The Petrology of Thingmuli, a Tertiary Volcano in Eastern Iceland

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WITH TWO PLATES

ABSTRACT

The Tertiary flood-basalt sequence of eastern Iceland is intermittently disturbed by central volcanic activity with the voluminous eruption of acid magma. Associated with one of these central volcanoes, described in this paper, is an intense swarm of acid and basic dykes, a set of acid cone-sheets, and extensive superimposed hydrothermal alteration. The lavas and intrusions which make up the volcano grade in composition from olivine-tholeiites, through olivine-free tholeiites, basaltic-andesites, and andesites (icelandites), to rhyolites. This series is unusually rich in iron, titanium, and manganese, and poor in magnesium; alumina and total alkalis also tend to be low in the basic members. Magnetite (*sensu lato*) plays a varied role in the order of crystallization, and it is only in the intermediate stages of this fractionated series that magnetite is available for crystal fractionation. The otherwise progressive enrichment of iron relative to magnesium throughout the successive liquids of the series is halted during an intermediate stage, as magnetite becomes an early-crystallizing phase.

INTRODUCTION

ICELAND is almost completely volcanic and its structure is 'broadly synclinal, the axis crossing the country from the north-east to the south-west extremity' (Walker, 1960, p. 526). Along the axis the Quaternary volcanic rocks are found (Fig. 1) and are underlain by the Tertiary lava series exposed to the east and to the west, with the glacial palagonite series sandwiched at the base of the Quaternary.

The sequence of Tertiary flood-basalts so prominent in eastern Iceland has been interrupted from time to time by central volcanic activity with the large-scale eruption of acid magma. At the top of the Reydarfjördur flood-basalt succession (Walker, 1959) there is one of these central volcanoes (Thingmuli), and like the Breiddalur volcano to the south-east (Walker, 1963) it was finally buried by the enveloping flood-basalts.

The main lava-types found at Thingmuli are olivine-tholeiite, olivine-free tholeiite, porphyritic tholeiite, andesite, and rhyolite, and the characteristic field features of each type have been recorded by Walker (1959, 1963). As each lava type tends to be erupted as groups of flows, a group may be used as a stratigraphic marker horizon and in this way the volcanic succession established; there is, however, a complete gradation in composition, in field character, and in mineralogy between the lava types. The relatively infrequent groups of

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porphyritic- and olivine-tholeiite lavas are valuable volcanic horizons, but the rhyolite flows and some andesites at Thingmuli are not of great stratigraphic use as they tend to form thick flows (max. 950 ft) of small areal extent, whereas in contrast the thin tholeiite flows are too abundant (Table 1) to be useful. The stratigraphic succession of the flanks of Thingmuli volcano has been established to the north and south (Fig. 1) but towards the west and the core of the volcano the structure becomes increasingly complex, and the superimposed hydro-thermal alteration becomes so intense that to a large extent the distinguishing features of the basaltic and andesitic lava types have been obliterated.

The stratigraphic base of Thingmuli volcano has been taken arbitrarily at the base of a group of andesites exposed in Areyjardalur (Fig. 1), the underlying basalt series belonging to the Reydarfjördur flood-basalt succession. Although

TABLE 1

Abundance and average thickness of the main lava types at Thingmuli

Lava-type	Average thickness (ft)	Relative abundance (per cent)
Olivine-tholeiite . .	16	7
Tholeiite . . .	21	50
Andesite . . .	60	18
Rhyolite . . .	300	21
Porphyritic basalt .	40	1
Pyroclastics . .	35	3

some of these basalts may have been erupted by Thingmuli volcano at an early stage of its development, this group of andesites are the first undoubted products of the volcano. The underlying basalt groups show a progressive increase in dip towards Thingmuli and indicate sagging of the volcano due to the superin-cumbent load; Walker (1963, p. 32) has estimated that the base of Thingmuli has sagged at least 2000 feet.

In the core of the volcano, acid intrusions and lavas become more numerous and tuffs, which are composed mainly of acid fragments, become thicker and less well sorted; boulders of basalt 10 feet or more in diameter indicate a nearby eruptive source. The basic lavas in the core may be folded and may have abnormally steep dips caused, in one case, by the collapse of the volcano's superstructure.

Among the intrusions associated with this volcano is a narrow and intense dyke swarm (Walker, 1963, fig. 8), the greatest intensity of which corresponds to the volcano's core. Acid dykes are almost completely localized within, or ad-jacent to, the core, and a late set of acid cone sheets is also developed (Fig. 1).

The superimposed hydrothermal alteration is one of the characteristic features of Thingmuli volcano and is of a progressive nature, becoming more intense towards the volcano's centre. The first indication of the increasing effect of the hydrothermal alteration is a change in colour of the thin, red, dust beds between the lavas, which become pale green. This colour change progressively affects the scoriaceous lava tops and then the massive centres of the flows, so

that basalts and andesites in the core of the volcano are found as pale-green rocks rich in calcite and epidote. In the most intensely altered zones, rhyolites and basaltic rocks may contain abundant disseminated pyrite, which on weathering produces extensive iron staining; moreover, epidote is common in veins, in basaltic amygdales with laumontite as the sole zeolite, and in the massive body of the basaltic rocks. In the less intensely altered zone (Fig. 1), epidote is absent and laumontite, platy calcite (on 0001), and occasional quartz are the vesicular infillings of the basaltic rocks. This less intensely altered zone may be further subdivided by the first appearance of the regional zeolite assemblage found in the enveloping flood-basalts (Walker, 1960). As the areas of greatest intensity are those in the core of the volcano, and as the intensity decreases both vertically and laterally away from the core, the zones of hydrothermal alteration are of a cupola form and are, in effect, a hydrothermal aureole.

This account is concerned with the petrology of the lavas and intrusions which make up Thingmuli volcano. However, the specimens described and analysed have all been taken from the volcano's flanks or from high stratigraphic levels and are therefore unaffected by the more intense hydrothermal alteration.

PETROGRAPHY

The described rocks are considered to be representative of all rock types at Thingmuli except for those in the hydrothermally altered core of the volcano. A brief petrographic synthesis of the main rock types, given below, is drawn mainly from those rocks which have been analysed. The various groups conform, for the sake of convenience, to those mapped in the field; a complete gradation in chemistry, mineralogy, and field character is, in fact, found. The porphyritic basalts (with greater than 10 per cent phenocrysts) are described separately as they are believed to be of accumulative origin.

In general the rocks of Thingmuli are fine-grained (the basaltic-andesites and andesites extremely so) and contain only sporadic phenocrysts, of which plagioclase is predominant. The mineralogy of the lavas and intrusions is simple, as pyroxene, plagioclase, occasional olivine, and notable amounts of the iron-titanium oxides are the essential mineral constituents of all but the acid rocks, where a silica mineral and alkali feldspar are predominant. (The specimen numbers refer to the analyses in the appropriate tables; the localities of the specimens are given on p. 440.)

Olivine-tholeiites (Table 2, nos. 1, 2, and 3)

Olivine-tholeiite is found predominantly as lavas, but a few dykes are present; all the rocks have more than accessory amounts of olivine. The lavas are fine-grained with occasional phenocrysts of bytownite, some of which are riddled with pyroxene and ore inclusions.[1] The plagioclase phenocrysts are mantled by

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[1] Many of the bytownite phenocrysts in the basaltic rocks may occur as crystal clusters and are riddled with inclusions of pyroxene, ore, and sometimes glass. Other bytownite phenocrysts, more

labradorite which corresponds in composition to the zoned plagioclase laths (An_{70}–An_{60}) of the groundmass. Small anhedral olivine crystals are prominent in the groundmass and are surrounded by intergranular or subophitic pyroxene,[1] and plagioclase. The olivine is occasionally altered to iddingsite at the crystal margins, together with a very fine rim of magnetite. Interstitial glass charged with iron-ore granules is sometimes found between the feldspar laths; apatite needles together with chlorite are also found interstitially to the groundmass plagioclase. Zeolites may be found in amygdales and are more conspicuous in no. 2 than in no. 1. The opaque oxides are unevenly distributed, and the magnetite is of a ragged, angular appearance (Plate 1, figs. A and B) as it occurs interstitially to the groundmass pyroxene and plagioclase. In reflected light, the magnetite is seen to be altered to haematite to a great extent; pseudobrookite may also be seen. Exsolution lamellae of ilmenite in magnetite are rare, although composite grains of magnetite (altered greatly to haematite) and ilmenite are common. Acicular, independent ilmenite is also present and contains irregular wisps of haematite. The alteration of olivine is very prominent in reflected light, with minute strings of magnetite grains surrounding each olivine crystal and forming trains through the crystals. No sulphides have been seen.

The olivine-tholeiite dykes are coarser-grained than the lavas, but are otherwise similar mineralogically. In one specimen (no. 3), glomero-porphyritic clusters of bytownite, frequently with strings of inclusions, occur with more evenly distributed phenocrysts of bytownite free of inclusions. The groundmass of olivine, lilac-tinted ophitic augite, and labradorite also contains relatively large, angular, ragged magnetite, which rarely shows octahedral exsolution lamellae of ilmenite. Most of the magnetite is homogeneous at a magnification of $\times 600$, although composite grains of magnetite and ilmenite, with gently curving grain boundaries, are common. Acicular, independent ilmenite is present, together with a few specks of pyrite. Accessory, interstitial apatite and chlorite occur, the latter sometimes with rare quartz.

Tholeiites (Table 2, nos. 4 to 10)

Tholeiite lavas are finer-grained than the olivine-tholeiite lavas and have small, sporadic phenocrysts of labradorite or bytownite and, more rarely, microphenocrysts of augite. The groundmass consists of pale-coloured augite and subordinate pigeonite in intergranular relationship to zoned laths of labradorite–andesine; the groundmass plagioclase may have a fluxion texture. Glass,

evenly distributed, are quite free of these inclusions and may represent true phenocrysts, rather than possible cognate xenocrysts of similar composition.

[1] In thin section the pyroxene is pale-coloured with 2 V (+) about 50°; it is zoned, with an outer margin having a small 2 V or it may, indeed, be uniaxial. It is suggested that this relationship represents augite zoned to sub-calcic augite or pigeonite, similar to the groundmass pyroxenes of the Hawaiian tholeiites (Muir & Tilley, 1963). Independent pyroxene grains of small 2 V are generally present although always subordinate in amount to augite. This characteristically tholeiitic relationship (op. cit.) is found in all the porphyritic basalts, basalts, and basaltic-andesites wherever the grain-size is sufficiently large to obtain interference figures; in the sequel it will be described as augite and pigeonite. Orthopyroxene has not been identified in the groundmass of any basalt.

charged with minute grains of ore minerals, and apatite are interstitial to the plagioclase and may form approximately 2 per cent of the rock. The red-brown or green-brown isotropic mineral, chlorophaeite, may occur in vesicles and may also be spread throughout the rock as an alteration product of the interstitial material (nos. 4, 7, and 8); the remaining tholeiites are free of chlorophaeite.

TABLE 2

Analyses and CIPW norms of olivine-tholeiite and tholeiite lavas and dykes

(For Key to analyses, see p. 440)

	1 (H.128)	2 (H.6)	3 (G.101)	4 (G.200)	5 (G.146)	6 (G.176)	7 (G.99)	8 (G.244)	9 (G.84)	10 (G.163)
SiO_2	47·07	46·82	48·44	48·28	49·29	48·48	49·25	49 30	49·74	50·83
TiO_2	1·66	1·95	2·95	2·52	2·74	3·00	3·05	3·86	3·33	3·44
Al_2O_3	14·86	14·50	13·15	12·80	12·75	12·77	12·30	13·03	12·37	12·67
Fe_2O_3	4·08	5 26	3·78	5·49	3 86	6·97	5·93	4·11	3·81	3·10
FeO	7·20	6 78	9·92	9·38	11·35	8·76	9·49	10 37	11 44	11 39
MnO	0·17	0·20	0·24	0·23	0·24	0·25	0·25	0 32	0·30	0·25
MgO	8·52	7 61	5·62	5·20	5·08	4·76	4·90	4·36	4·37	4·19
CaO	11·47	11 07	10·79	10·16	9 85	9·20	9 27	8·50	8·57	8·18
Na_2O	2·24	2·56	2·57	2·92	2·87	2·91	2 93	3·17	3·07	3·24
K_2O	0 20	0·36	0 43	0 26	0·46	0·41	0·51	0·64	0·80	0 87
P_2O_5	0·18	0·22	0 42	0·34	0·41	0·40	0·46	0·67	0·98	0·75
H_2O^+	1 32	1·74	0 70	0·62	0·82	0·61	0·57	0·71	0·77	0 64
H_2O^-	0·93	0·75	0 75	1 63	0·48	0·92	0·86	0·80	0 36	0 30
CO_2	—	—	—	—	—	0·33	0·13	—	—	—
TOTALS . . .	99·90	99·82	99·76	99·83	100·20	99·77	99·90	99 84	99·91	99·85
$\frac{(Fe'''+Fe''+Mn)\,100}{Fe'''+Fe''+Mn+Mg}$.	42·1	46·3	57·5	61·1	62·5	64·3	63 3	64·9	66 1	65·9
Molecular normative . $(Ab+Or)\,100/$ $Ab+Or+An$	41·5	48·1	52·6	56·9	58·1	58·2	60·8	62·2	64·7	66 2
Q . . .	—	—	2·64	3·30	2·58	6 66	6·24	5 16	4·38	4·44
Or . . .	1·11	2·22	2·22	1·67	2·78	2 22	2·78	3·34	5 00	5 56
Ab . . .	18·34	21·48	22·01	24·63	24·63	24·63	24·63	27·25	26·20	27·25
An . . .	30·30	26·97	23·07	20 85	20·29	20·57	19·18	19 18	17 51	17·51
Di ⎰ Wo . . .	10·79	11·37	11·72	11 72	10·90	9·40	9·86	7·89	8·12	7·89
Di ⎱ En . . .	7·40	8·10	6·40	6·30	5·20	5·90	5·70	4·10	3·70	3 50
⎱ Fs . . .	2·51	2·24	4·88	5·02	5·54	2·90	3·70	3·56	4·36	4·36
Hy ⎰ En . . .	11·10	9·00	7·60	6 70	7·20	6·00	6·50	6·80	7·20	7·20
Hy ⎱ Fs . . .	3·83	2 51	5·68	4 09	8·05	2·77	4·22	6·07	8·45	8·84
Ol ⎰ Fo . . .	1·96	1·33	—	—	—	—	—	—	—	—
Ol ⎱ Fa . . .	0·82	0·30	—	—	—	—	—	—	—	—
Mt . . .	6·03	7·66	5·57	7·89	5·57	10·21	8·58	6·03	5·57	4·41
Il . . .	3·19	3·80	5 62	4·71	5·17	5·78	5·78	7·45	6·23	6·54
Ap . . .	0·34	0·34	1 01	0·67	1 01	1·01	1·34	1·68	2·35	1·68
Rest . . .	2·25	2·49	1·45	2·25	1·30	1·86	1·56	1·51	1·13	0·94
TOTALS . .	99 97	99·81	99·87	99 80	100·22	99·91	100·07	100 02	100 20	100·12

Analyst: I. S. E. Carmichael

Olivine is rare (nos. 4, 5, 7, 8) or absent and is often almost completely pseudomorphed by bowlingite. Chloritic material may be interstitial to the plagioclase laths and presumably replaces glass. Carbonate may be confined to vesicles, or it may be distributed throughout the rock as small, ragged patches.

Perhaps the most prominent petrographic feature of the tholeiites is the abundant and evenly distributed iron-titanium oxides which can form up to 15 per cent of the rock. Magnetite[1] characteristically forms equant, euhedral

[1] Magnetite is used here and subsequently for the spinel phase which, when unaltered, is known to contain considerable amounts of the ulvöspinel molecule ($2\,FeO\,.\,TiO_2$) in solid solution (unpublished work).

grains larger than the groundmass pyroxene (Plate 1, figs. c and d; Plate 2, fig. A), in contradistinction to the olivine-tholeiites. Independent, acicular ilmenite is present in all tholeiites.

In those rocks with chlorophaeite (nos. 4, 7, and 8) the magnetite and ilmenite have been altered to haematite to a varying extent, and haematite as trails of small grains is associated with chlorophaeite. Where chlorophaeite and other secondary minerals are absent, the magnetite is homogeneous at $\times 600$. Pyrite can be seen only in relation to cross-cutting secondary veinlets; sulphides have not, apparently, crystallized from the liquid basalt.

Basaltic-andesites (Table 3, nos. 11, 12, and 13)

Characteristically, these rocks are extremely fine-grained and are similar, mineralogically, to the tholeiites. They also have sporadic, weakly zoned labradorite phenocrysts and rare phenocrysts of augite in a groundmass of zoned andesine laths, pyroxene granules, and a small amount of interstitial glass charged with minute ore grains. As the pyroxene crystals are very small, the identification of pigeonite is not always easy, but in all cases nearly uniaxial interference figures have been obtained indicating that it is present, although in subordinate amounts.

The crystals of magnetite show a considerable range in size in the basaltic-

KEY TO ANALYSES IN TABLES 2–7

1. Olivine-tholeiite lava, north of Kistufell at 3140 ft (H. 128).
2. Olivine-tholeiite lava, east of Höttur at 2650 ft (H. 6).
3. Olivine-tholeiite dyke, 36 ft thick, main member of multiple dyke in stream east of Ketilhnjúkur (G. 101).
4. Tholeiite lava at 1560 ft on south side of Hallbjarnarstadatindur (G. 200).
5. Tholeiite dyke, 3 ft thick, in bed of stream north of Hallbjarnarstadatindur (G. 146).
6. Tholeiitic lava, at 3600 ft, just beneath Sandfell spot height 3674 ft (G. 176).
7. Tholeiitic lava, at 2070 ft on south-west side of Eggjar ridge (G. 99).
8. Tholeiitic lava, to south of Eggjar ridge (G. 244).
9. Tholeiitic lava at 2350 ft by second lake on Eggjar ridge (G. 84).
10. Tholeiitic lava, on Thingmuli hill (spot height 1666 ft) (G. 163).
11. Basaltic-andesite lava, at 1720 ft on south side of Hallbjarnarstadatindur (G. 194).
12. Basaltic-andesite lava, overlying acid lava, south of Eggjar ridge (G. 247).
13. Basaltic-andesite lava, west side of whale-backed ridge by Thingmuli hill (H. 20).
14. Andesite, top of andesite group at 2580 ft on Kaldakinn (H. 107).
15. Chilled margin of intrusion, head of Arey-jardalur, by spot height 2873 ft (G. 159).
16. Andesite dyke, 3 ft thick, in stream-bed south of Skúmhöttur (G. 230).
17. Andesite lava, base of volcano, north-west of Höttur (H. 96A).
18. Glassy margin of acid dyke in stream bed north-east of Hallbjarnarstadatindur (G. 151). (Carmichael, 1960a, table 6, 6R.)
19. Vesicular pitchstone cone-sheet, south end of Höttur (H. 49). (Carmichael, 1962, table 3, K.)
20. Granophyric boulder in acid tuff (G. 100A).
21. Small rhyolitic intrusion north of Kistufell (H. 1).
22. Acid plug, east of Skúmhöttur (H. 31).
23. Pitchstone dyke, in stream-bed north-east of Hallbjarnarstadatindur (G. 239). (Carmichael, 1962, table 3, o).
24. Residual glass separated from porphyritic pitchstone No. 18. (Carmichael, 1960a, Table 6, 6G.)
25. Picrite-basalt lava at 3500 ft on Skúmhöttur (G. 94).
26. Porphyritic basalt lava at 2760 ft at south end of Höttur (H. 92).
27. Gabbro fragments in tuff, west side of Sandfell (H. 94).
28. Porphyritic dyke, 12 ft thick, south side of Eggjar ridge at 2430 ft (G. 98).

andesites, the large fraction being larger than any other groundmass mineral, whereas the smaller interstitial size-fraction (Plate 2, fig. B) is smaller than the other ground-mass minerals. There is little gradation between what is considered to be two contrasted size fractions. Both independent ilmenite and magnetite-ilmenite composite grains are found, but oriented ilmenite lamellae in the magnetite are absent. A few random specks of pyrite are found, which are not, in the basaltic-andesites, demonstrably associated with veinlets, so that these sulphides may represent primary precipitation.

TABLE 3

Analyses and CIPW norms of basaltic-andesites

(For Key to analyses, see p. 440)

	11 (G. 194)	12 (G. 247)	13 (H. 20)		Norms		
					11	12	13
SiO_2	54·11	55·87	52·68	Q	10·86	12·18	8·94
TiO_2	2·65	2·40	3·13	Or	7·23	7·78	6·67
Al_2O_3	12·64	13·56	12·83	Ab	28·82	31·44	29·34
Fe_2O_3	5·27	3·91	4·04	An	15·57	16·40	15·85
FeO	8·07	7·56	9·50	Di (Wo	7·31	4·41	5·92
MnO	0·23	0·25	0·28	Di {En	4·10	2·20	2·70
MgO	3·61	2·91	3·36	Di (Fs	2·90	2·11	3·17
CaO	7·35	6·47	7·43	Hy (En	4·80	5·10	5·70
Na_2O	3·42	3·69	3·53	Hy {Fs	3·56	5·15	6·34
K_2O	1·17	1·29	1·06	Mt	7·66	5·57	5·80
P_2O_5	0·50	0·80	1·16	Il	5·17	4·56	5·93
H_2O^+	0·56	0·64	0·61	Ap	1·34	2·02	2·69
H_2O^-	0·38	0·56	0·27	Rest	0·94	1·20	0·88
CO_2	—	—	—	TOTALS	100·26	100·12	99·93
TOTALS	99·96	99·91	99·88				
$\frac{Fe'''+Fe''+Mn)\ 100}{Fe'''+Fe''+Mn+Mg}$	67·0	68·6	69·1	.			
Molecular normative (Ab+Or) 100/Ab+Or+An	70·6	71·0	70·3				

Analyst: I. S. E. Carmichael

Andesites (Table 4, nos. 14, 15, 16, 17)

Texturally these rocks are variable, being in some cases even finer-grained than the basaltic-andesites and microcrystalline, whereas others are fairly coarse-grained. No. 14 contains small, scattered phenocrysts of weakly zoned andesine (An_{40}–An_{45}) together with very rare ferroaugite ($\beta = 1·708$; $2V\gamma = 48°$), hypersthene ($\gamma = 1·726$; $2V\alpha = 53°$), and fayalitic olivine. The groundmass is microcrystalline with microlites of plagioclase, pyroxene, and iron-ores. There are sporadic microphenocrysts of magnetite, but the great majority of magnetite is interstitial to the groundmass minerals—a characteristic feature of all the andesites (Plate 2, fig. C). Andesine phenocrysts are generally more abundant in no. 15 and occur together with rare phenocrysts of ferroaugite and olivine

in a very finely crystalline groundmass of andesine–oligoclase laths, pyroxene, magnetite granules, and interstitial glass. No. 16 has abundant zoned, stumpy, microphenocrysts of andesine which show all gradations in size to the feldspar of the groundmass. The groundmass plagioclase is surrounded by small, sub-hedral crystals of pyroxene, rare olivine, glass, and magnetite grains. Chlorophaeite is present in vesicles and may also extend through the groundmass, to a varying extent replacing the glassy mesostasis. The last andesite (no. 17) is extremely fine-grained, again with scattered andesine microphenocrysts, and

TABLE 4

Analyses and CIPW norms of andesites (icelandites)

(For Key to analyses, see p. 440)

| | 14 (H.107) | 15 (G.159) | 16 (G.230) | 17 (H.96A) | | Norms | | | |
						14	15	16	17
SiO_2	60·59	64·47	59·27	62·39	Q	15·42	24·66	15·54	17 22
TiO_2	1·25	0·71	1·12	0·83	Or	9·45	12·23	11·68	16·12
Al_2O_3	15·07	14·41	13 68	14·24	Ab	36·15	34·58	38 25	38·77
Fe_2O_3	2·31	3·54	5 33	4·62	An	17·24	14 73	11·12	10·01
FeO	5·73	2·57	5·10	3·82	Di ⎰ Wo	2·09	0·81	3 83	3·25
MnO	0·19	0·12	0 28	0·19	Di ⎱ En	0·80	0·50	1·50	1·40
MgO	1·73	0·66	1·07	0·70	Fs	1·32	0·26	2 38	1·85
CaO	4·94	3·52	4·76	3·92	Hy ⎰ En	3·50	1·10	0 90	0 40
Na_2O	4 29	4·07	4 51	4·64	Hy ⎱ Fs	5·54	0·53	1·32	0·40
K_2O	1 59	2·14	2 00	2·70	Mt	3·25	5·10	7·66	6 73
P_2O_5	0 43	0 22	0·42	0·27	Il	2·43	1·37	2·13	1·52
H_2O+	1·58	1·92	1 42	0·84	Ap	1·01	0·34	1·01	0·67
H_2O-	0·26	1·24	1 39	0·58	Rest	1 84	3·45	2·81	1·61
CO_2	—	0·29	—	0·19	TOTALS	100·04	99·66	100·13	99·95
TOTALS	99·96	99·88	100·35	99·93					

$\frac{(Fe'''+Fe''+Mn)\ 100}{Fe'''+Fe''+Mn+Mg}$ . .	72·2	78·4	84·2	86·7
Molecular normative . . (Ab+Or) 100/Ab+Or+An	73·6	76·9	82·3	85·1

Analyst: I. S. E. Carmichael

with rare olivine (invariably pseudomorphed by bowlingite) resting in a ground-mass of plagioclase, pyroxene, and magnetite grains. Carbonate occurs in irregular patches.

These rocks of intermediate composition, with silica percentage ranging from 59 to 65 (Table 4) are often extremely fine-grained and chemically unlike, for example, the average Cascade andesite (Table 8), being poorer in alumina and richer in iron. In order to avoid confusion with the typical orogenic andesites, with their varied assemblages of phenocryst minerals, it is perhaps better to call these Icelandic andesites 'icelandites'.

Acid rocks (Table 5, nos. 18 to 24)

Acid rocks are found as rhyolites, pitchstones, and granophyric boulders in tuffs. The rhyolites are pale-coloured rocks with a few scattered phenocrysts of andesine (An_{30}–An_{35}), rare ferroaugite, and fayalitic olivine, in a finely crystalline patchwork groundmass of alkali feldspar and quartz. As in the andesites, magnetite occurs as sparse microphenocrysts of early crystallization (Carmichael,

TABLE 5

Analyses and CIPW norms of pitchstones, rhyolites, and granophyres

(For Key to analyses, see p. 440)

	18 (G.151)	19 (H.49)	20 (G.100A)	21 (H.1)	22 (H.31)	23 (G.239)	24 (G.151G)
SiO_2	69·8	69·4	75·74	74·96	74·32	72·4	72·3
TiO_2	0·34	0·20	0·38	0·23	0·24	0·18	0·22
Al_2O_3	12·9	11·2	12·69	12·55	12·66	11·5	12·1
Fe_2O_3	0·7	1·0	1·27	1·72	1·71	0·6	0·4
FeO	2·4	1·5	0·69	0·71	0·50	1·3	1·4
MnO	0·08	0·08	0·02	0·04	0·05	0·06	0·05
MgO	0·21	0·24	0·02	0·02	0·02	0·11	0·09
CaO	1·7	1·2	1·04	0·90	0·94	0·92	1·0
Na_2O	4·8	4·4	4·81	4·41	5·08	4·5	4·9
K_2O	3·1	2·7	2·89	3·65	3·55	3·6	3·5
P_2O_5	0·07	0·05	0·04	0·04	0·05	0·03	0·04
H_2O^+	3·4	5·9	0·23	0·65	0·43	4·6	3·8
H_2O^-	0·4	1·9	0·06	0·34	0·30	0·3	0·1
CO_2	—	—	—	—	—	—	—
TOTALS	99·9	99·8	99·88	100·22	99·85	100·1	99·9
$\dfrac{(Fe''' + Fe'' + Mn)\,100}{Fe''' + Fe'' + Mn + Mg}$	89·3	85·2	98·1	98·5	98·3	90·8	92·6
Molecular normative $(Ab+Or)\,100/Ab+Or+An$	93·2	95·2	93·0	94·3	98·2	98·2	99·1

Analyst: I. S. E. Carmichael

Norms

	18	19	20	21	22	23	24
Q	25·6	30·4	34·68	33·54	29·82	30·5	28·3
Or	18·4	16·1	17·24	21·68	21·13	21·1	20·6
Ab	40·4	37·2	40·35	37·20	42·97	38·2	41·4
An	4·4	2·8	4·73	3·89	1·39	0·6	0·8
Wo	1·6	1·3	0·23	0·23	1·39	1·6	1·7
En	0·5	0·6	—	—	—	0·3	0·2
Fs	3·4	1·7	—	—	—	1·6	1·8
Mt	0·9	1·4	1·16	1·86	1·16	0·9	0·7
Il	0·6	0·5	0·76	0·46	0·46	0·5	0·5
Ap	—	—	—	—	—	—	—
Ht	—	—	0·48	0·48	0·96	—	—
Rest	3·8	7·8	0·29	0·99	0·73	4·9	3·9
TOTALS	99·6	99·8	99·92	100·33	100·01	100·2	99·9

1963a) but is predominantly found as small interstitial specks scattered through the crystalline groundmass. Phenocrysts of quartz and sanidine are absent from all the Thingmuli acid rocks.

The granophyre is relatively coarse-grained and is composed of oligoclase zoned continuously to, and mantled by, anorthoclase in granophyric intergrowth

TABLE 6

Analyses and CIPW norms of accumulative rocks

(For Key to analyses, see p. 440)

	25 (G.94)	26 (H.92)	27 (H.94)	28 (G.98)			Norms			
							25	26	27	28
SiO$_2$	44·22	46·10	46·56	48·05	Q		—	1·26	—	—
TiO$_2$	1·64	1·28	0·59	2·28	Or		1·11	1·11	0·56	2·22
Al$_2$O$_3$	8·91	20·67	27·22	16·56	Ab		12·05	16·77	18·34	24·63
Fe$_2$O$_3$	3·55	4·17	0·65	2·65	An		17·24	46·98	64·22	31·14
FeO	9·04	4·30	2·68	9·07	Di { Wo		6·84	4·99	4·29	9·86
MnO	0·20	0·12	0·07	0·18	Di { En		5·00	3·80	2·20	5·10
MgO	19·73	5·74	1·69	5·01	Di { Fs		1·19	0·66	1·98	4·49
CaO	7·07	12·04	15·19	11·54	Hy { En		14·60	10·60	1·00	4·70
Na$_2$O	1·40	2·12	2·22	2·94	Hy { Fs		3·30	1·85	0·79	4·09
K$_2$O	0·16	0·23	0·11	0·41	Ol { Fo		20·79	—	1·02	1·89
P$_2$O$_5$	0·30	0·15	0·08	0·35	Ol { Fa		5·20	—	0·42	1·94
H$_2$O$^+$	2·07	1·64	1·65	0·78	Mt		5·57	6·03	0·93	3·71
H$_2$O$^-$	0·98	1·14	0·05	0·47	Il		3·04	2·43	1·22	4·41
CO$_2$	0·44	0·18	1·13	—	Ap		0·67	0·34	0·34	1·01
					Rest		3·49	2·96	2·83	1 25
TOTALS	99 86*	99·88	99·89	100·29						
					TOTALS		100·09	99·78	100·14	100·44
$\dfrac{(Fe'''+Fe''+Mn)\ 100}{Fe'''+Fe''+Mn+Mg}$ . .	26·1	44·4	52·6	56·6						
Molecular normative . . (Ab+Or) 100/Ab+Or+An	43·5	30·6	24·3	48·4						

* Includes 0·15% Cr$_2$O$_3$.

Analyst: I. S. E. Carmichael

Modes (volume per cent)

Anal. no.	Plagioclase	Pyroxene	Olivine	Groundmass
25 . .	3·4	0·1	25·6	70·9
26 . .	46·0	0·4	4·3	49·3
27 . .	83·6	5·4	—	11·0*
28 . .	17·4	0·1	0·3	82·2

* Chlorite, carbonate, and iron-ore interstitial material.

with quartz. Accessory zircon and magnetite occur, the latter being surrounded by a corona of sphene grains. The Thingmuli pitchstones have been previously studied, and the results recorded elsewhere (Carmichael, 1960a, 1960b, 1962). Petrographically they are similar to the rhyolites, with phenocrysts of andesine, ferroaugite, and fayalite surrounded by brown or pale-coloured glass of varying crystallinity.

Porphyritic rocks (Table 6, nos. 25 to 28)

Plagioclase is the predominant phenocryst in the porphyritic lavas and dykes and is almost invariably bytownite in the range An$_{80}$–An$_{85}$. Bytownite phenocrysts (Table 7, no. 26 F) may form over 45 per cent of one lava (no. 26) and,

together with rare phenocrysts of olivine (Fo$_{75}$) and augite (Table 7, no. 26 P), are enclosed in a groundmass of partially altered olivine, subophitic augite and granular pigeonite, and zoned labradorite laths, together with magnetite and acicular ilmenite. An iron-rich, interstitial mesostasis has been extensively altered to chlorite, which may also spread into the feldspar phenocrysts. Small patches of carbonate are present.

TABLE 7

Analyses of pyroxene, olivine and feldspar phenocrysts, together with the formulae of the ferromagnesian minerals

(For Key to analyses, see p. 440)

	25 Ol	26 Px	26 F	28 F		25 Ol	26 Px
SiO$_2$ . . .	40·03	50·54	47·64	—	Si	0·995	1·878
TiO$_2$ . . .	0·04	0·90	—	—	Ti	0·001	—
Al$_2$O$_3$ . . .	—	3·08	32·72	—	Al^{IV}	—	0·108
Cr$_2$O$_3$ . . .	0·04	0·32	—	—	Al^{VI}	—	0·027
Fe$_2$O$_3$ . . .	0·08	1·97	0·82	0·78	Ti	—	0·025
FeO . . .	11·90	6·17	—	—	Fe^{III}	0·001	0·055
NiO . . .	0·26	0·01	—	—	Fe^{II}	0·247	0·192
MnO . . .	0·19	0·17	—	—	Mn	0·004	0·005
MgO . . .	47·03	15·29	—	—	Mg	1·742	0·846
CaO . . .	0·24	20·97	16·48	16·60	Ca	0·006	0·835
Na$_2$O . . .	—	0·46	2·14	2·14	Na	—	0·033
K$_2$O . . .	—	0·02	0·06	0·08	K	—	0·001
					Cr	0·001	0·009
TOTALS . . .	99·81	99·90	100·09*		Ni	0·005	—

			Composition of feldspar (recalculated to 100 Wt. per cent)		Z	0·996	1·986
		Atomic per cent			XY	2·006	2·028
					% Al in Z	—	5·4
Ca . . .	—	43·2	Or 0·3	0·5			
Mg . . .	87·4	43·8	Ab 18·1	17·9			
Fe . . .	12·6	13·0	An 81·6	81·6			

* Includes 0·23% H$_2$O+; H$_2$O⁻ nil.

Analyst: I. S. E. Carmichael

Another porphyritic lava (no. 25) contains large, partially serpentinized olivine phenocrysts (Table 7, no. 25 Ol), infrequent bytownite, and rare augite phenocrysts. The groundmass is made up of zoned labradorite laths, serpentinized olivine, intergranular augite and pigeonite, abundant acicular ilmenite, and interstitial, ragged grains of magnetite. Secondary chlorite is extensively developed in the groundmass, together with patches of carbonate. Chromite is found as small, anhedral grains contained in the olivine phenocrysts and also, rarely, as independent microphenocrysts.

No 28 is a porphyritic dyke, with phenocrysts of bytownite (Table 7, no. 28 F) having an outer rim of labradorite which corresponds in composition to the groundmass feldspar. Other groundmass minerals are granular augite and pigeonite, scarce olivine, ragged interstitial magnetite, acicular ilmenite, and interstitial glass often replaced by chlorite.

In an intensely hydrothermally altered tuff, small boulders of feldspathic gabbro have been found. One specimen (no. 27), a bytownite (An_{82}) orthocumulate (Wager *et al.*, 1960), is composed of approximately 85 per cent bytownite with an outer zone of sodic labradorite (An_{65}), large, interstitial, optically continuous crystals of augite (Plate 1, fig. D), and the remaining interstices filled with chlorite, carbonate, and zeolites; the latter mineral may also form small veinlets, cutting through the bytownite crystals.

Summary and discussion

In this series of fine-grained and essentially non-porphyritic basalts, basaltic-andesites, andesites (icelandites) and rhyolites, plagioclase and pyroxenes are found throughout. Olivine is present only in the more magnesian basalts, is absent from the more iron-rich tholeiites and basaltic-andesites, and sporadically reappears as an iron-rich representative in the icelandites and rhyolites. The optics of the groundmass augite indicate that it is zoned to sub-calcic augite or pigeonite, and small, independent crystals of a subordinate, monoclinic, calcium-poor pyroxene have been found in all but the extremely fine-grained rocks. Although no reaction relationship between olivine and groundmass (liquid) has been observed, the groundmass pyroxenes are characteristically tholeiitic (Muir & Tilley, 1963).

Perhaps the most interesting feature of the petrography of this tholeiitic series is the mode of occurrence of the iron-titanium oxides, and of magnetite (*sensu lato*) in particular. In a general way, magnetite crystallized late as interstitial, angular, ragged grains partially enclosing groundmass plagioclase and pyroxene in the olivine-tholeiites (Plate 1, figs. A and B). In the olivine-free basalts the order of crystallization is changed, and magnetite no longer fills the interstices between groundmass plagioclase and pyroxene but forms numerous and evenly distributed, equant grains crystallizing before the remaining groundmass minerals (Plate 1, figs. C and D; Plate 2, fig. A). This texture is considered to indicate that magnetite crystallized early as a microphenocryst in the tholeiites, the small size of the grains being due to ease of nucleation.[1] In the basaltic-andesites, magnetite is found in two relatively clear-cut size fractions (Plate 2, fig. B), the larger size fraction being interpreted as microphenocrysts and the smaller size fraction, or second generation of smaller size than the other groundmass ferromagnesian minerals, may be considered as part of the groundmass and hence a product of the rapid cooling. In the

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[1] The preservation of early precipitated magnetite is perhaps unexpected as it would normally be considered to sink rapidly (fractionate) in a tholeiitic liquid, but calculations show that these small magnetite microphenocrysts would have approximately the same velocity of sinking in a tholeiitic liquid as the larger olivine crystals in a liquid of olivine-tholeiite composition. As olivine has not been completely fractionated, for olivine-tholeiites are present which contain olivine as the first ferromagnesian phase, it is suggested that the tholeiites analogously show the incomplete fractionation of magnetite which is similarly considered to be the first ferromagnesian phase. It is unknown to what extent magnetite as larger crystals has fractionated from these tholeiitic lavas, for no magnetite accumulates have been found.

icelandites and rhyolites, however, only a small proportion of the total mag-
netite is found as microphenocrysts, the large majority of magnetite occurring
in the groundmass as tiny grains (Plate 2, fig. c). There appears to be a stage in
this volcanic series at which magnetite becomes stable at the liquidus, perhaps
taking the place of olivine, and is thereafter *almost* completely suppressed in the
icelandites and rhyolites (the basaltic-andesites representing an intermediate
stage) where, perhaps coincidentally, an iron-rich olivine occurs sporadically as
a phenocryst.

In the basaltic rocks, ilmenite as a separate phrase generally crystallizes late
as acicular crystals, and the impression obtained is that independent ilmenite
is least abundant where magnetite is most abundant. There is accordingly little
correlation between the TiO_2 content of these rocks and the amount of ilmenite.

The secondary alteration of most of the originally homogeneous magnetite
to haematite is characteristic of the olivine-tholeiites and those tholeiites where
chlorophaeite is notable. It may be suggested that reflected light examination of
all but very recent and/or fresh lavas would show that secondary oxidation of
magnetite exists to a greater or less extent, a factor not often considered in dis-
cussion of basalt analyses. It is probable that all basaltic lavas subjected to a
subsequent hydrothermal alteration, of which zeolites are one manifestation,
will show some change in their iron-titanium oxides.

The only sulphide found is pyrite, which in the basalts occurs as specks asso-
ciated with late veinlets. In the basaltic-andesites and more acid rocks, specks
of pyrite are very rare and are not always demonstrably associated with second-
ary veinlets.

A later argument will be anticipated here for the accumulative origin of the
porphyritic rocks, so that if the Thingmuli tholeiitic series are derived by frac-
tional crystallization from a basaltic parent, then the composition of any
crystal extract deemed to set a parent on the desired liquid line of descent is
unconvincing if it cannot be expressed almost completely in terms of phases
demonstrably crystallizing early, and found as phenocrysts in the accumulative
porphyritic rocks. The common phenocrysts are bytownite, olivine, and augite,
and analyses are set down, in Table 7, of each type of phenocryst mineral.

CHEMICAL ANALYSES

The analyses of the Thingmuli lavas and intrusions are given in Tables 2
and 6, and they are generally low in alumina, magnesia, and combined alkalis
(Fig. 2) but are characteristically high in iron and titania. The iron-rich nature
of these rocks is shown in Fig. 3; the absolute enrichment in iron of Icelandic
lavas has been noted by Nockolds and Allen (1956), and these rocks show a
similar trend. The norms of the basalts and andesites (icelandites) have high
hypersthene in relation to diopside, particularly in those rocks unaffected by
subsequent oxidation. Although the characteristic separation of olivine in
stoichiometric excess in tholeiitic basalts results in modal olivine being in excess
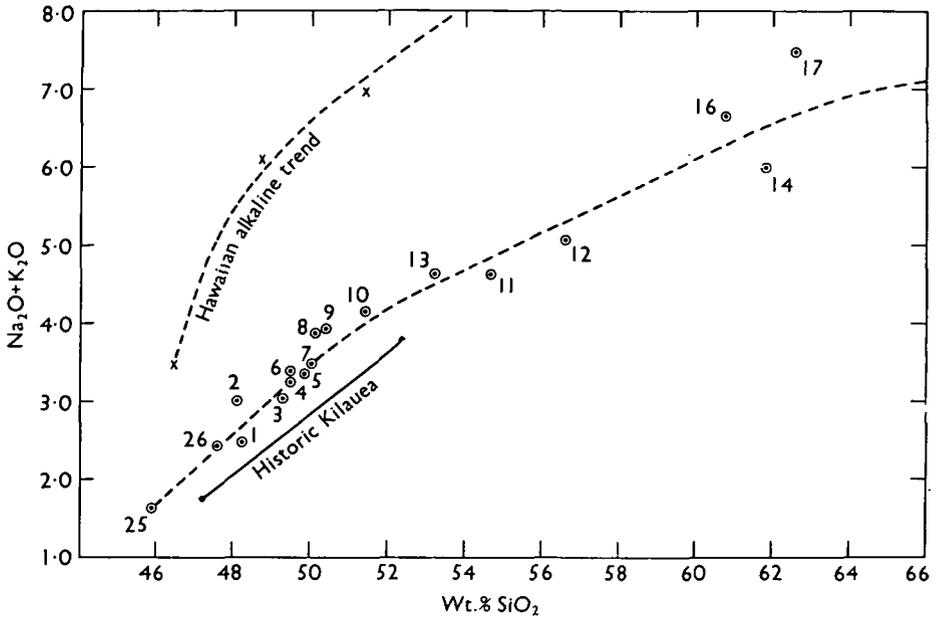
FIG. 2. Total alkalis for the Thingmuli basalts and basaltic-andesites plotted against silica (Table 9). The Hawaiian alkaline trend (Muir & Tilley, 1961) and the tholeiitic trend of the historic lavas of Kilauea, Hawaii, are also shown (Tilley, 1960; Muir & Tilley, 1963).
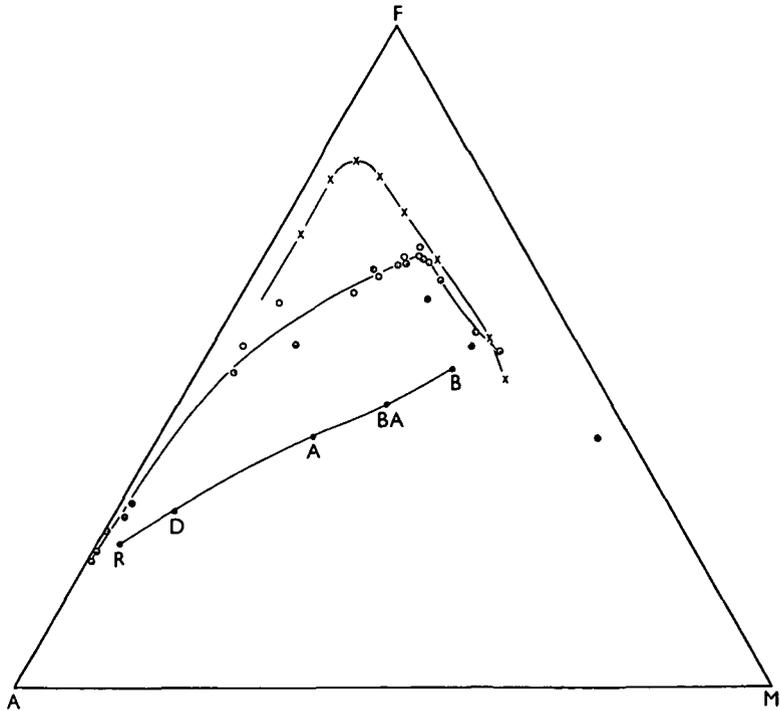

FIG. 3. Plot of the Thingmuli series (open circles) with accumulative rocks represented by solid circles. The Skaergaard trend x–x–x is taken from Wager (1960); B, BA, A, D, and R are average analyses of the Cascade province (Table 8). F = FeO + Fe₂O₃; M = MgO; A = Na₂O + K₂O (wt. per cent).

of normative olivine, this excess is over-emphasized in the Thingmuli olivine-tholeiites (Table 2, nos. 1, 2, and 3) because of the subsequent oxidation of much of the magnetite to haematite.

The products of this volcano are clearly tholeiitic (Yoder & Tilley, 1962, pp. 353–4), and the complete gradation in composition, mineralogy, and field character indicates that the Thingmuli lavas and intrusions are serial and are undoubtedly related one to the other in origin.

VARIATION DIAGRAMS

On the basis of studies in the system $MgO-FeO-Fe_2O_3-SiO_2$ (Muan & Osborn, 1956), the course of a synthetic liquid fractionally crystallizing in this system was shown to be controlled by the behaviour of oxygen in the gas phase. Osborn (1959) illustrated the change in composition of such a liquid fractionally crystallizing under conditions of constant total composition (oxygen content fixed) by plotting the ratio $FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$ against silica for the successive liquid fractions. This fractionation trend is shown in Fig. 4 (n–132–40–24). In contrast the same initial liquid crystallized fractionally with a constant partial pressure of oxygen has quite a different trend (Fig. 4, n–c–d); with an increase in the partial pressure of oxygen, the path of successive liquids is represented by n–a–b (Fig. 4).

The general similarity in trend between the initial liquids of the Skaergaard intrusion (Fig. 4) and a synthetic liquid fractionally crystallizing at constant total composition led Osborn (op. cit.) to suggest that the Skaergaard also crystallized with a low, fixed oxygen content. Furthermore, the similarity between the trend of the Cascade orogenic series and a synthetic liquid fractionating with a constant partial pressure of oxygen indicated that this volcanic series also resulted from fractional crystallization, but with a variable oxygen content (constant P_{O_2}).

The Thingmuli series have been plotted in Fig. 4 (the silica contents have been taken from the recalculated analyses, Table 9) and show that in the initial stages the trend is similar to the Skaergaard, except that silica increases slightly in contrast to the slight decrease in the Skaergaard. The change in trend at approximately 50 per cent silica, towards high silica values, coincides generally, from the petrographic evidence, with the appearance of magnetite (*sensu lato*) as a microphenocryst. Fractionation of the magnetite phase would effectively prevent the continued enrichment of iron in the successive liquids and would therefore account for this change in trend (Fig. 4). Exactly the same feature of the restriction of the progressive enrichment in iron in the Thingmuli series is shown in Fig. 3.

The contrast, or otherwise, between the fractionation trends of synthetic liquids in the system $MgO-FeO-Fe_2O_3-SiO_2$ and natural rock series assumes that the feldspathic components play a purely passive role with respect to the ratio $FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$; moreover, the silica parameter (Fig. 4)

of natural rock series contains the silica component of the feldspathic constituents, so that the lack of correspondence between the trends of synthetic and of natural liquids in Fig. 4, particularly in the later stages of fractionation, is to be expected. In neither of the oxide variation diagrams (Figs. 3 and 4) is it very easy to relate the individual trends to the fractionation of those possible mineral assemblages which may control the trend.
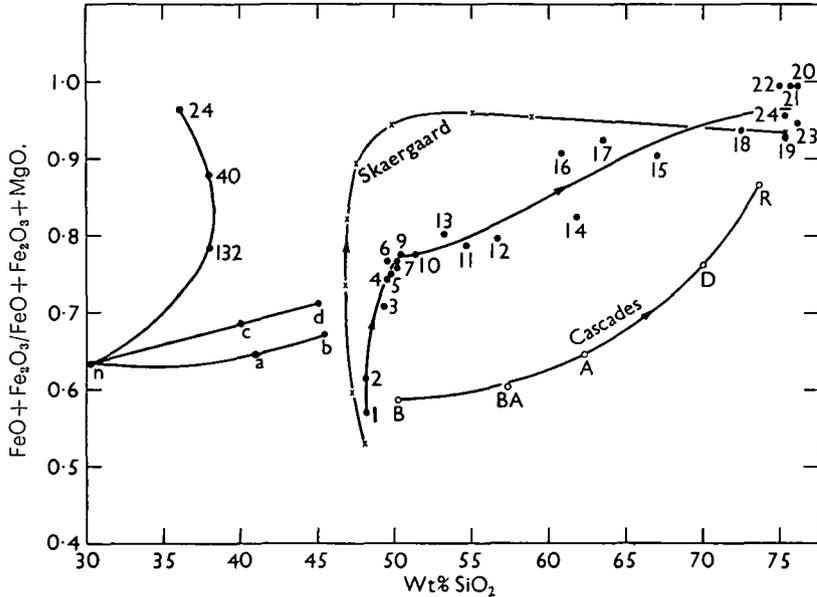

Fig. 4. The ratio $FeO + Fe_2O_3/FeO + Fe_2O_3 + MgO$ plotted against silica for the Thingmuli series (solid circles); the data used are the recalculated dry analyses (Table 9), with accumulative rocks not shown. The Skaergaard trend is taken from Wager (1960), and the Cascades data are taken from Table 8. An initial liquid n, fractionally crystallized in the system $MgO–FeO–Fe_2O_3–SiO_2$ (Osborn, 1959) at constant total composition, takes the course n–132–40–24; at a constant partial pressure of oxygen the successive liquids take the course n–c–d, and at an increasing partial pressure of oxygen the successive liquids of n take the course n–a–b. The enumeration of the Thingmuli analyses corresponds to the analyses of Tables 2 to 5.

Wager (1956) has used a diagram for basalt series in which the molecular normative plagioclase (Ab/Ab+An) (albite ratio) is plotted against the atomic ratio $Fe'' + Mn/Fe'' + Mn + Mg$ (iron ratio). These ratios represent the low-temperature components of the plagioclase and the ferromagnesian solid-solution series. However, the parameters used by Wager have been changed here, and the albite ratios amended to the molecular normative ratio Ab+Or/Ab+Or+An, because Or increases concomitantly with Ab in basalt series (Carmichael, 1963b). The exclusion of Fe''' from the iron ratio makes the numerical value of this function susceptible to subsequent oxidation of a basalt, so that this function, hereafter called the iron ratio, has been changed to include Fe'''.

In Fig. 5, the amended feldspar (Ab+Or/Ab+Or+An) and iron ratios

$(Fe''' + Fe'' + Mn/Fe''' + Fe'' + Mn + Mg)$ of the successive liquids of the Skaergaard, the average analyses of the Cascades (Table 8), and the Thingmuli series have been plotted. The initial trend of the Cascades illustrates the virtually constant iron ratio (cf. Fig. 4) as the normative feldspar becomes progressively enriched in the low-melting components. The initial trend of the Skaergaard contrasts with this and shows a marked increase in the iron ratio for a small increase in the alkali components of the feldspar.

TABLE 8

Averages computed from analyses of the Cascades lavas

	Basalt	Basaltic-andesite	Andesite	Dacite	Rhyolite
SiO_2	49·91	56·96	61·89	69·68	73·23
TiO_2	1·47	0·78	0·68	0·36	0·24
Al_2O_3	17·91	17·80	17·07	15·21	14·03
Fe_2O_3	2·45	2·39	1·89	1·08	0·60
FeO	7·02	4·42	3·38	1·90	1·70
MnO	0·16	0·11	0·10	0·04	0·02
MgO	6·62	4·47	2·88	0·91	0·35
CaO	10·02	7·50	5·60	2·70	1·32
Na_2O	3·02	3·56	4·06	4·47	3·94
K_2O	0·64	1·23	1·81	3·01	4·08
P_2O_5	0·20	0·18	0·19	0·10	0·05
H_2O^+	0·31	0·50	0·45	0·41	0·49
H_2O^-	0·40	0·18	0·16	0·13	0·09
TOTALS	100·13	100·08	100·16	100·00	100·14
Number averaged ◀	13	20	20	19	9
$\dfrac{(Fe''' + Fe'' + Mn)\ 100}{Fe''' + Fe'' + Mn + Mg}$ . . .	44·3	45·6	50·2	64·2	91·6
Molecular normative $\dfrac{(Ab + Or)\ 100}{Ab + Or + An}$ . . .	48·0	57·6	67·2	82·2	87·5

Analyses taken from Anderson (1941); Williams (1932, 1935, 1942); Yoder & Tilley (1962).

The Thingmuli trend has features common to both, and apparently has two clear changes in direction. The initial stage, from no. 1 to the cluster of points for nos. 4–6, is subparallel to the Skaergaard; these basalts are all olivine-bearing and do not have magnetite occurring as a microphenocryst. The trend from nos. 4–6, to nos. 11–13 changes in direction and indicates that the normative feldspar is becoming progressively enriched in the alkali components, whereas the iron ratio remains essentially constant. These tholeiites and basaltic-andesites all have notable amounts of magnetite microphenocrysts and olivine is essentially absent. The trend again changes in direction from nos. 11–13 to the andesites (icelandites), nos. 14–17, and then to the acid rocks, and the iron ratio of the liquid line of descent increases at broadly the same rate as the
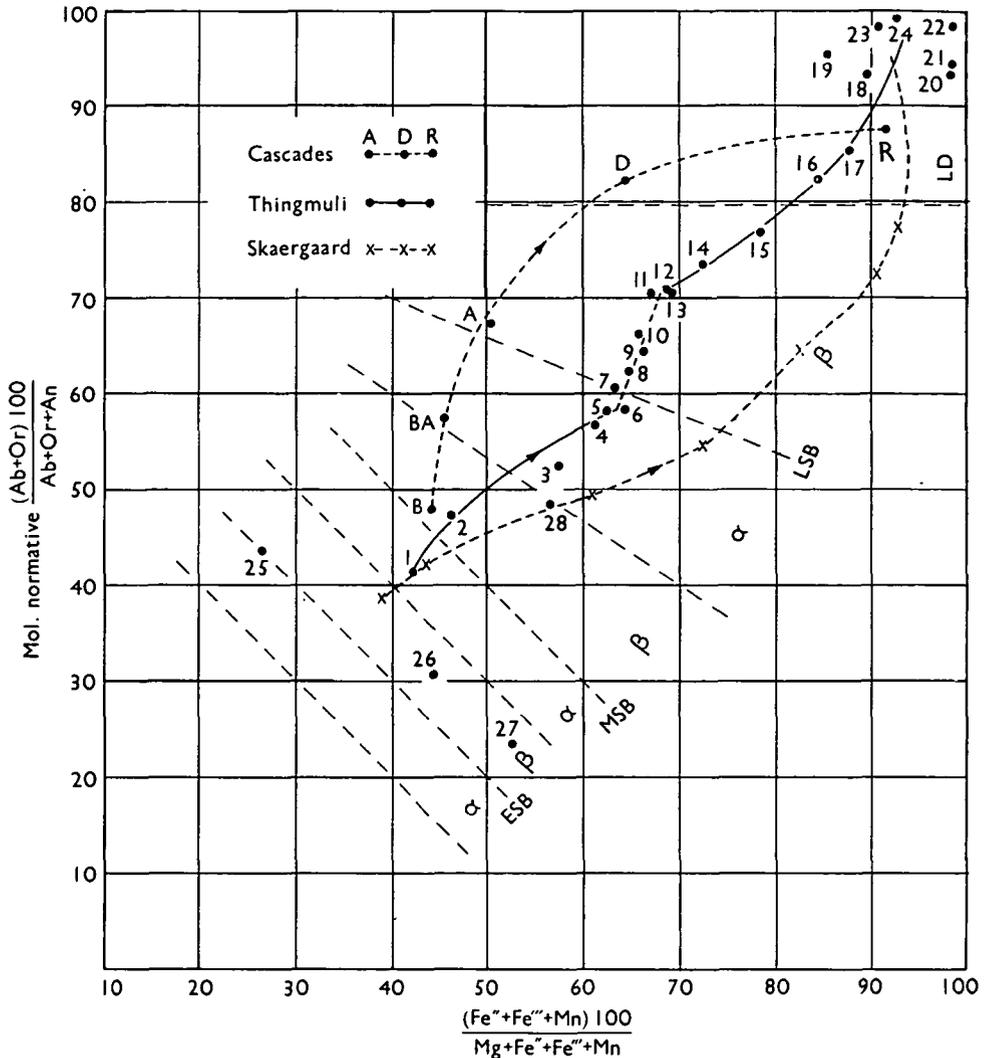
FIG. 5. The molecular normative feldspar ratio (Ab+Or) 100/Ab+Or+An, plotted against the atomic ratio (Fe″+Fe‴+Mn) 100/Mg+Fe″+Fe‴+Mn, for the Thingmuli series (Tables 2 to 6), for the successive liquids of the Skaergaard intrusion (Wager, 1960), and for the average analyses of the Cascades lavas (Table 8). The fractionation stages and their boundaries (dashed lines) have been taken from Wager (1956).

feldspar ratio. In the andesites and rhyolites, however, the great majority of the magnetite exists in the groundmass, with only sporadic microphenocrysts.

Two interesting features emerge from this type of plot (Fig. 5), with respect to the Thingmuli series. The first is that the middle or the nearly vertical part of the Thingmuli trend corresponds to a change in the order of crystallization of magnetite (*sensu lato*) so that the fractionation of this now early crystallizing phase, together with pyroxene, would keep the iron ratio more or less constant

in the successively derived liquids. In contrast, the two limbs of the Thingmuli trend correspond to the suppression, or virtual suppression, of magnetite as a primary phase and the occurrence, perhaps coincidentally, of olivine. Fractional crystallization of liquids on these two limbs would not include significant amounts of magnetite in the fractionated mineral assemblages,[1] and the iron ratios of the successively derived liquids would, therefore, progressively increase.

The second feature of interest is that the variation of silica is not simply progressive. From no. 1 to the average of nos. 4, 5, and 6 (Table 9), silica increases from 48·2 per cent to 49·6 per cent, whereas from nos. 4, 5, and 6 to nos. 11, 12, and 13 it increases progressively from 49·6 per cent to 54·8 per cent (average) with little change in the iron ratios. Thereafter, in the andesites (ice-landites) the increase in silica is haphazard, no. 16 (Table 9) having less silica (60·8 per cent) than all the other andesites, whereas no. 15 has more (66·9 per cent) than all the other andesites. This indicates that silica, alone, plotted against $FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$, as in Fig. 4, will give a different order of analyses than that shown in Fig. 5; in the later stages of fractionation this is due to the silica component of the increasingly abundant feldspathic constituents.

The initial path of variation of the Thingmuli series (Fig. 5) may perhaps be matched by the fractionation path of an analogous synthetic liquid confined to an oxygen isobaric surface in the system $MgO-FeO-Fe_2O_3-SiO_2$ (Osborn, 1959). In such a synthetic liquid, magnetite can take the place of primary-phase olivine so that the path the liquid takes changes sharply in direction to become enriched in silica; furthermore, the appearance of magnetite prevents the further enrichment of iron in the fractionating liquid, and the Mg/Fe ratio of the liquid remains essentially constant until it is consumed.

Although the Thingmuli trend from no. 1 to nos. 11–13 (Fig. 5) corresponds, possibly, to the synthetic fractionation path described above, the almost complete suppression of magnetite as an early crystallizing phase in the later andesites allows the later part of the series to become progressively enriched in iron with respect to magnesium.

There is, however, no indication in the experimental systems that once magnetite has prevented a liquid (on an isobaric surface) from becoming enriched in iron (the Mg/Fe ratio remaining constant) the liquid may subsequently become enriched in iron.

This, then, is the problem of the Thingmuli series with respect to the simplified basalt systems: namely, the apparent restriction of the basalts and basaltic-andesites to a simulated isobaric surface, indicated by the iron ratios remaining essentially constant, silica increasing notably, and magnetite occurring as a microphenocryst (Fig. 5, nos. 6 to 13); whereas in the andesites (nos. 14 to 17) the iron ratio increases, magnetite as a microphenocryst is sporadic, and silica

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[1] In the andesites the fractionation of the early crystallizing mineral assemblages would be expected to include subordinate magnetite, unless the progressively increasing viscosity of the liquids prevented the accumulation of the small iron-ore crystals.

TABLE 9   *Analyses of Thingmuli rocks*

	1	2	3	4	5	6	7	8	9	10
SiO_2	48·21	48·11	49·27	49·48	49·85	49·51	50·08	50·14	50·36	51·39
TiO_2	1·70	2·00	3·00	2·58	2·77	3·06	3·10	3·92	3·37	3·48
Al_2O_3	15·23	14·91	13·38	13·12	12·89	13·04	12·51	13·25	12·52	12·81
Fe_2O_3	4·18	5·40	3·84	5·63	3·90	7·12	6·03	4·18	3·86	3·13
FeO	7·37	6·97	10·09	9·61	11·48	8·95	9·65	10·56	11·58	11·52
MnO	0·17	0·20	0·24	0·23	0·24	0·26	0·25	0·33	0·30	0·25
MgO	8·72	7·82	5·72	5·33	5·14	4·86	4·98	4·43	4·42	4·24
CaO	11·75	11·37	10·98	10·41	9·96	9·40	9·43	8·64	8·68	8·27
Na_2O	2·29	2·63	2·61	2·99	2·90	2·97	2·98	3·22	3·11	3·27
K_2O	0·20	0·37	0·44	0·27	0·46	0·42	0·52	0·65	0·81	0·88
P_2O_5	0·18	0·22	0·43	0·35	0·41	0·41	0·47	0·68	0·99	0·76
TOTALS	100·00	100·00	100·00	100·00	100·00	100·00	100·00	100·00	100·00	100·00
$\dfrac{100\,(FeO+Fe_2O_3)}{FeO+Fe_2O_3+MgO}$ . .	57·0	61·3	70·9	74·1	75·0	76·8	75·9	76·9	77·7	77·6

Recalculated analyses of Nos. 18, 19, 23, and 24 have already been published (Carmichael & McDonald, 1961).

increases, but not progressively. It is as if a synthetic liquid, no longer confined to an isobaric surface, was moving down the magnetite roof (Osborn, 1959) to become progressively enriched in iron.

It is difficult to visualize the conditions in an erupting volcano that would allow oxygen to vary so that the more basic, presumably higher-temperature, members of the Thingmuli series fractionated isobarically, whereas the lower-temperature derivatives do not seem to have had the same restrictions. However, any comparison with the system MgO–FeO–Fe_2O_3–SiO_2 implies that magnetite as $FeO.Fe_2O_3$ is present in the Thingmuli series, whereas in fact the unaltered magnetite contains significant amounts (up to 50 per cent) of the ulvöspinel molecule ($2FeO.TiO_2$), and the presence of a complex solid-solution spinel phase is more than likely to invalidate any deduction about the behaviour of oxygen from the relationships of a synthetic system.

Another possible explanation of the Thingmuli trend (Fig. 5) is that the basaltic-andesites (nos. 11, 12, and 13) are at the equivalent of one of the quaternary isobaric eutectics (piercing points) in the system MgO–FeO–Fe_2O_3–SiO_2, and that the andesites (nos. 14 to 17) therefore represent mixtures of basaltic-andesite in all proportions with an acid liquid of independent origin. The evidence bearing on the independent existence of acid magma at Thingmuli and in eastern Iceland is considered below.

The trend shown in Fig. 5 is defined by analyses of rocks which are essentially non-porphyritic, and typically only a few sporadic phenocrysts of plagioclase are present. Accumulative rocks will, accordingly, be displaced from this trend, and those accumulative in calcic feldspar will be displaced below the curve, as are nos. 26, 27, and 28; the glomeroporphyritic clusters of bytownite in no. 3 (p. 438) suggest that this dyke is slightly accumulative and accordingly may not lie on the liquid line of descent. Those rocks with accumulative olivine and pyroxene will be displaced to the left of the curve, as is the picrite basalt, no. 25.

(Tables 2 to 6) recalculated water- and CO₂-free

11	12	13	14	15	16	17	20	21	22	25	26	27	28
54·65	56·60	53·22	61·76	66·87	60·77	63·46	76·06	75·54	75·00	45·89	47·56	47·97	48·52
2·68	2·43	3·16	1·27	0·74	1·15	0·84	0·38	0·23	0·24	1·70	1·32	0·61	2·30
12·77	13·74	12·96	15·36	14·94	14·02	14·48	12·74	12·65	12·77	9·24	21·33	28·04	16·72
5·32	3·96	4·08	2·35	3·67	5·46	4·70	1·28	1·73	1·72	3·68	4·30	0·67	2·68
8·15	7·66	9·60	5·84	2·66	5·23	3·88	0·69	0·72	0·50	9·38	4·44	2·76	9·16
0·23	0·25	0·28	0·19	0·12	0·29	0·19	0·02	0·04	0·05	0·21	0·12	0·07	0·18
3·65	2·95	3·39	1·76	0·68	1·10	0·71	0·02	0·02	0·02	20·47	5·92	1·74	5·06
7·42	6·55	7·50	5·04	3·65	4·88	3·99	1·04	0·91	0·95	7·34	12·42	15·66	11·65
3·45	3·74	3·57	4·37	4·22	4·62	4·72	4·83	4·44	5·12	1·45	2·19	2·29	2·97
1·18	1·31	1·07	1·62	2·22	2·05	2·75	2·90	3·68	3·58	0·17	0·24	0·11	0·41
0·50	0·81	1·17	0·44	0·23	0·43	0·28	0·04	0·04	0·05	0·31	0·16	0·08	0·35
100·00	100·00	100·00	100·00	100·00	100·00	100·00	100·00	100·00	100·00	100·00*	100·00	100·00	100·00
78·7	79·8	80·1	82·3	90·3	90·7	92·4	99·1	99·3	99·3	—	—	—	—

* Includes 0·16% Cr₂O₃.

The positions on the plot (Fig. 5) of nos. 25 and 26 indicate (by projection) that these two porphyritic lavas have groundmasses of similar composition to one another and similar to the olivine-tholeiites, nos. 1 and 2. No. 2 may itself be slightly displaced from a true variation curve, as the content of zeolites in this rock is higher than average—and this would tend to displace the plotted point above the curve.

ACID MAGMA: ITS PARENTAGE

The existence of a magma chamber at a high level in the flood-basalt succession beneath Thingmuli volcano is indicated by the extensive, superimposed hydrothermal aureole, the concentrations of dykes into a narrow swarm of great intensity, and the present of both acid and basic cone-sheets. It is to these well-defined areas of central volcanicity in eastern Iceland (Walker, 1963) that acid rocks are confined, for acid lavas are absent from the normal flood-basalt succession. It is clear that the origin of these acid rocks is in some way connected with the upward intrusion of basic magma into the volcanic succession, and although the nature of this relationship is not known, two possibilities in general exist; either the acid magma is produced by some process of fractional crystallization of a basaltic parent, or it exists in its own right, probably as a result of the fusion of sialic material.

One of the factors limiting the hypothetical derivation of an acid liquid from a basaltic parent is the volume relationship of the product to the parent. Calculations show that by extreme and thorough fractionation approximately 12 per cent of acid material may be produced from a tholeiitic basalt parent (Table 2, nos. 4, 5, and 6) and about 7 per cent from an olivine-tholeiite parent (Table 2, no. 1). Quite clearly the amount of acid material within the arbitrary geological limits of Thingmuli volcano (Table 1) is in excess of the volume of an acid differentiate produced by extreme fractionation. However, the volume of acid

magma, which is likely to be concentrated at the top of a magma column and therefore preferentially erupted (Kennedy, 1955), should be related to the volume of the magma body which may have given rise to it; it is difficult to assess this, especially as the intrusion may be floored by a gabbroic crystal accumulate (Table 6, no. 28). Perhaps the volume of acid rock exposed throughout the whole of Iceland (5–10 per cent) provides a more realistic estimate. If so, then it would seem just possible, by virtue of the volume relationship, to produce enough acid material by basaltic fractionation; the observed susceptibility of acid tuffs to fusion by basic dykes suggests that some acid material may be recycled if basic magma moves to a high level in the volcanic succession.

A recent seismic survey of the west of Iceland (Tryggvason & Bath, 1961) failed to find any layer that could be identified as sial; moreover, sialic material has yet to be found in the volcanic agglomerates of eastern Iceland (Walker, 1963).

In a previous paper (Carmichael, 1963*b*) it was suggested that basaltic magma which had been contaminated with sialic material would fractionate to produce a potassic acid liquid. Phenocrysts of two feldspars, a plagioclase and a sanidine, are characteristically present in such potassic rhyolites whereas in contrast the acid derivatives of uncontaminated tholeiitic basalt are considered to be the one-feldspar (plagioclase–anorthoclase) rhyolites, such as are found in Iceland. If, however, sialic material exists which, by fusion, produced a liquid similar in composition to the Thingmuli rhyolites, namely one relatively poor in silica and with Na_2O dominant over K_2O (Fig. 6), then the only lavas conceivably resulting from the mixing of two magmas are the andesites (icelandites) (Table 4, nos. 14 to 17), as the curves between the basaltic-andesites (Table 3, nos. 11 to 13) and the rhyolites most closely approach straight lines in any variation diagram (Figs. 3, 4, and 5). Unless differentiation has been superimposed on mixed liquids then their variation curves are essentially straight, as has been shown for the dolerite–granite Satakunta hybrids (Kahma, 1951; Nockolds & Allen, 1956); however, no petrographic evidence of such postulated mixing has been found in these Icelandic andesites. Although the evidence is not conclusive, the writer considers that the balance of that presently available indicates that the Thingmuli series are derived by a process of fractionation from a basaltic parent, the composition of which is discussed below.

PARENTAL MAGMA

The rock equivalent of a parental magma is generally considered to be non-porphyritic and thus capable of existing as a true liquid, to be widespread and voluminous in whichever volcanic province is under examination, and predominantly to give a chemical indication that its liquidus temperature was higher than all the possible derivatives; in chemical terms, this may approximate to a low content of the low-melting components of the feldspar and ferromagnesian solid-solution series. Those basalts which are essentially non-porphyritic,

and are rich in magnesia and calcium relative to iron and combined alkalis, may be taken to represent a possible parent.

The most abundant basic rock-type at Thingmuli is a tholeiite (Table 1), whereas the olivine-tholeiites are considerably less abundant; whether or not the tholeiites have all been erupted by the volcano is unknown (cf. Walker,
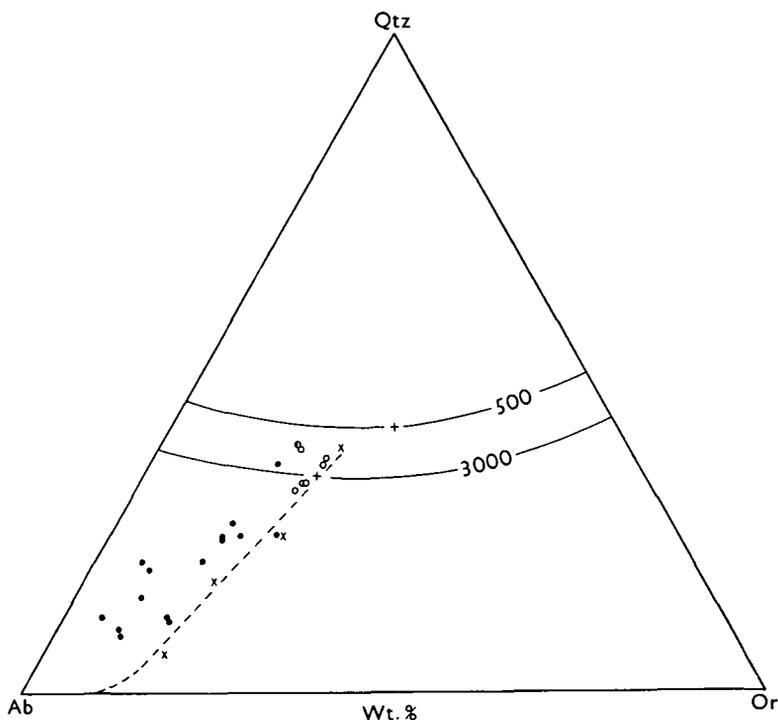

FIG. 6. The salic normative constituents of the Thingmuli series plotted in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2. The acid rocks are shown as open circles, whereas the more basic rocks are shown as solid circles; the scatter of the basic rocks is in part due to subsequent oxidation of the iron-ores, leading to higher normative quartz. The Skaergaard trend x–x–x (Wager, 1960) is also shown. The boundary curves and minima at 500 and 3000 kg/cm² water-vapour pressure are also shown (Tuttle & Bowen, 1958).

1963). However, in the first instance the relationship of the fine-grained olivine-tholeiites to the tholeiites will be examined. In chemical terms, the fine-grained and essentially non-porphyritic olivine-tholeiite no. 1 (Table 2 and Fig. 5) is likely to have a higher liquidus temperature than the other olivine-tholeiites. If the average of the recalculated dry analyses of three basic olivine-free tholeiites (nos. 4, 5, and 6; Table 9) and the recalculated analysis of no. 1 are plotted on a silica variation diagram, the composition of a possible crystal extract from the olivine-tholeiite to give the average of the three tholeiites may be calculated. The composition so obtained disregards the oxidation states of iron because of the subsequent oxidation of magnetite in some of these rocks; the derived composition is set down in Table 10 together with the norm. By assuming that

only 10 per cent of the total iron is ferric in the crystal extract, the norm indicates that this extract is composed of plagioclase (An_{78}), augite, and olivine, with a little ore. Normative hypersthene is absent in accord with its absence as a primary phase in the olivine-tholeiites. Also shown in Table 10 is a calculated composition of a crystal extract composed of 50 per cent analysed bytownite, 25 per cent analysed augite, and 25 per cent analysed olivine, all found as phenocrysts in porphyritic lavas (Table 7). With the exception of iron and magnesia the correspondence is satisfactory. The higher magnesia and lower iron in the extract calculated from the analysed phenocrysts suggests that the olivine

TABLE 10

Composition of possible crystal extract from olivine-tholeiite no. 1 (Table 9) to give average basic tholeiite (nos. 4, 5, and 6; Table 9)

	1	2		3
SiO_2	46·9	46·2	Ab	12·05
TiO_2 . . .	0·4	0·2	An	42·26
Al_2O_3 . . .	17·9	18·0	Di	20·91
Fe_2O_3 . . .	0·7	0·9	Ol	22·76
FeO	6·0	4·5	Mt	0·93
MnO . . .	0·1	0·1	Il	0·76
MgO . . .	12·8	15·4		
CaO . . .	13·8	13·5	An/Ab+An An_{78}	
Na_2O . . .	1·4	1·2		

1. Calculated crystal extract at zero K_2O in a silica variation diagram.
2. Composition computed from 50 per cent of 26 F, 25 per cent of 26 Px, and 25 per cent of 25 Ol (Table 7).
3. Norm of 1.

controlling a possible fractionation course is more iron-rich than the olivine phenocrysts in the picrite-basalt (no. 25); more iron-rich olivine phenocrysts have been found in the porphyritic basalt no. 26 (p. 445). No account has been taken of chrome spinel, which is found with olivine in the picrite-basalt, and this again would tend to decrease the magnesia and increase the iron in the computed crystal extract. It is apparent, however, that the basic olivine-free tholeiites may be derived from an olivine-tholeiite parent by the sole subtraction of its early crystallizing phases, which are also found as phenocrysts in the porphyritic accumulative rocks. Thereafter, the trend of the Thingmuli series requires that an iron-titanium oxide phase is a component of a fractionated mineral assemblage, in accord with its appearance as an early crystallizing phase.

It is unlikely that, in a central volcano similar to Thingmuli, the volume of the rock types found at the surface will closely correspond to the volume of fractionating liquids which may have given rise to them. The concentration of the differentiated liquid at the top of the magma column, and represented in the first phases of the eruption which becomes steadily more basic (Tilley, 1960; Wilcox, 1954), indicates that fractionated liquids are likely to be the dominant

eruptive type (Kennedy, 1955). It is considered, then, that the small volume of olivine-tholeiite found within the arbitrary geological limits of Thingmuli does not preclude its being a possible parent.

ACKNOWLEDGEMENTS

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EXPLANATION OF PLATES

PLATE 1

FIG. A. Olivine-tholeiite (Table 2, no. 1) with olivine, pyroxene (augite and pigeonite), plagioclase (pale grey), and iron-ores. Most of the iron-ore is magnetite (black) occurring as irregular grains in the interstices between the feldspar crystals. × 120.

FIG. B. Olivine-tholeiite (Table 2, no. 2) with olivine, pyroxene, plagioclase, and iron-ore. A feldspar-rich patch is shown with the magnetite characteristically filling up the interstices between the feldspar crystals. The blotchy appearance of the feldspar is due to zeolites and small inclusions. × 120.

FIG. C. Tholeiitic lava (Table 2, no. 8) with more equant magnetite microphenocrysts (cf. fig. A) surrounded by plagioclase and granules of pyroxene (augite and pigeonite). × 150.

FIG. D. Fine-grained lava (Table 2, no. 9) with magnetite microphenocrysts in a groundmass of plagioclase, inter-granular pyroxene, and interstitial glass. × 150.
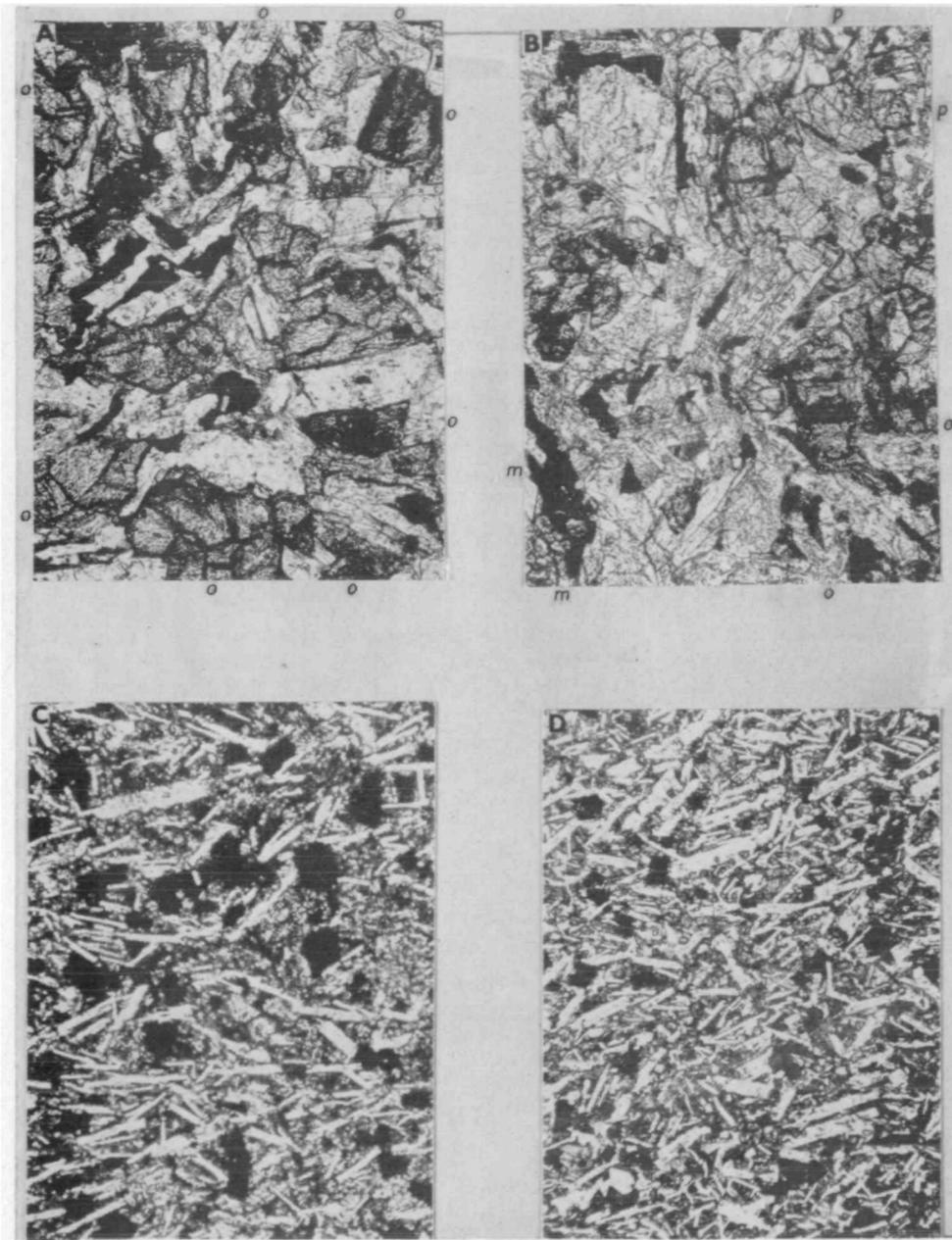
PLATE 2

FIG. A. Polished section of a tholeiitic lava (Table 2, no. 10) with microphenocrysts of magnetite (white) surrounded by pyroxene (medium grey) and plagioclase laths (dark grey). × 250.

FIG. B. Polished section of a basaltic-andesite (Table 3, no. 13) with microphenocrysts of magnetite (white) in a groundmass of pyroxene (medium grey), plagioclase (dark grey), and a second generation of small magnetite grains (white). × 400.
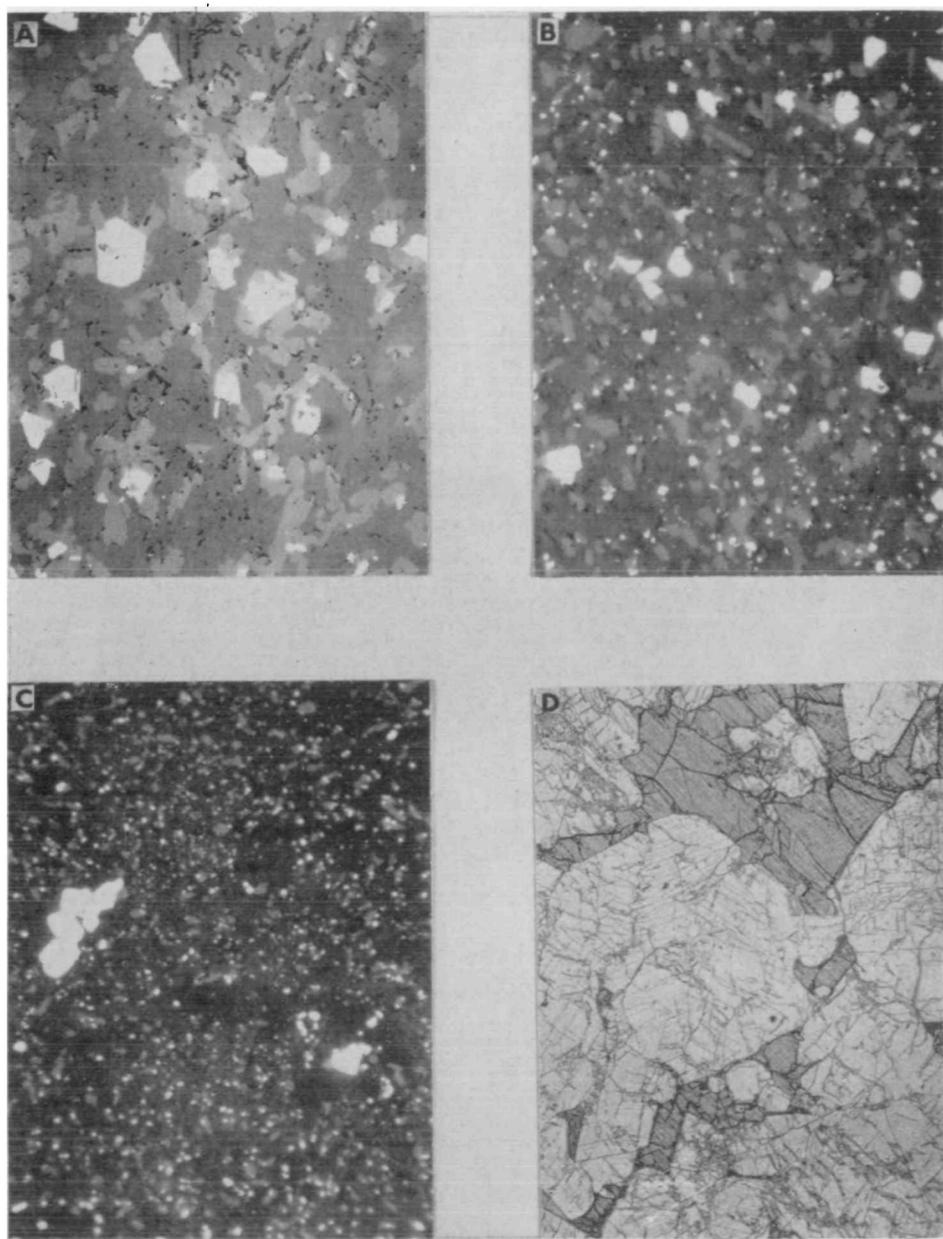
FIG. C. Polished section of an andesite (icelandite) (Table 4, no. 14) showing a cluster of magnetite microphenocrysts (white) enclosed by a groundmass of pyroxene (medium grey), plagioclase (dark grey), interstitial glass (black), and small magnetite crystals (white) frequently attached to the groundmass pyroxene. × 400.

FIG. D. Feldspathic gabbro (Table 6, no. 27) with cumulus bytownite extended by reaction with the intercumulus liquid (seen only under crossed nicols) and interstitial augite (dark grey). × 20.

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Plate 1

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Plate 2