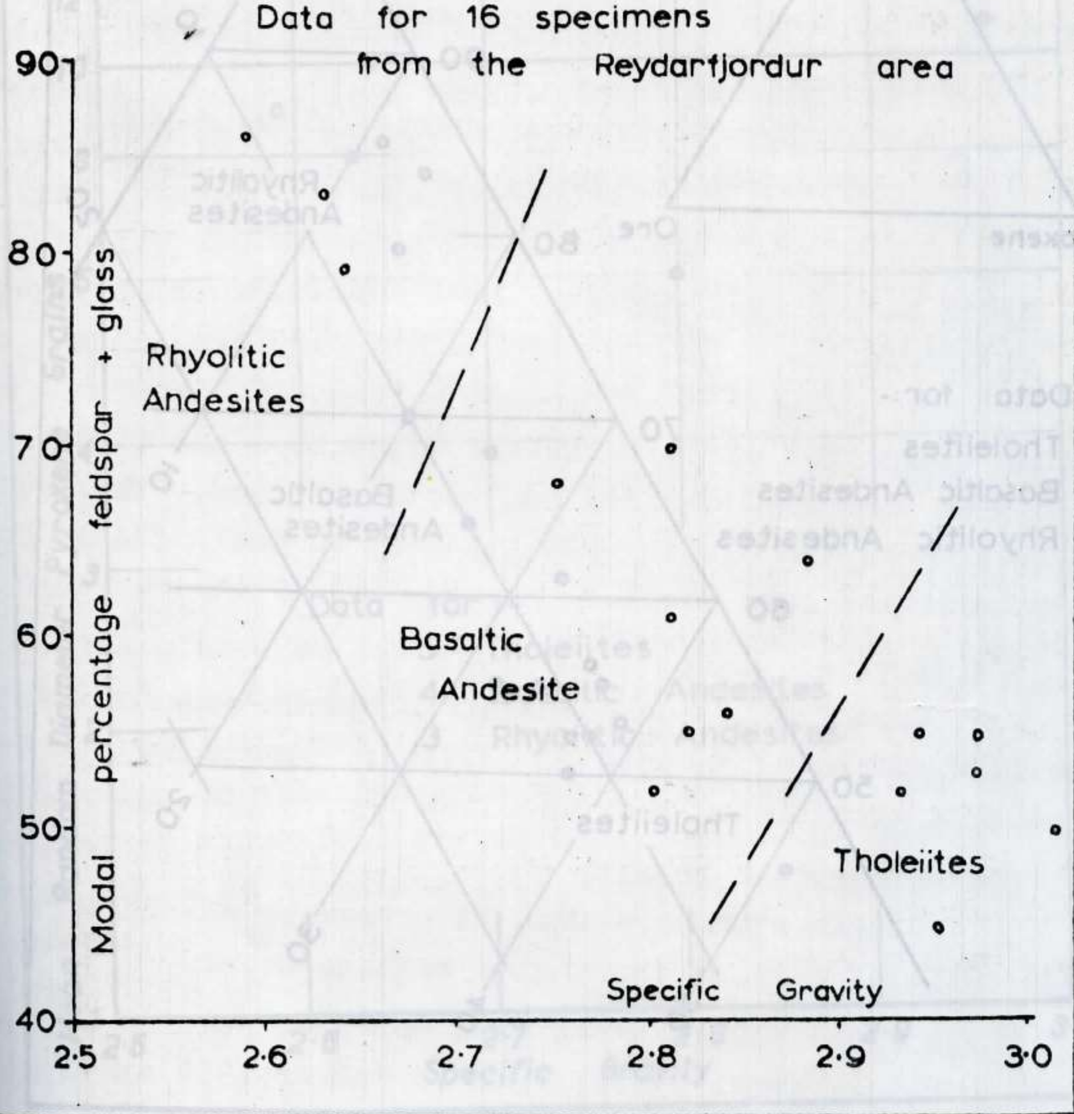


Fig. 51

MODAL COMPOSITION OF BASIC AND INTERMEDIATE LAVAS FROM THE REYDARFJORDUR AREA

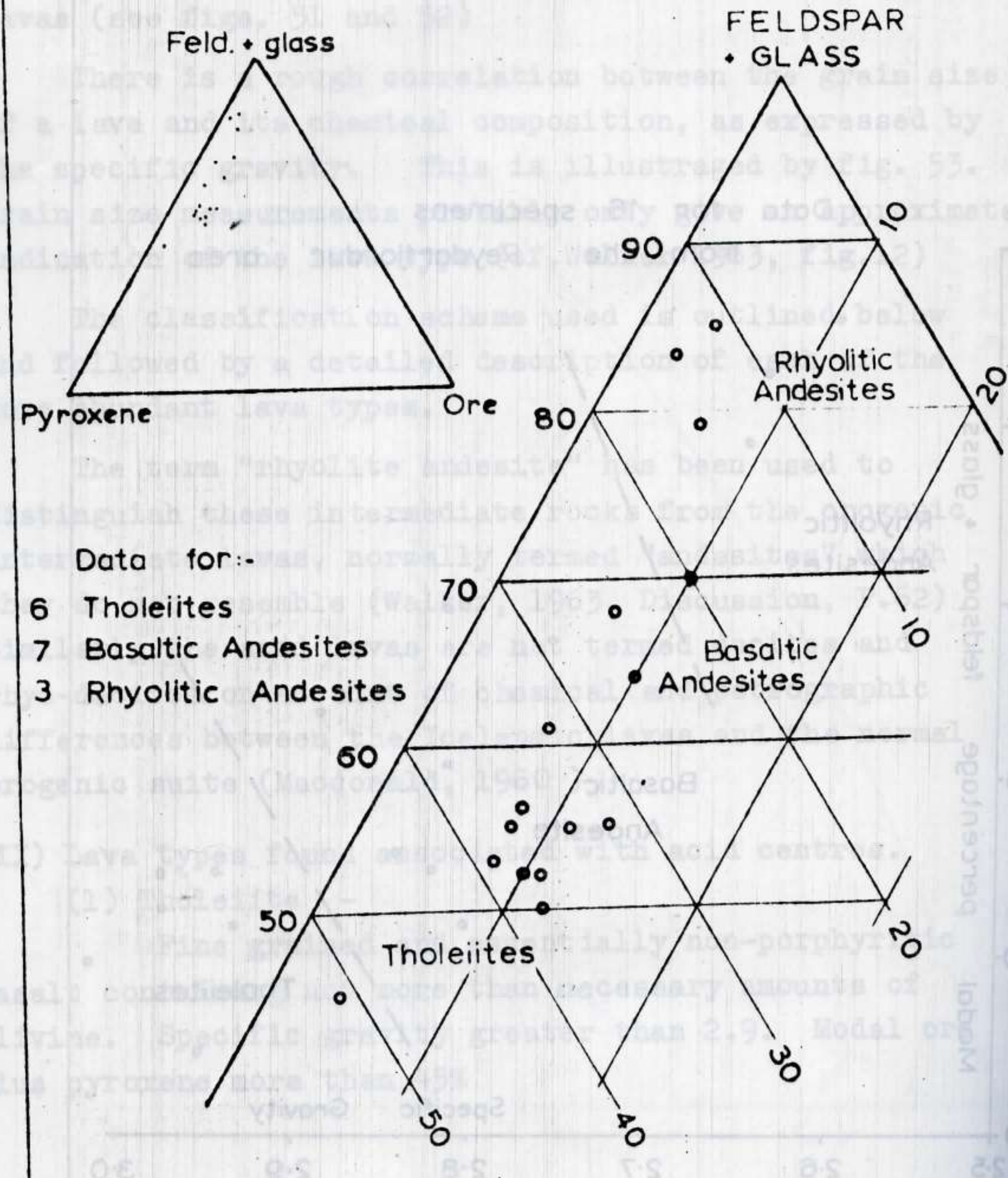


Fig. 52

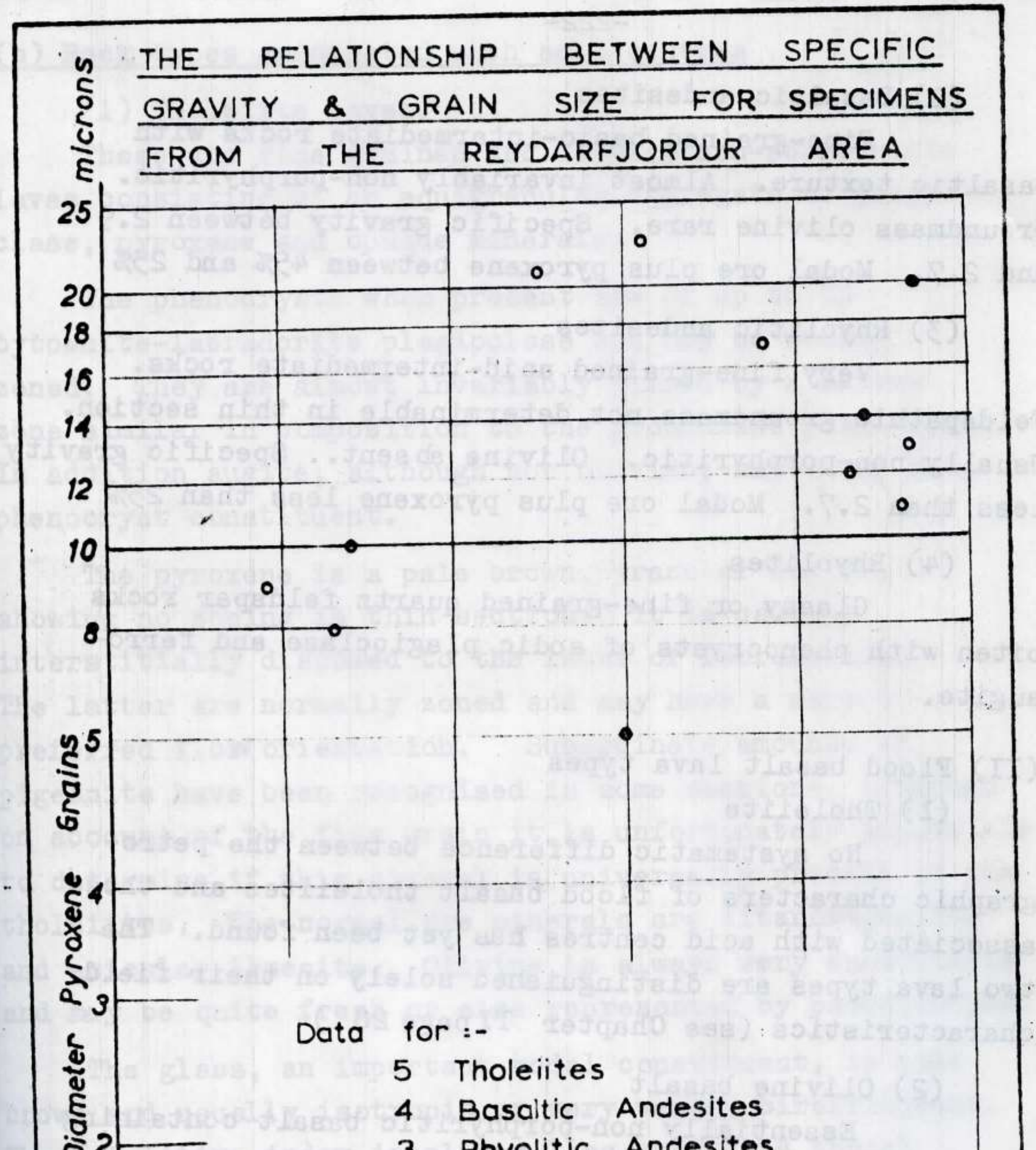

THE RELATIONSHIP BETWEEN SPECIFIC GRAVITY & GRAIN SIZE FOR SPECIMENS FROM THE REYDARFJORDUR AREA
Mean Random Diameter Pyroxene Grains microns
25
20
18
16
14
12
10
8
5
4
3
2
1
2·5
2·6
2·7
2·8
2·9
3·0
Specific Gravity
Data for :-
5 Tholeiites
4 Basaltic Andesites
3 Rhyolitic Andesites

Fig 53

(2) Basaltic andesites

Fine-grained basic-intermediate rocks with basaltic texture. Almost invariably non-porphyritic. Groundmass olivine rare. Specific gravity between 2.9 and 2.7. Modal ore plus pyroxene between 45% and 25%

(3) Rhyolitic andesites

Very fine-grained acid-intermediate rocks. Feldspathic groundmass not determinable in thin section. Usually non-porphyritic. Olivine absent. Specific gravity less than 2.7. Modal ore plus pyroxene less than 25%

(4) Rhyolites

Glassy or fine-grained quartz feldspar rocks often with phenocrysts of sodic plagioclase and ferro-augite.

(II) Flood basalt lava types

(1) Tholeiite

No systematic difference between the petrographic characters of flood basalt tholeiites and those associated with acid centres has yet been found. The two lava types are distinguished solely on their field characteristics (see Chapter II page 28 )

(2) Olivine basalt

Essentially non-porphyritic basalt containing more than accessory amounts of olivine; commonly associated with silica poor zeolites

(3) Porphyritic basalt

Basalt with more than 5% bytownite phenocrysts; phenocrysts of olivine and augite may also accur.

These flood basalt types have not been studied in detail and the reader is referred to Walker 1959 and 1963 for further information.

## (b) Rock types associated with acid centres

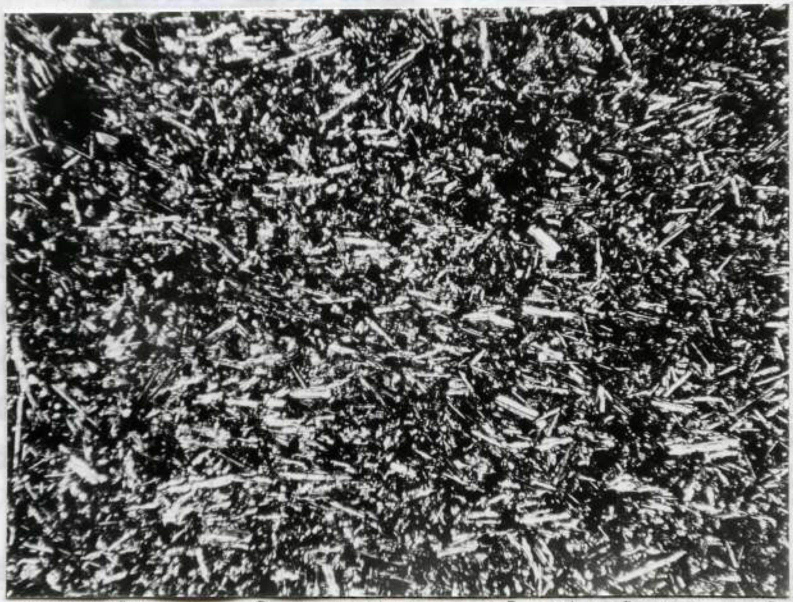
### (1) Tholeiite lavas.

These are fine grained and usually non-porphyritic lavas consisting of an equigranular aggregate of plagioclase, pyroxene and opaque minerals.

The phenocrysts when present are of up to 5% bytownite-labradorite plagioclase and may be weakly zoned. They are almost invariably rimmed by a narrow zone similar in composition to the groundmass plagioclase. In addition augite, although not olivine, may occur as a phenocryst constituent.

The pyroxene is a pale brown, granular augite, showing no zoning in thin section. It is usually interstitially disposed to the laths of labradorite. The latter are normally zoned and may have a marked preferred flow orientation. Subordinate amounts of pigeonite have been recognised in some sections, although on account of the fine grain it is unfortunately impossible to determine if this mineral is universally present in the tholeiites. The normal ore minerals are titanomagnetite and acicular ilmenite. Olivine is always very subordinate and may be quite fresh or else represented by pseudomorphs.

The glass, an important modal constituent, is pale brown and usually isotropic or very weakly birefringeant. The refractive index is always less than 1.54 though alteration to chlorophaeite may prevent determination. The latter mineraloid may also be present in vesicles which can also contain quartz, calcite or silica-rich zeolites.



groundmass of pyroxene, plagioclase and ore together with interstitial glass (X 100)

Tholeiite z.305

Modal analyses of typical tholeiites
(300 points)

| Specimen number | Volume % feld | gl. | pyr. | ore | s.g. | average grain size in mm. |
|---|---|---|---|---|---|---|
| z.176 | 50 | 5 | 34 | 11 | 2.97 | 0.020 |
| z.190 | 44 | 1 | 51 | 4 | 2.95 | 0.011 |
| z.305 | 46 | 7 | 39 | 8 | 2.97 | 0.013 |
| z.143 | 46 | 9 | 32 | 13 | 2.94 | 0.014 |
| z.144 | 46 | 6 | 37 | 11 | 2.93 | 0.012 |
| e.462 | 47 | 3 | 38 | 12 | 3.01 | n.d. |

Location of specimens

| | | |
|---|---|---|
| z.176 | S.E.face of Sodulhnjukur. | 1,600 ft. |
| z.190 | N.W.side of Breiddalur. | 1,850 ft. |
| z.305 | Shore near Thernunes | |
| z.143 | N.E.face of Sodulhnjukur. | 840 ft. |
| z.144 | N.E.face of Sodulhnjukur. | 880 ft. |
| e.462 | Holmanes peninsula. | 120 ft. |

Figure 54

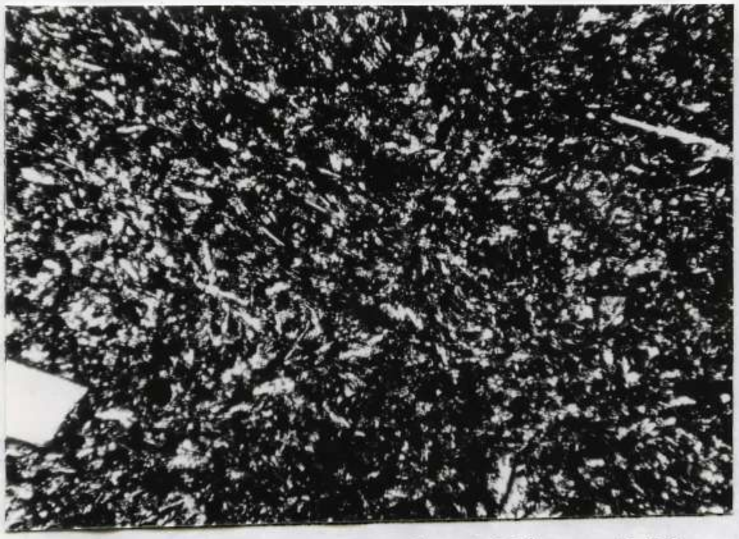
(2) Basaltic andesite lavas.

Basaltic andesite lavas show a clear tendency to be finer in grain than the tholeiites which they otherwise closely resemble. Transitional types exist and it is almost certain that there is a complete gradation between typical tholeiites and typical basaltic andesites. The boundary is rather arbitrarily drawn where the specific gravity falls below 2.9 or the colour index falls below 45. However, as can be seen from the data in fig. 55, there is a certain amount of overlap.

The majority of the basaltic andesite lavas are non-porphyritic though occasional flows contain sparse phenocrysts of labradorite, set in a groundmass of plagioclase, pyroxene, ore and interstitial glass. The groundmass plagioclase is always noticeably zoned. Although fine-grained it is still occasionally possible to determine the approximate composition in thin section using carlsbadalbite twins. The mean value for Nos.z.206, e.531, e.535 and e.581 was An 50 (four determinations on each rock)

The dominant pyroxene is augite which occurs as pale coloured prismatic crystals interstitial to the feldspar laths. Pigeonite is also present in some examples and in e.532 the ratio of augite to pigeonite is probably about 2:1.

In contrast to the tholeiites, titano-magnetite predominates over ilmenite as the ore mineral, which normally forms 10% of the mode. The normally isotropic glass is more abundant than in the tholeiites, forming up to 20% of the rock. Olivine occurs in some specimens, although it may be altered, particularly when carbonate or chlorite are also present.



Basaltic andesite (x 100) z.156

Modal analyses of typical Basaltic andesites
(300 points)

| Specimen Number | feld | gl. | pyr. | ore | s.g. | average grain size in mm. |
|---|---|---|---|---|---|---|
| z.156 | 50 | 14 | 26 | 10 | 2.88 | 0.017 |
| z.166 | 68 | | 25 | 7 | 2.75 | 0.021 |
| z.206 | 52 | | 38 | 10 | 2.80 | 0.005 |
| e.532 | 44 | 17 | 32 | 7 | 2.81 | n.d. |
| e.535 | 48 | 8 | 36 | 8 | 2.84 | n.d. |
| e.581 | 43 | 12 | 37 | 8 | 2.82 | n.d. |

Location of samples

| | | |
|---|---|---|
| z.156 | N.W. face of Sodulhnjukur. | 380 ft. |
| z.166 | E.face of Sodulhnjukur. | 1,850 ft. |
| z.206 | S. side of Breiddalur. | 880 ft. |
| e.532 | ½ mile N.W. of Glamsauga. | |
| e.535 | ½ mile N.W. of Glamsauga. | |
| e.581 | S.E. spur of Vindhals. | 2,600 ft. |

Figure 55.

### (3) Rhyolitic Andesite Lavas

Perhaps the most interesting lavas are the rhyolitic andesites. These acid-intermediate flows are composed essentially of ore, pyroxene, plagioclase and glass, with a colour index of less than 25 and a specific gravity of less than 2.7. The limited amount of analytical data suggests that the majority of these lavas have a silica content between 60% and 69% showing that the group is transitional between rhyolites and basaltic andesites.

The majority of the lavas in this group are too fine-grained to permit any microscopic determination of the constituent minerals and often it is impossible to make an accurate assessment of the colour index. The diameter of the pyroxene grains is normally about 0.01 mm.

The plagioclase occurs as small laths - often showing marked fluxion structure. The exact composition of the feldspar is unknown although the preponderance of small extinction angles suggests that it is considerably more sodic than in the basaltic andesites, and is probably about oligoclase-andesine. Interstitial glass is always abundant, normally constituting more than 20% of the mode and is usually isotropic, only rarely being altered.

The intergranular pyroxene is probably augite, but is generally too small to identify with confidence. Olivine is rare.

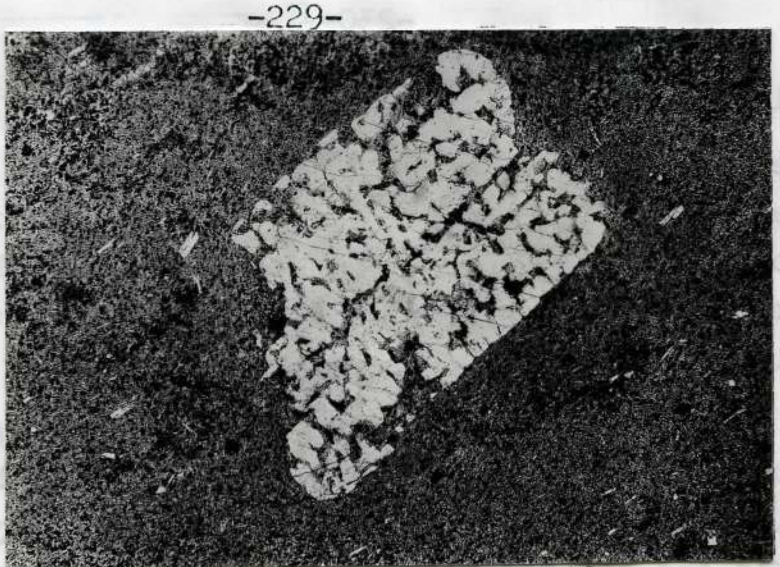
The majority of the lavas of this type may best be described as "non-porphyritic", but repeated sectioning reveals rare plagioclase phenocrysts in most examples. These are of three types:-

(i) Rounded bytownite-labradorites with pronounced sodic rims approximating in composition to the groundmass feldspar.

(ii) Very rarely sodic plagioclase phenocrysts are found. These always show fretting and corrosion - presumably produced by the crystals being incorporated into a hotter and chemically different magma, in which they were outof equilibrium. These acid phenocrysts probably grew in rhyolite magma.

(iii) Several examples, including z.308, show phenocrysts which are intermediate in composition (An 45?) and are apparently in equilibrium with the host rock. Characteristically, phenocrysts of this type show many inclusions of groundmass material, perhaps due to rapid conditions of crystal growth. Similar crystals occasionally occur in basaltic andesite lavas.

The petrogenetic significance of the phenocrysts and xenocrysts in the rhyolitic andesite lavas is discussed in the section on petrogenesis.



Rhyolitic Andesite z.308

Large skeletal plagioclase crystal (An45?) in a very fine-grained groundmass of pyroxene, plagioclase ore and interstital glass. (x 25)

Modal Analyses of typicel rhyolitic andesites
(300 points)

| Specimen No. | Volume % feld & glass | pyr. | ore | s.g. | Average grain size in mm. |
|---|---|---|---|---|---|
| z.308 | 83 | 14 | 3 | 2.63 | 0.008 |
| z.261 | 86 | 10 | 4 | 2.59 | 0.009 |
| z.307 | Indeterminate | | | 2.58 | ? |
| z.287 | Indeterminate | | | 2.59 | ? |
| H96A | 79 | 15 | 6 | 2.64 | 0.010 |

See also chemical analyses 5, 6, 7 & 8, fig. 67

Location of samples

| | |
|---|---|
| z.308 | 1,900 ft. North side of Gilsardalur |
| z.261 | 1,830 ft. North side of Gilsardalur |
| z.307 | 1,850 ft. North side of Kerlingarfjall |
| z.287 | Faskrudsfjordur (exact locality unknown) |
| H.96A | Thingmuli |

Figure 56

## (4) Rhyolite lavas

Under this heading are grouped all the acid lavas. These are easily distinguished from the intermediate members of the suite as they are either almost wholly glassy or composed of an irregular crystalline mosaic of a silica mineral and alkali feldspar.

The glassy rocks are usually pale brown or green in thin section and may show perlitic structure. Rhyolite lavas which develop a pitchstone are almost always porphyritic and all the fifteen sectioned examples contain phenocrysts. Flow structure is occasionally visible in thin section. The refractive index of the glasses varies between 1.49 and 1.51.

The crystalline parts of the lavas are composed of a fine-grained intergrowth of alkali-feldspar and tridymite and/or quartz. Tridymite may also be present in vesicles. Secondary silicification also gave rise to the small irregular patches of quartz occasionally present in the groundmass.

Both crystalline and glassy rocks contain essentially the same suite of phenocrysts - sodic plagioclase, pyroxene, ore, and an iron-rich olivine. The phenocrysts in some Icelandic glassy rocks have received detailed study from Carmichael (1960A, 1960B, 1963A, 1963B) and the only detailed work carried out by the author has been on the relative abundance of the sodic plagioclase and anorthoclase of varying compositions in the whole suite of rhyolite lavas.

Pale green ferro-augite is the normal pyroxene phenocryst. It is never abundant and only rarely forms more than 1% of the mode. It is often intergrown with

Modal Analyses of nine Rhyolites
from the Reydarfjordur area (5000 points)

| Spec. No. | Phenocrysts - volume % | | | |
|---|---|---|---|---|
| | feldspar | monoclinic pyroxene | ore | |
| z.126 | 4.3 | 0.2 | 0.2 | |
| z.157 | 2.2 | 0.2 | 0.1 | |
| z.224 | 10.4 | 1.2 | 1.8 | 0.2 olivine |
| e.204 | 3.9 | 0.3 | 0.2 | |
| e.205 | 12.1 | 0.3 | 0.2 | 0.4 Bas. xen. |
| e.461 | 6.1 | 0.3 | 0.4 | 0.6 Orth.pyr. |
| e.868 | 6.0 | 0.4 | 0.4 | |

Also see chemical analyses 9, 11 & 12, fig. 67.

Location of samples

| | |
|---|---|
| z.126 | Raudafell, south side of Reydarfjordur. |
| z.157 | First Phase Rhyolite, north of Sodulhnjukur. |
| z.224 | Porphyritic Rhyolite, Sela 180 ft. south side of Reydarfjordur. |
| e.204 | Sixth Phase Rhyolite above Sellatradalur. |
| e.205 | Sixth Phase Rhyolite north of Sellatratindur. |
| e.461 | Fifth Phase Rhyolite, Holmanes Peninsula. |
| e.868 | Pitchstone margin Sellatur plug. |

Figure 57

the other phenocryst constituents, especially the plagioclase. Very occasionally an orthorhombic pyroxene is present in addition to the ferro-augite, in which case olivine is always absent.

Olivine, when present, is usually partially altered, but some remnants of the pale-coloured ferro-hortonolite usually remain. The crystals are always small, usually idiomorphic and never exceed 0.5% in the mode.

Plagioclase, or alternatively anorthoclase, is the most important phenocrystic modal constituent forming up to 12% of the rock. All the phenocrysts are extremely fresh and usually only slightly zoned. The crystals vary from elongate laths, a form typical of the plagioclases, to more equidimensional crystals. Anorthoclase, distinguished by the presence of extremely fine cross-hatched twinning, has been found in three rhyolite lavas, i.e. in two of the sixth phase rhyolites and the associated Sellatur plug on the north side of Reydarfjordur, and the upper rhyolite on Flatafjall on the south side of the fjord.

Carmichael (1963A) in his study of the crystallisation of feldspar, deduced that during the formation of plagioclase from Icelandic rhyolite magma the composition of the phenocrysts changes progressively along the line A - B - C - D (see fig. 58) The first formed phenocrysts are thus sodic plagioclases, but further cooling and reaction with the melt eventually produced anorthoclases (D) If, as seems possible, the acid maga was derived from a more basic parent, all the liquids must originally have crystallised feldspar near the composition (A). If at any time the reaction of the plagioclase and liquid is halted by the extrusion of the magma, a porphyritic rhyolite will result.

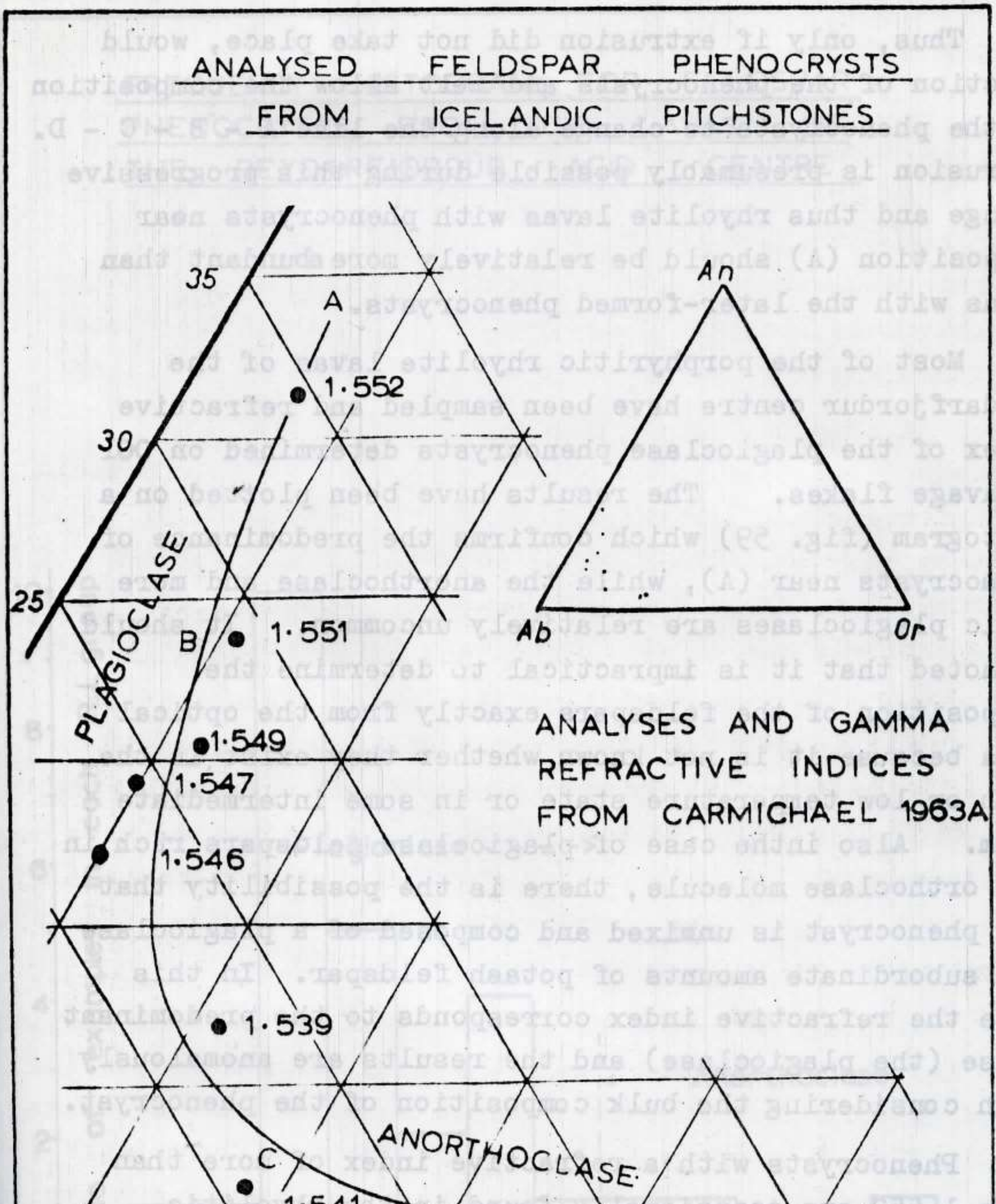

ANALYSED FELDSPAR PHENOCRYSTS
FROM ICELANDIC PITCHSTONES
An
Ab
Or
35
30
25
A
1·552
B
1·551
1·549
1·547
1·546
1·539
C
1·541
D
1·536
PLAGIOCLASE
ANORTHOCLASE
ANALYSES AND GAMMA
REFRACTIVE INDICES
FROM CARMICHAEL 1963A
15
20
25
30
35

Fig 58

Thus, only if extrusion did not take place, would reaction of the phenocrysts and melt allow the composition of the phenocrysts to change along the line A - B - C - D. Extrusion is presumably possible during this progressive change and thus rhyolite lavas with phenocrysts near composition (A) should be relatively more abundant than lavas with the later-formed phenocrysts.

Most of the porphyritic rhyolite lavas of the Reydarfjordur centre have been sampled and refractive index of the plagioclase phenocrysts determined on 001 cleavage flakes. The results have been plotted on a histogram (fig. 59) which confirms the predominance of phenocrysts near (A), while the anorthoclase and more sodic plagioclases are relatively uncommon. It should be noted that it is impractical to determine the composition of the feldspars exactly from the optical data because it is not known whether they exist in the high or low temperature state or in some intermediate form. Also inthe case of plagioclase feldspars rich in the orthoclase molecule, there is the possibility that the phenocryst is unmixed and composed of a plagioclase and subordinate amounts of potash feldspar. In this case the refractive index corresponds to the predominant phase (the plagioclase) and the results are anomalously high considering the bulk composition of the phenocryst.

Phenocrysts with a refractive index of more than $\gamma' = 1.552$ are occasionally found in the rhyolitic andesites, though as stated earlier many of these acid/intermediate lavas are non-porphyritic.

FREQUENCY HISTOGRAM FOR FELDSPAR PHENOCRYSTS FROM ACID LAVAS OF THE REYDARFJORDUR ACID CENTRE

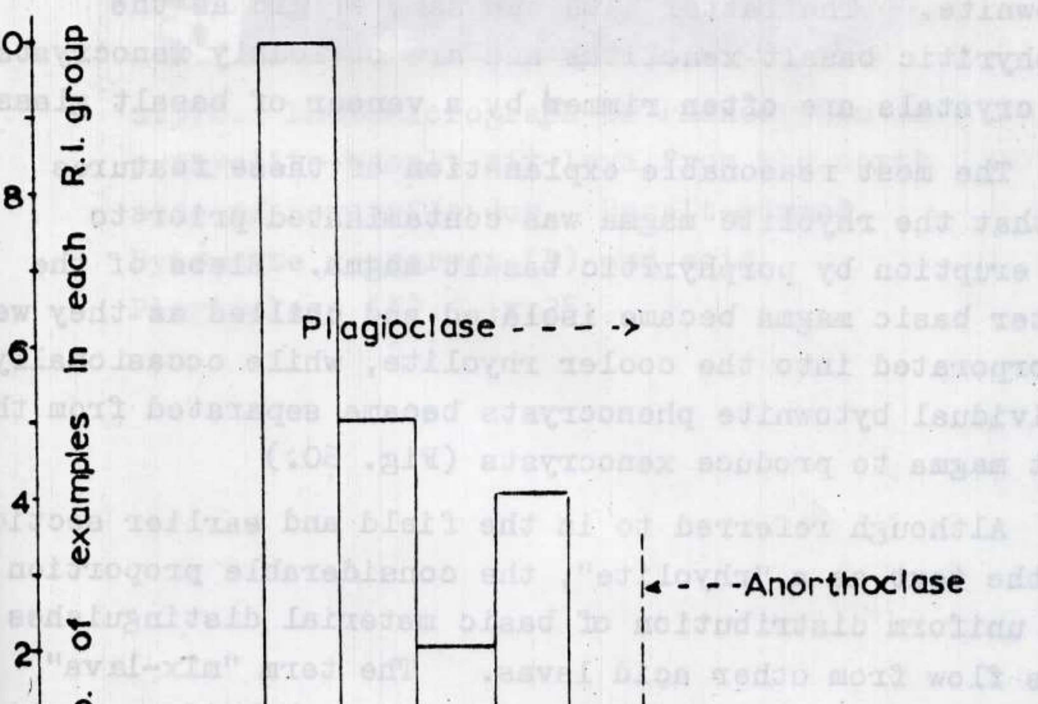


Fig 59

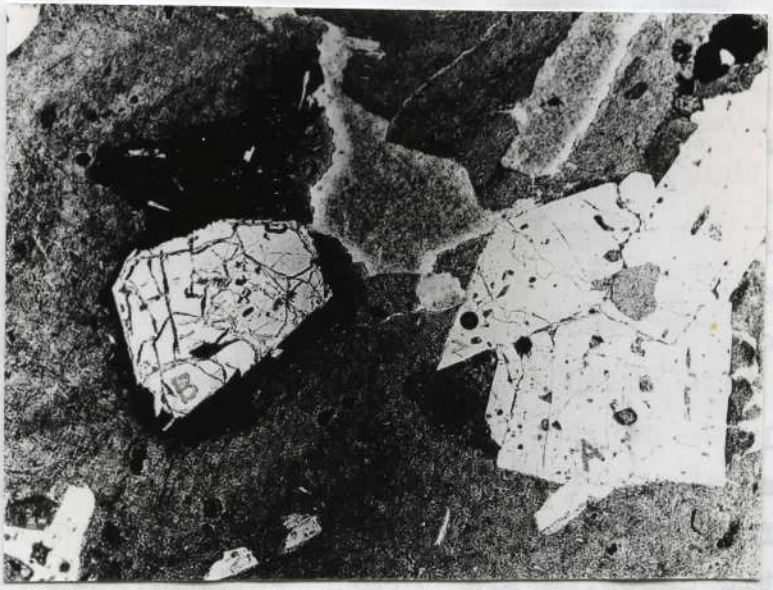
(5) Mix Lavas

The routine petrographic examination of one of the porphyritic Reydarfjordur rhyolite lavas ($R_{3g}$) revealed several anomalous features. It was noted in the field that this lava contains a large number of basic xenoliths, all of the same composition - a richly porphyritic basalt. All the xenoliths have crenulate margins and the larger examples show marginal chilling.

In thin section it can also be seen that the abundant feldspar phenocrysts are of two types - a sodic plagioclase and larger equidimensional crystals of bytownite. The latter have the same origin as the porphyritic basalt xenoliths and are obviously xenocrysts; the crystals are often rimmed by a veneer of basalt glass.

The most reasonable explanation of these features is that the rhyolite magma was contaminated prior to its eruption by porphyritic basalt magma. Blebs of the hotter basic magma became isolated and chilled as they were inrorporated into the cooler rhyolite, while occasionally individual bytownite phenocrysts became separated from the host magma to produce xenocrysts (Fig. 60.)

Although referred to in the field and earlier sections of the text as a "rhyolite", the considerable proportion and uniform distribution of basic material distinguishes this flow from other acid lavas. The term "mix-lava" is to be preferred, indicating the flows hybrid properties. Similar lavas have been noted from the Yellowstone Park Area (Boyd, 1961)



z.570. Photomicrograph of Phenocrysts in a rhyolite-basalt mix-lava from the north side of Reydarfjordur. Basalt-rimmed Bytownite xenocryst (B) and acid Plagioclase (A). x.25.

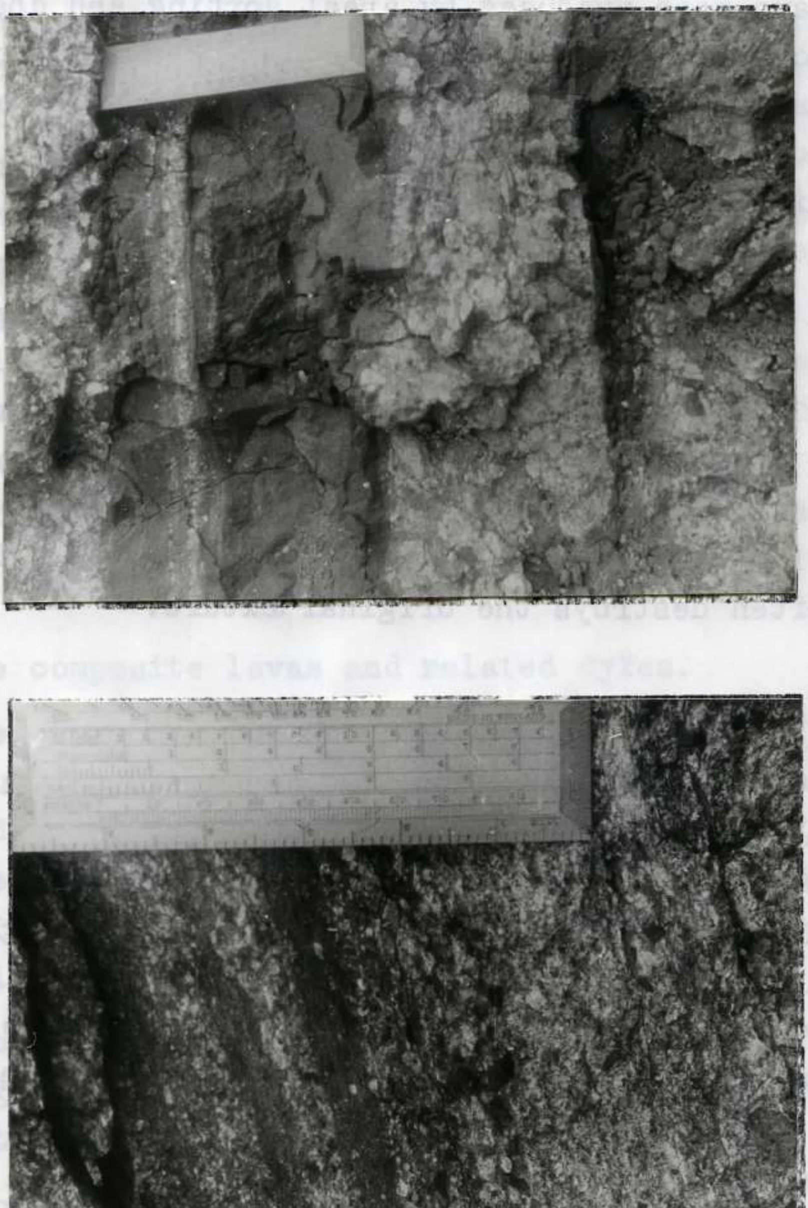
Fig. 60.

## (6) Pyroclastic rocks

A preliminary survey of the pyroclastic deposits intercalated between the lavas of Eastern Iceland showed that rapid grain-size variations took place both vertically within individual horizons, and laterally along the strike. Thus if the grain size had been used as a criterion for nomenclature, certain anomalies would have arisen. The same pyroclastic deposit would have been termed a "tuff" at one locality and an "agglomerate" elsewhere. To avoid this complication all the deposits intercalated between the lavas, some of which show well marked bedding, are termed "tuffs". The thicker, non-bedded, very coarse pyroclastic deposits are termed "agglomerates", and in the Reydarfjordur area these are always associated with rhyolite lavas. It seems likely that the two types of deposit are equivalent, the agglomerates accumulating in or near the vent, and the tuffs in the surrounding regions.

### Tuffs.

The tuff horizons occurring between the lavas vary in thickness from 5 ft. or less to over 200 ft. and often show well marked bedding (fig. 61) Rock fragments may either be abundant or almost entirely absent and are of a wide variety of lava types, all of which are found at the surface at the present day; the average size of the fragments is about 1½" but in some places these are larger. Exceptional are the granophyre fragments found in $T_3$ on Gràkollur, which are thought to have been derived from an unexposed granophyre intrusion. Fragments of sedimentary or metamorphic rocks, granite or gabbro have not been recorded from the Reydarfjordur area. Normal and reversed grading and bedding are often present and



Bedded tuffs overlying the First Phase Agglomerates

Fig. 61

thought to have been produced by areal sorting and changes in the character and violence of the eruption. None of the tuff beds mapped by the autbor contains red weathered horizons, and each is thought to be the product of a single eruption or group of eruptions, lasting at the most for a few years or tens of years.

In thin section, in addition to rock fragments, phenocrysts are visible. Usually these are of sodic plagioclase, but ferro-augite is also present, together with rare bytownite and basaltic augite. The pale-green, white or brown groundmass is predominently acid in composition and composed of fragments of pumice rather than shards, although alteration often destroys the original texture.

Agglomerates.

The thicker agglomerate deposits are only local in extent. They occur near the major centres of acid volcanism and are thought to represent pyroclastic material deposited in or around the vents. In the Reydarfjordur area these deposits have suffered a high degree of alteration and all the groundmass textures have been destroyed. However the diagmostic features are visible in the field, i.e. the complete absence of bedding and sorting and the presence of large fragments and blocks of basalt and rhyolite up to several feet in diameter.

Welded Tuffs.

A few of the tuff layers contain thin horizontal pitchstone bands which are interpreted as auto-welded horizons, but no widespread welded tuffs comparable to the Skessa tuff (Walker, 1962) have been discovered in the mapped area.

Texturally these thin welded tuff layers are distinct from non-welded acid tuffs. Thin sections show that although the tuff particles are similar in size and shape to those in non-welded portions, they are always more flattened and rounded and may be moulded round phenocrysts or rock fragments (fig. 62) The only reasonable explanation is that the tuff particles were plastic when emplaced and were apparently still hot enough in some cases to fuse into a nearly homogeneous glass. Some felsitic tuffs also show some degree of welding, although the diagnostic texture in thin section is often destroyed by subsequent alteration.

### (c) The composite lavas and related dykes.

Petrographically the composite lavas are of particular interest on account of the intimate association of acid and basic magma. The lavas show the effects produced by the contamination of acid magma by basic magma, while the xenocrysts in the basic portions pose a difficult petrogenetic problem.

The description below is in two sections, the first dealing with the acid portions of the lava and dykes, while the second covers the basic components.

#### Acid Portions.

The acid portions invariably consist of finely crystalline quartz(?)/feldspar material. The rocks may be vuggy or vesicular and all the Faskrudsfjordur examples develop spherulites. This is in marked contrast to the non-composite rhyolites which only rarely show this feature. Of the four composite lavas, the acid portions

z.461. Welded tuff. Tuff particles moulded round plagioclase phenocryst. X. 20

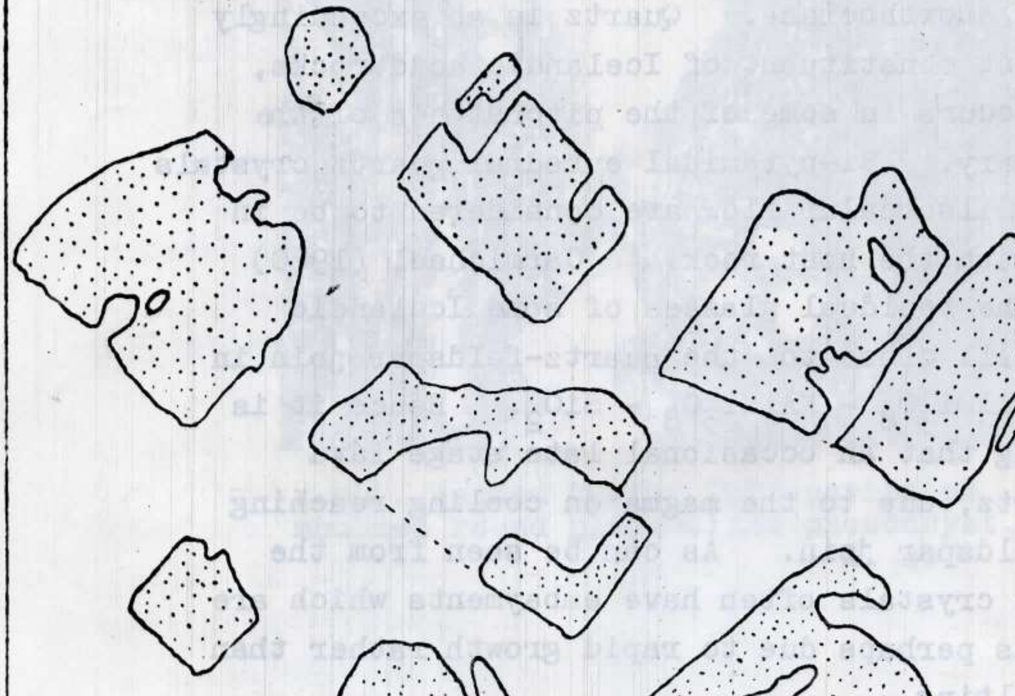
Fig. 62.

of two are non-porphyritic, while the Lower Gilsardalur composite lava contains quartz and sodic plagioclase phenocrysts, and the acid portion of the Kottur composite lava contains anorthoclase. Quartz is an exceedingly rare phenocryst constituent of Icelandic acid rocks, although it occurs in some of the pitchstones of the British Tertiary. Bi-pyramidal euhedral quartz crystals in the Lower Gilsardalur flow are considered to be in equilibrium with the host rock. Carmichael (1960) showed that the residual glasses of some Icelandic pitchstones fall close to the quartz-feldspar join in the system $NaAlSi_3O_8$ - $KAlSi_3O_8$ - $SiO_2$. Hence it is not surprising that an occasional late stage lava develops quartz, due to the magma on cooling reaching the quartz-feldspar join. As can be seen from the figure 63 the crystals often have embayments which are interpreted as perhaps due to rapid growth rather than to partial melting.

The phenocrysts in the Kottur composite lava are unusual for Iceland in that they are Anorthoclase (Carmichael 1963A) Similar phenocrysts have been found in the rare minor acid intrusions in the Kottur area (Hawkes & Harwood, 1932)

The acid portions of the composite lavas always show some evidence of contamination by basic material. The effect is most marked adjecent to the basic portion of the dyke or lava, where the host rock usually contains abundant xenoliths of basaltic material. As described previously, the xenoliths have carious margins, are very fine-grained or glassy and may be marginally chilled. Micro-phenocrysts of pyroxene and lath-like

DRAWINGS OF QUARTZ — PHENOCRYSTS FROM THE LOWER GILSARDALUR COMPOSITE LAVA

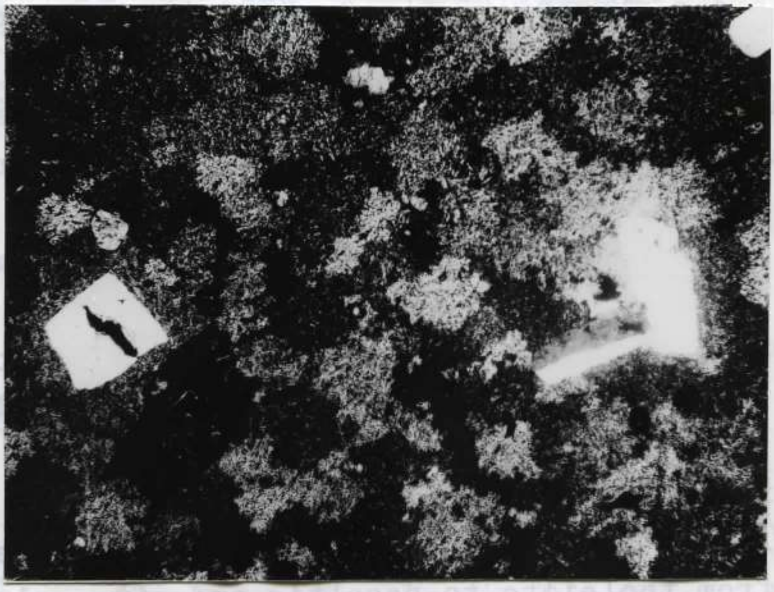


Examples taken from acid portion of both lava and dyke feeder plagioclase are a characteristic feature of the xenoliths (fig. 64). In addition to the xenoliths, the host rhyolite also contains micro-xenocrysts derived from the basaltic material, which are invariably rimmed by small amounts of basic glass. It is considered that these textural features showing the intimate association of basic and acid material, can only be accounted for by the incorporation into the acid magma of liquid basalt and its associated micro-phenocrysts (For further evidence bearing on this see Chap.VII)

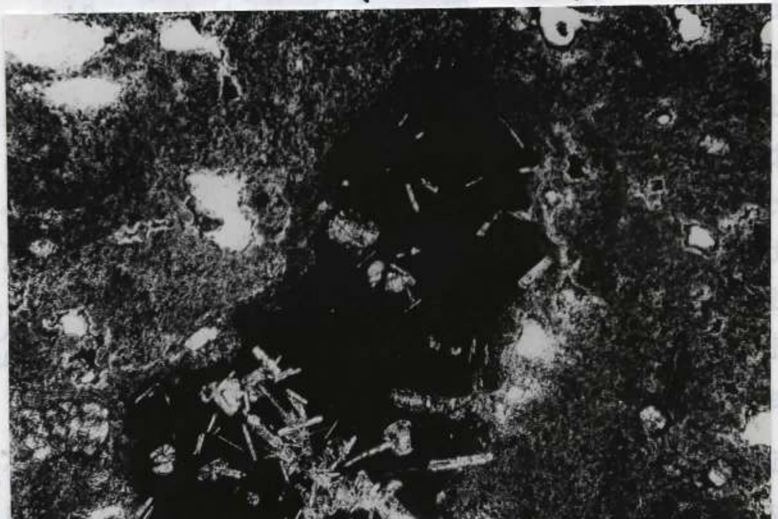
Basic Portions

The basic components of the composite bodies vary in composition from tholeiite to basaltic andesite, although they show broadly similar textural features. The dominant mineralogical components are the phenocrysts; small, lath-shaped labradorite, about 1 mm.long, and equant grains of augite. These are set in a fine-grained or glassy groundmass. In the fine grained examples the groundmass is composed of feldspar, ore and pyroxene, together with up to 20% interstitial glass. Where the basic component has undergone drastic chilling, for instance along flow tops, the micro-phenocrysts are set in a partly glassy matrix. The refractive index of the glass suggests that it is intermediate in composition and not normal basalt glass.

Bytownite is occasionally present as a phenocryst but more obvious are the xenocrysts which are found in some of the basic portions. Wherever the acid portion of the composite body contains phenocrysts, some of these are also found in the basic portion as xenocrysts. Thus the basic component of the Lower Gilsardalur composite lava contains quartz and sodic-plagioclase xenocrysts (fig.65) Both of these show evidence of dis-equilibrium;

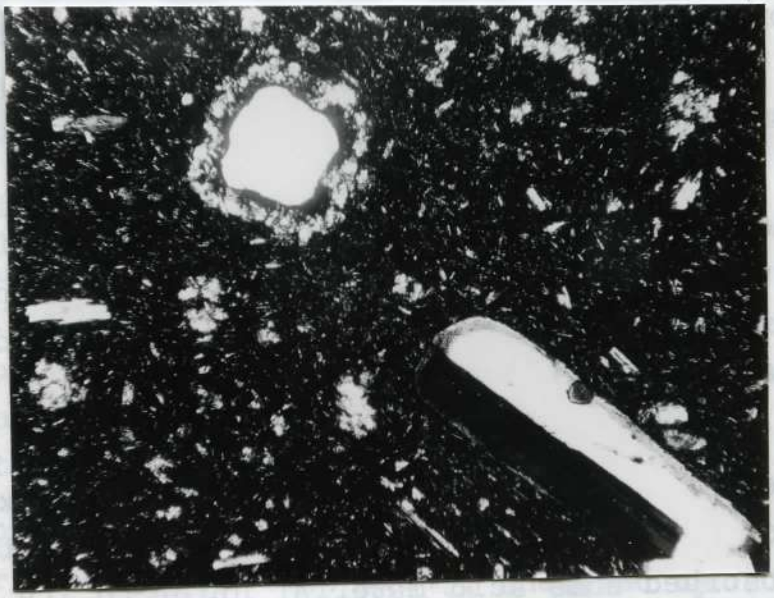


z.267. Acid Portion of Lower Gilsardalur Composite Lava showing Quartz and sodic-plagioclase phenocrysts, together with small basic xenoliths. (Lower left) x.20.



z.269. Glassy basalt xenolith, containing micro-phenocrysts of labradorite and prismatic augite, in the acid portion of the Upper Gilsardalur composite lava.

Fig. 64



z.282 Basic portion of the Lower Gilsardalur composite lava with quartz xenocrysts rimmed with augite and sodic-plagioclase with narrow melted zone. x.100

Fig. 65

the quartz is rimmed by augite granules, while the feldspar shows marginal melting and sometimes an additional rim of more basic feldspar beyond the melted zone. The limited amount of sampling done suggests that the xenocrysts are rather uniformly distributed throughout the basic component.

Where seen on the north shore of Faskrudsfjordur, the Kottur composite dyke has a rather different texture from normal in that the 5 ft. thick basic components are of normal, non-porphyritic coarse tholeiite.

As stated earlier, the basic components in some instances are not truly basic and may contain xenocrysts. This fact can be accounted for by assuming that the basic magma absorbed some acid material prior to its extrusion. It is often assumed that this acidification took place during the passage, via dyke-like fissure, of basic magma through highly viscous acid magma. The basic material would then become contaminated by marginally mobilising and subsequently incorporating part of the acid material. At a later stage the fused acid magma would follow the basic material into the upper regions of the crust via the plane of weakness represented by the centre of the earlier basic dyke, producing a composite dyke. This is the generally accepted hypothesis for the origin of composite dykes. However, it fails to account satisfactorily for:-

1. The uniform composition of the basic component.
2. The uniform distribution of xenocrysts in the basic component.
3. The nearly simultaneous eruption of basic and acid magma in the composite lavas.

## (d) Chemical Data

Six chemical analyses were made by the author of rocks from the Reydarfjordur acid volcanic succession Initially it was hoped to make a chemical study of the intermediate lavas, but it was soon realised that due to the limited time available and the author's lack of analytical experience, this would not be practical.

The analyses were carried out using rapid methods based on those of Shapiro and Brannock (1952) and which have later been partially modified by Mercy (1956) As the techniques and method have been broadly standardized discussion is not warranted.

As a check on the accuracy of the analyses carried out by the author, the grandiorite M.149, analysed by Mercy (1956) was analysed with each of the two batches of samples. The results obtained are shown in figure 66, together with the original analysis. The agreement as a whole may be considered only moderately satisfactory and the variable results for $Na_2O$ and $K_2O$ are almost certainly due to analytical error on the part of the author. However, this explanation does not account for the results $SiO_2$, as this determination was carried out with particular care by an improved method giving greater accuracy than the colourometric method of Mercy.

Data for the six analyses by the author, together with six other available analyses, are given in figure 67. These represent the only available analyses of rocks from the Reydarfjordur acid volcanic succession. It is considered that these analyses are insufficient in number and that some are of too poor a quality to use for detailed petrogenetic discussion. However, of interest are the results for z.547 and z.548. These two samples are taken

Analytical Results for the
Standard rock N.149. Donegal Granodicrite.

| | Analyses by I.L.G. | | Data from Mercy (1956) table 3. Arithmetic mean on six analyses. |
|---|---|---|---|
| | Batch 1 | Batch 2 | |
| $SiO_2$ | 72.1 | 72.5 | 73.4 |
| $TiO_2$ | 0.27 | 0.30 | 0.21 |
| $Al_2O_3$ | 14.4 | 14.2 | 14.2 |
| $Fe_2O_3$ | 0.65 | 0.63 | 0.55 |
| FeO | 0.95 | 0.92 | 0.94 |
| MnO | 0.04 | 0.05 | 0.04 |
| MgO | 0.81 | 0.77 | 0.80 |
| CaO | 1.03 | 1.01 | 0.94 |
| $Na_2O$ | 4.2 | 4.6 | 4.1 |
| $K_2O$ | 4.5 | 4.2 | 4.2 |
| $P_2O_5$ | 0.09 | 0.09 | 0.09 |
| $H_2O$ plus | 0.79 | 0.73 | 1.0 |
| $H_2O$ minus | 0.06 | 0.22 | |
| | 99.9 | 100.2 | 100.4 |

Fig. 66

## Analyses of Rocks from the Reydarfjordur Acid Volcanic Succession

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 46.9 | 48.4 | 54.2 | 54.2 | 60.0 | 62.5 | 64.4 | 67.8 | 69.8 | 69.0 | 70.0 | 70.0 |
| $TiO_2$ | 3.4 | 3.4 | 2.4 | 2.3 | 1.3 | 1.1 | 0.66 | 0.60 | 0.29 | 0.15 | 0.28 | 0.40 |
| $Al_2O_3$ | 13.1 | 12.3 | 12.5 | 12.5 | 12.8 | 13.6 | 13.4 | 13.6 | 12.6 | 11.8 | 13.3 | 12.7 |
| $Fe_2O_3$ | 4.7 | 6.4 | 3.3 | 3.0 | 7.4 | 3.2 | 4.4 | 4.8 | 1.2 | 0.85 | 2.1 | 2.7 |
| FeO | 9.7 | 9.1 | 7.6 | 7.7 | 3.9 | 3.5 | 3.5 | 2.0 | 1.7 | 0.59 | 3.0 | 1.9 |
| MnO | 0.23 | 0.26 | 0.17 | 0.18 | 0.22 | 0.19 | 0.23 | 0.21 | 0.10 | 0.04 | 0.13 | 0.10 |
| MgO | 5.7 | 4.5 | 5.5 | 5.5 | 1.2 | 1.6 | 0.56 | 0.03 | 0.32 | 0.11 | 0.60 | 0.46 |
| CaO | 10.2 | 9.4 | 8.4 | 8.3 | 4.6 | 3.8 | 3.1 | 2.7 | 0.92 | 1.5 | 1.2 | 1.4 |
| $Na_2O$ | 3.6 | 3.5 | 3.2 | 3.8 | 4.3 | 5.3 | 5.1 | 4.9 | 5.2 | 3.6 | 4.3 | 5.3 |
| $K_2O$ | 0.59 | 0.71 | 1.3 | 1.2 | 1.9 | 2.9 | 3.1 | 2.8 | 3.2 | 3.3 | 3.3 | 3.7 |
| $P_2O_5$ | 0.48 | 0.57 | 0.22 | 0.20 | 0.50 | 0.22 | 0.14 | 0.14 | 0.04 | 0.03 | 0.04 | 0.03 |
| $H_2O$ | 0.49 | 0.76 | 0.32 | 0.37 | 1.1 | 0.72 | 0.87 | 0.88 | 4.0 | 5.5 | 1.2 | 0.59 |
| | 1.04 | | 0.71 | 1.02 | | 0.84 | 0.38 | | 0.3 | 3.4 | | 1.02 |
| | 100.1 | 99.3 | 99.8 | 100.3 | 99.2 | 99.5 | 99.8 | 100.5 | 99.7 | 99.9 | 99.8 | 100.3 |
| | | | | | | | | | | | includes $CO_2$ 0.38 | |

### Key to Analyses

1. z.305 Tholeiite Lava. Shore near Thernunes. Reydarfjordur.
2. e.462 Tholeiite Lava. Holmanes Peninsula. Reydarfjordur.
3. z.547 Basic portion of composite lava. Ornolsfjall. 2 ft. from Acid/Basic contact.
4. z.548 " " " " " " Near base of flow
5. e.536 Rhyolite andesite lava. 1,250 ft. Oddsdalur Nordfjordur.
6. z.307 Rhyolitic andesite lava. Kerlingarfjall. 1,850 ft. South side of Reydarfjordur.
7. z.308 Rhyolitic andesite. 1,900 ft. North side of Gilsardalur.
8. e.580 "Andesite" 2,360 ft. Vindhals. North side of Reydarfjordur.
9. e.868 Pitchstone. Margin of Sellatur plug. Reydarfjordur. (Carmichael 1960A table 6, 4R
10. p.127 Pitchstone. Acid portion of Kottur composite lava. (Carmichael 1962B table 3 M)
11. e.625 Rhyolite. Lava below Sellatur. North side of Reydarfjordur.
12. z.303 Rhyolite. Hafranesfell. South side of Reydarfjordur.

Analysis. 1, 3, 4, 6, 7 and 12 by I.L.Gibson.
2, 5, 8 and 11 by R.Thomas
9 and 10 by I.S.E.Carmichael

from different parts of the basic component of the Ornolafjall composite lava. The close agreement between the two results suggests that the basic component may be very uniform in composition.

## (e) Petrogenisis.

Only a limited amount of petrographic and chemical work has been carried out by the author. Therefore, discussion of the petrogenisis of the lavas forming the Reydarfjordur acid volcanic succession must be limited in scope. It includes a review of some of the previous literature combined with a few additional observations.

The present study has confirmed the views of most of the earlier workers that there is a complete series of lava types ranging in composition from the olivine basalts and tholeiites, through the intermediate basaltic and rhyolitic andesites, to the acid rhyolites. At least two different mechanisms are capable of producing such a series. In one, members of the series are all developed from a basaltic parent magma by a process of differentiation; in the other two parental magmas are envisaged, the one basic and the other acid, and intermediate magmas are produced by some form of mixing or contamination. In the second case it is probably necessary to postulate the existence of a sialic basement underlying Iceland. Fusion of these basement rocks would then produce the acid material.

Although it is at present impossible to rule out either of these alternatives, three lines of evidence mitigate against the presence of any underlying sialic basement in Iceland :-

(1) Geophysical evidence in North-west Iceland

strongly suggests that there is no low density layer underlying basalts (Barth & Tryggvason 1961)

(2) No exposures of pre-basaltic basement rocks are known and fragments of metamorphic or sedimentary rocks are absent either as xenoliths in the lavas or as rock fragments in the agglomerates. Yet when such a basement does exist, as for instance in Mull, fragments of the underlying rock types are quite common, particularly in the agglomerates.

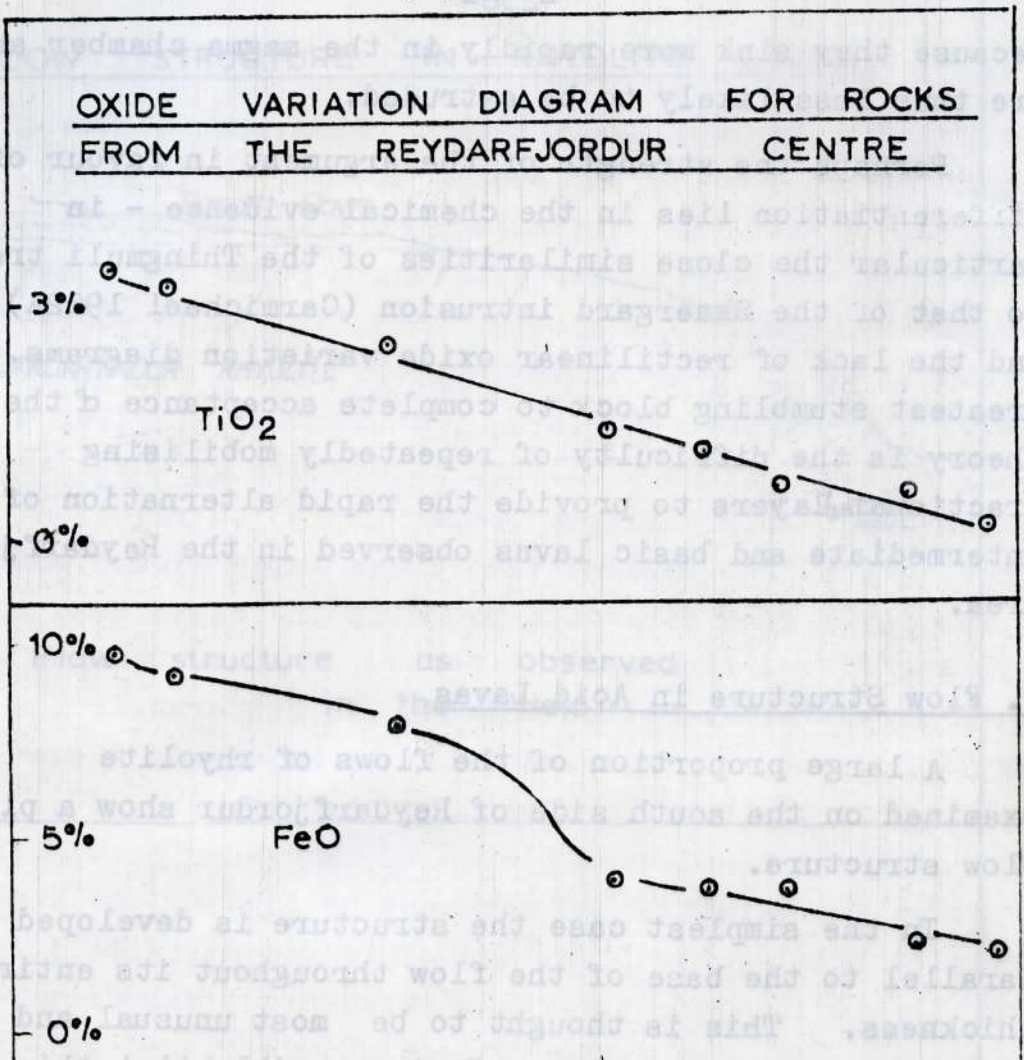
(3) In a recent paper on the Feldspar Phenocrysts of Tertiary acid glasses, Carmichael (1963A) has shown that there is a marked difference between Icelandic acid phenocrysts and those from acid glasses from north-west Britain. This difference is ascribed to the presence in the British area of sialic basement rocks beneath the basalts and to its absence in Iceland.

Of course negative evidence of this type does not prove that differentiation was the active process in the formation of the Reydarfjordur series. Therefore two further lines of evidence are considered below, evidence suggesting that a process of sialic fusion and subsequent mixing is unlikely, and evidence bearing on a possible method of differentiation which although unable to be substantiated is at least compatible with the available field, and with petrographic, chemical and experimental evidence.

It has been suggested that if mixing or contamination were an important factor in petrogenisis, many of the intermediate rocks, presumably formed in this way, would not be homogeneous and would show other signs of their mixed parentage. In fact, the majority of the intermediate Icelandic lavas are remarkably uniform in texture and composition. The only evidence suggesting that they may be the product of contamination or mixing of magmas is the presence of occasional bytownite and sodic plagioclase xenocrysts, though of course these could be derived from small scale assimilation of porphyritic rhyolite and basalt.

When analysed, rock series produced by the mixing of two magmas produce straight line variation diagrams. (Kahma 1951 & Bowen 1928, Chap.VII). Carmichael, 1962A, has carried out a series of careful analyses of rocks from the Thingmuli area and shown that these do not follow variation diagrams of this type. Hence these rocks are unlikely to have been produced by straight-forward mixing. The present author is loth to rely on the assortment of analyses of rocks from the Reydarfjordur area, but the indications are that these also do not follow rectilinear variation diagrams (fig. 68)

Finally it is necessary to suggest a possible mechanism which might have given rise to the lavas of the Reydarfjordur series. Carmichael (1962A) has suggested that the lavas of the Thingmuli series could have been derived by the fractional crystallisation of olivine basalt magma, with the separation of early formed olivine, pyroxene and plagioclase, the more salic rocks being produced under conditions of increasing oxygen pressure. This hypothesis can equally be applied to the lavas of the Reydarfjordur series, where it again depends on the accumulation of the early precipitate in the form of a layered intrusion which must underlie the acid centre. Although there is no direct evidence for such a mass the porphyritic basalts would represent the partial accumulation of early formed bytownite. Presumably pyroxene and olivine are rare in the accumulative rocks



OXIDE VARIATION DIAGRAM FOR ROCKS FROM THE REYDARFJORDUR CENTRE because they sink more rapidly in the magma chamber and are thus less likely to be extruded.

Perhaps the strength of the argument in favour of differentiation lies in the chemical evidence - in particular the close similarities of the Thingmuli trend to that of the Skaergard intrusion (Carmichael 1962A), and the lack of rectilinear oxide variation diagrams. The greatest stumbling block to complete acceptance of the theory is the difficulty of repeatedly mobilising fractionated layers to provide the rapid alternation of acid, intermediate and basic lavas observed in the Reydarfjordur area.

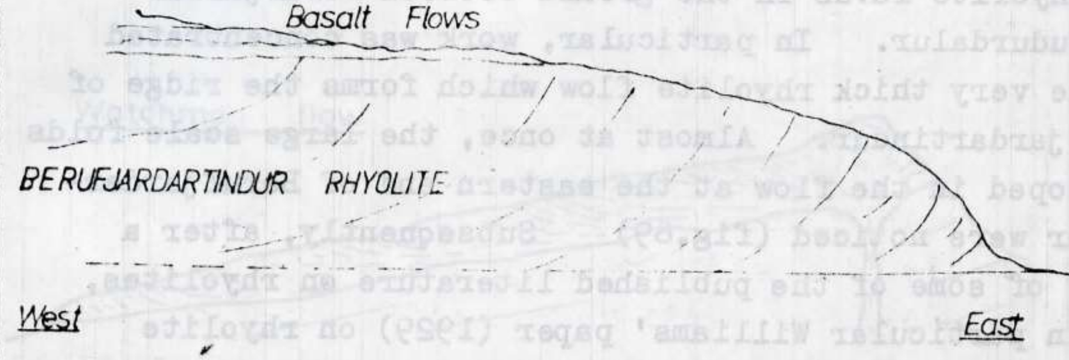
## 2. Flow Structure in Acid Lavas

A large proportion of the flows of rhyolite examined on the south side of Reydarfjordur show a platy flow structure.

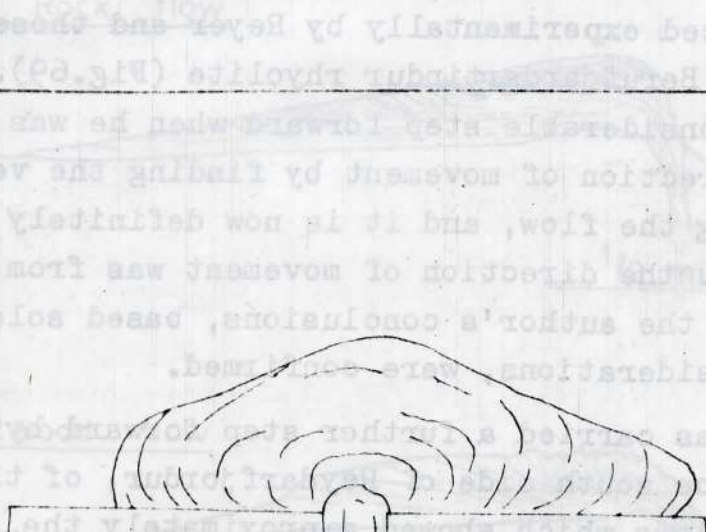
In the simplest case the structure is developed parallel to the base of the flow throughout its entire thickness. This is thought to be most unusual and was only observed in one flow. It is possible that this simple structure is only developed when a relatively fluid magma is poured out down a considerable slope, when true laminar flow may be developed.

The more usual case is when the lower part of the flow shows platy flow structure developed parallel to the flow base and the upper part of the flow, platy flow structure contorted by minor folds developed on varying scales, there being a gradational contact between the two divisions. It is in these folds that the main hope for determining the structure of the flow and the movement direction lies.

FLOW STRUCTURE IN RHYOLITE LAVAS



A. Flow structure as observed in the field

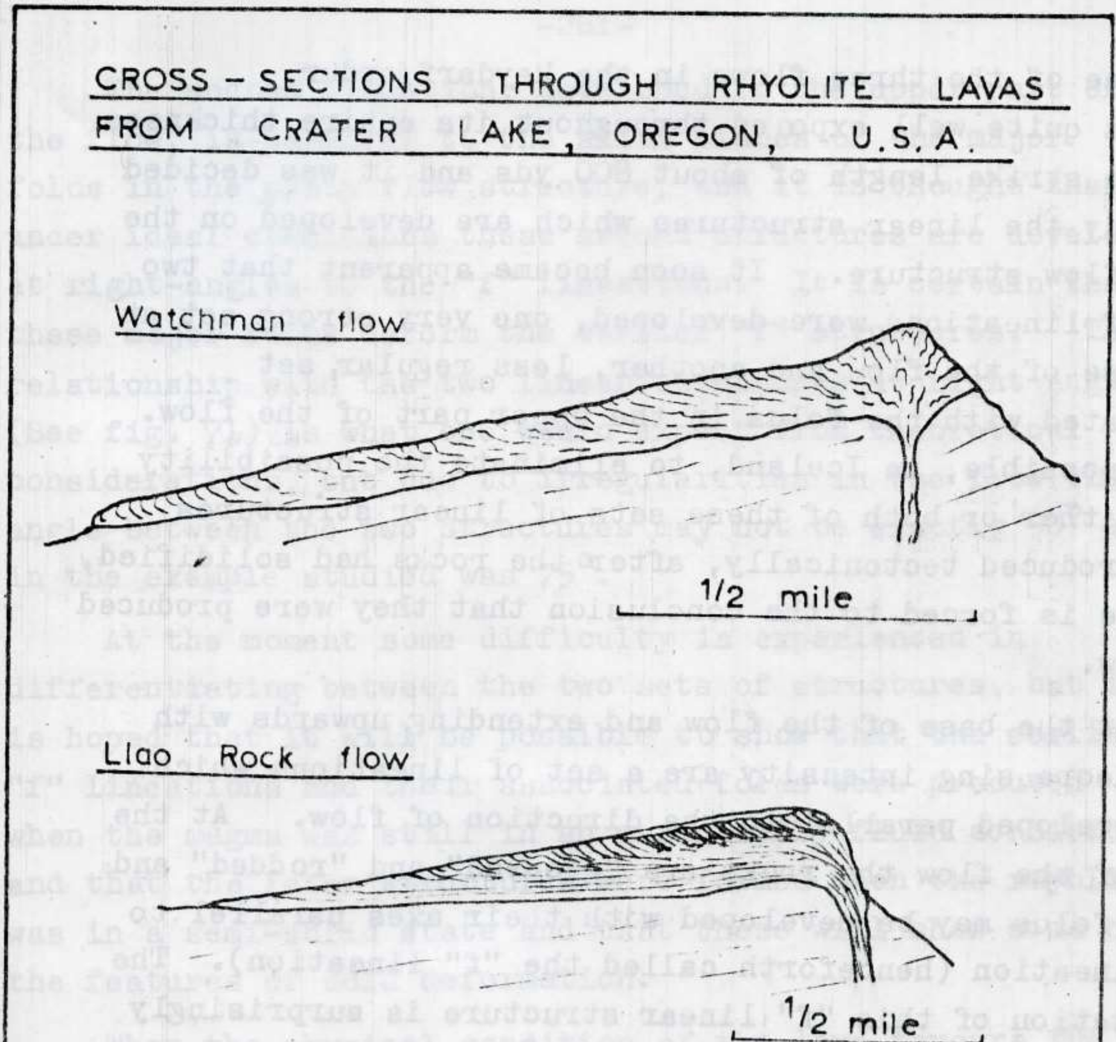


B. Flow structure produced experimentally

Fig 69

Work in this field was started in 1959 when some preliminary investigations were carried out on some of the rhyolite lavas in the ground between Berufjardur and Sudurdalur. In particular, work was concentrated on the very thick rhyolite flow which forms the ridge of Berufjardartindur. Almost at once, the large scale folds developed in the flow at the eastern end of Berufjardartindur were noticed (fig.69) Subsequently, after a study of some of the published literature on rhyolites, and in particular Williams' paper (1929) on rhyolite domes, the author decided that these large upward swirls in the platy flow structure probably indicated that the rhyolite flowed from east to west. This contention was based on the similarities between the patterns in the flow structure produced experimentally by Reyer and those observed in the Berufjardartindur rhyolite (Fig.69). Walker made a considerable step forward when he was able to prove the direction of movement by finding the vent actually feeding the flow, and it is now definitely established that the direction of movement was from west to east. Thus the author's conclusions, based solely on theoretical considerations, were confirmed.

The work was carried a further step forward by the discovery, on the south side of Reydarfjordur, of three more rhyolite flows which showed approximately the same type of large scale folds in the platy flow structure as the Berufjardartindur rhyolite; three rhyolite lavas from Crater Lake, Oregon, show similar features (fig.70) However, it should be noted that the perfect development of this structure is far from common. Generally, it can be said that the movement is from the "concave" side to the "convex side" of the swirls in the platy flow structure.



CROSS – SECTIONS THROUGH RHYOLITE LAVAS FROM CRATER LAKE, OREGON, U.S.A.

AFTER H. WILLIAMS

Fig. 70

One of the three flows in the Reydarfjordur area is quite well exposed throughout its entire thickness along a strike length of about 800 yds and it was decided to study the linear structures which are developed on the platy flow structure. It soon became apparent that two sets of lineations were developed, one very strong set at the base of the flow and another, less regular, set associated with the folds in the upper part of the flow. It is possible, in Iceland, to eliminate the possibility that either or both of these sets of linear structures were produced tectonically, after the rocks had solidified, and one is forced to the conclusion that they were produced by flow.

At the base of the flow and extending upwards with ever decreasing intensity are a set of lineations which are developed parallel to the direction of flow. At the base of the flow the rocks are "grooved" and "rodded" and minor folds may be developed with their axes parallel to the lineation (henceforth called the "f" lineation). The orientation of this "f" linear structure is surprisingly regular and varies by only about 15° either side of a mean value, but as stated previously it is not present (? not preserved) in the upper parts of the flow. The suggested reason for this is that the lower marginal part of the flow is rapidly chilled and "freezes" what appears to be an early structure - whereas it is destroyed in the upper part of the flow by later movement. The particular flow studied was unfortunately non-porphyritic so the relationship of any phenocrysts to this early "f" lineation could not be seen.

The second lineation, developed in the upper part of the flow, is parallel to the axial planes of the major folds in the platy flow structure, and it is thought that under ideal conditions these second structures are developed at right-angles to the "f" lineations. It is certain that these major folds deform the earlier "f" structures. This relationship with the two linear structures at right angles (See fig. 71) is what one would expect from theoretical considerations, but due to irregularities in the flow the angle between the two structures may not be exactly 90° and in the example studied was 75°.

At the moment some difficulty is experienced in differentiating between the two sets of structures, but it is hoped that it will be possible to show that the earlier "f" lineations and their associated folds were produced when the magma was still in an essentially fluid condition and that the later structures were formed when the rhyolite was in a semi-solid state and that these will show some of the features of cold deformation.

When the physical condition of the lava favours the development of more turbulent flow, the relatively simple structures described above are not produced. Highly complex folds are formed, often with variable fold axes, and these may be present throughout the entire thickness of the flow. It is thought that there is still a tendency for the folds to be developed at right-angles to the direction of movement, but this has not yet been shown statistically.

IDEALIZED DIAGRAM OF LINEAR STRUCTURES IN A RHYOLITE LAVA ON THE N. SIDE OF BREIDDALUR

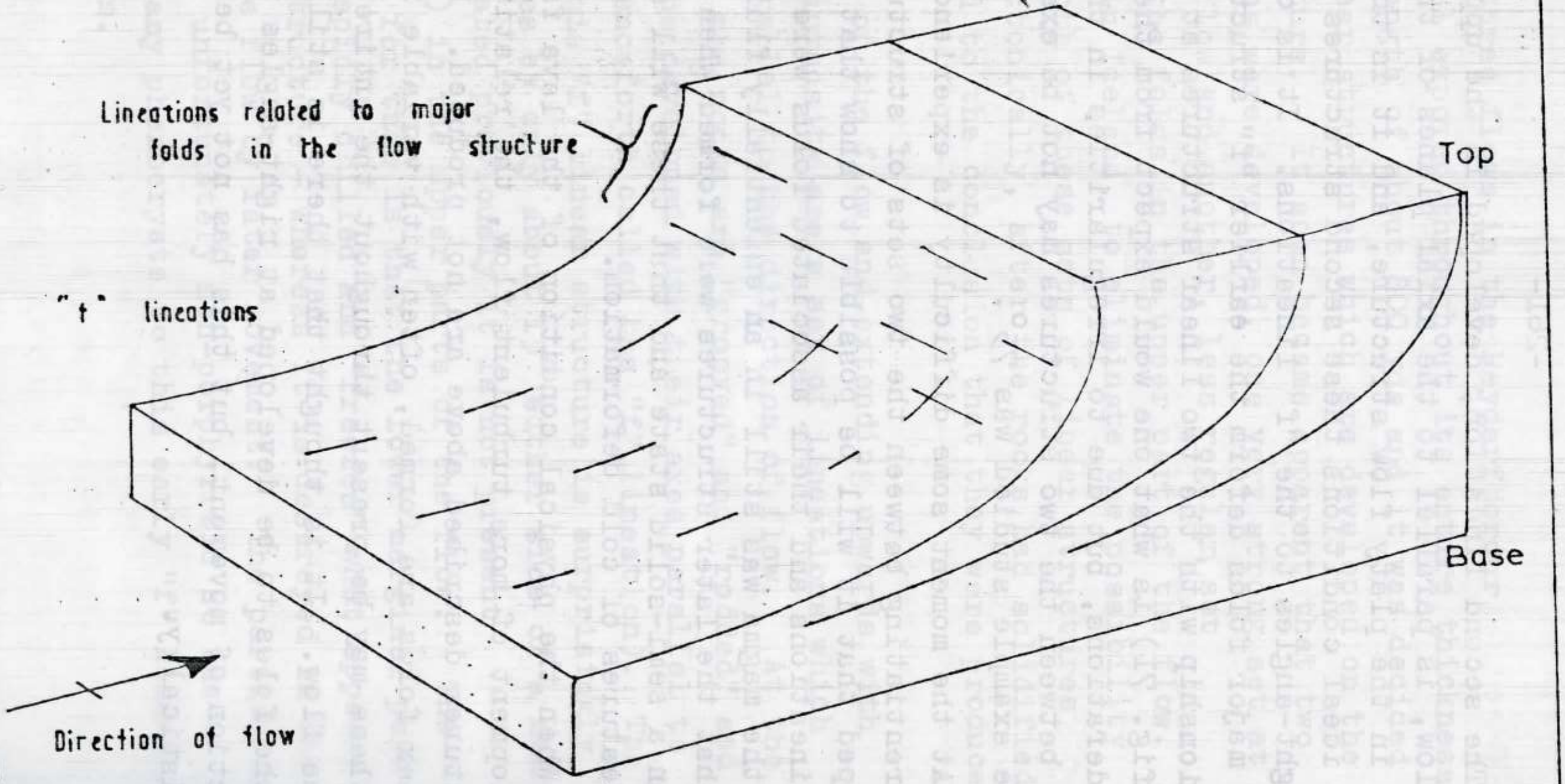


Fig 71.

## ACKNOWLEDGMENTS

The writer is indebted to Dr.G.P.L.Walker who suggested the study initially and supervised the work with thoroughness and interest, both in the field and in the laboratory; to Dr.I.S.E.Carmichael who initiated the author into the mysteries of silicate analysis and gave much useful theoretical data; to the other members of the staff and the students at Imperial College who encouraged the author with their interest and advice; to the technical staff at Imperial College, especially Mr.J.P.Gee for his photo-micrographs, and Mr.E.J.Hill and his assistants for the thin sections.

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