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PHASE RELATIONS IN TRANSITIONAL AND ALKALI BASALTIC GLASSES FROM ICELAND

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Abstract

Basaltic glasses from the three alkalic areas of Iceland: Snaefellsnes Volcanic Zone, Sudurlend Volcanic Zone and Vestmannaeyjar Volcanic Area contain plagioclase, olivine, clinopyroxene, chromian spinel and titanomagnetite as phenocryst phases. The glasses are nepheline to hypersthene normative alkali basaltic with FeO/MgO ratios between 1.4-4.7. Olivine range in composition from Fo_{90} to Fo_{55}, plagioclase from An_{90} to An_{50} and clinopyroxene from $En_{45}Fs_{10}Wo_{45}$ to $En_{40}Fs_{17}Wo_{43}$. Clinopyroxene reveals systematic Ti:Al metastable crystallization trends related to the composition of the enclosing glass. Two types of phenocryst are present in most glasses showing a bimodality in size and composition. Microphenocrysts is the phase most likely to have crystallized from the enclosing glass, while macrophenocrysts may have crystallized from a liquid of a slightly less evolved composition. The glasses show complex phenocryst-glass relations which can be related to a polybaric effect. The normative glass compostions are related to divariant surfaces in the basalt tetrahedron and define the position of the four phase cotectic line. In general with increasing FeO/MgO in the glass the phenocryst assemblages vary from clinopyroxene, olivine and plagioclase along a clinopyroxene-olivine surface to olivine and plagioclase along a olivine-plagioclase surface. A deflection is seen in the normative glass compositions from clinopyroxene containing glasses to clinopyroxene free glasses. The appearance of plagioclase together with clinopyroxene and olivine can be explained in the light of experimental investigations of the effect of pressure on phase relations. The major element variation of the glasses is interpreted as representing mantle derived magma batches

of primary liquids modified to various degree by high, intermediate and low pressure crystal fractionation towards equilibrium phase relations during ascent and residence in magma chambers. The bimodality in size and composition of plagioclase and olivine phenocrysts can be related to high to intermediate pressure crystal fractionation in the melt. The relatively evolved glass compositions from Vestmannaeyjar (mugearite) and Fe-Ti basalt glasses from Sudurland are belived to be quenched high pressure (with or without volatiles) compositions only with minor lower pressure crystal fractionation.

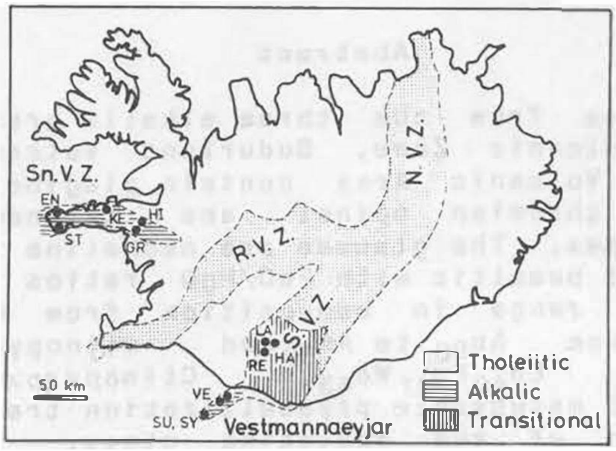

Figure 1. Sample localities (refer to Table 1) and general outline of the active volcanic zones of Iceland simplified from Palmason & Saemundsson (1974). Petrochemical division between tholeiitic, alkalic and transitional alkalic basalts based on Jakobsson (1972). The transitional zone shows a complex interrelationship between tholeiites, alkali and Fe-Ti basalts (Jakobsson 1972, 1979; Imsland 1978). The Fe-Ti basalts have been referred to as a transitional alkalic series (Jakobsson 1979). Sn.V.Z. - Snaefellsnes Volcanic Zone; R.V.Z. - Reykjanes Volcanic Zone; S.V.Z. - Sudurland Volcanic Zone.

INTRODUCTION

Alkali basalts play an important role in abyssal petrogenesis in spite of their low abundance (Gast 1968). Alkali basalts, together with tholeiitic basalts with variable enrichment in incompatible elements, appear to be confined to topographic highs, abnormal crustal thicknesses and fracture zones (e.g. Shibata et al. 1979a). The close spatial relationship between tholeiitic end alkali basalts in interplate oceanic islands has been interpreted in terms of different conditions and greater depths of alkali magma generation (e.g. McBirney & Gass 1967; Gast 1968; Frey et al. 1978), compositional variation in their mantle source (Sun & Hanson 1975) or high pressure fractionation from tholeiite (e.g. Macdonald 1968; Maaløe & Petersen 1976).

The systematic regional elemental variation and the, relative to primitive Mid-Ocean Ridge basalts, undepleted nature of most tholeiitic basalts in the active volcanic zones of Iceland and associated Mid-Ocean areas have been explained in the light of a mantle plume theory (e.g. Sigvaldason 1974). A binary mantle source has been advocated (Schilling 1973). Various degrees of heterogeneties, previous depletion events and mixing in the source region and in the oceanic crust seem, however, to be preferred based on trace element and isotope studies (e.g. O'Nions et al. 1976; Wood et al. 1979; Zindler et al. 1979). The alkali basalts have been attributed to a low degree of partial melting of a relatively undepleted mantle (O'Nions et al. 1973; O'Nions & Grönvold 1973) and may be related to deep-seated fracture zones cutting thick crustal piles (Sigurdsson 1970a). Oskarsson et al. (1982), however, proposed that alkali basalts in Iceland could have originated from partial melting of a hydrated oceanic crust as a result of a thermal impact from an active rift zone.

In the active volcanic zones of Iceland alkali basalts are restricted to three areas (Fig. 1), which in pert are separated from the main tholeiitic rift zone (Jakobsson 1972; Imsland 1978). Alkali basalts are found in the westward extending Snaefellsnes Volcanic Zone (Fig. 1). The magma production has been related to a flank position relative to the tholeiitic rift zone (Jakobsson 1972), digressive spreading of plate trapped volcanic centers from a former rift segment (Oskarsson et al. 1982), a transcurrent fault zone (Sigurdsson 1970a), or to en extinct rift zone (Johannesson 1980). The Sudurlend Volcanic Zone is, in the southern part, in general transitional to alkalic, but shows a complex relationship between tholeiitic, alkalic and Fe-Ti basalt types. The Fe-Ti basalts have been referred to as a transitional alkali series (Jakobsson 1979). The Sudurland Volcanic Zone can be viewed as a southward offshot from the main rift zone (Jakobsson 1972; Saemundsson 1978), or may be a transgressive volcanic zone where volcanism is regenerated in a cooling plate due to thermal impact from an active rift zone (Oskersson et al. 1982). The Vestmannaeyjar Volcanic Area is dominated by alkali basalts, and has been viewed as a southward extension of the Sudurland Volcanic Zone (Jakobsson 1972) and the deepest regeneration of magma in transgressive volcanism (Oskarsson et al. 1982).

Petrogenetic models for alkali basalts have mainly been based on whole rock lava geochemistry, where accumulation of phenocrysts can restrict detailed comparison with experimental phase equilibrium studies on natural basaltic systems. Detailed analyses of rapidly quenched magmas with relatively high proportions of glass will allow liquid variation and crystal-liquid relations to be studied. The present contribution reports the results of major element analyses of coexisting glass and phenocryst phases in alkali basaltic glasses from Iceland. The term glass is, following Bryan (1979), used to denote either a rock or a phase. The actual meaning should, however, be clear from the context. The aim of the study is to examine to what extent the phenocryst assemblage is in equilibrium with the enclosing glass, and to compare the glass composition and equilibrium phenocrysts with experimental phase relations in the basalt system. The ultimate aim is to see to what extent is it possible to explore petrologic constraints on petrogenesis and evolution of alkali basaltic magmas in Iceland.

PETROGRAPHY

A total of 35 samples of basaltic glasses from 17 localities were studied (Fig. 1). Localities and petrographic details of the analysed samples are given in Table 1. The majority of the samples (31) are Pleistocene glacial or subaquatic quenched glasses. Four samples from Vestmannaeyjar are tephra from the recent Surtsey and Heimaey eruptions (Thorarinsson 1965, 1968; Thorarinsson et al. 1973; Jakobsson et al. 1973).

All samples are highly vesicular and fragmental, containing different amounts of phenocrysts, brown translucent sideromelan glass, opaque tachylite glass, palagonitized glass, holocrystalline basaltic and rare silicic glass fragments. This study is concerned with the non-oxidized sideromelan glasses and their phanocrysts. The relative amounts of phenocrysts varies from trace amounts to more than 25 vol.% crystals, and no correlation between the amounts of phenocrysts and chemistry of the glass is observed. A more detailed study of the modal variation end whole rock major and trace element geochemistry is in progress.

All analyses reported were performed with a fully automatic ARL-SEMQ microprobe with on-line data reduction using a standard alpha-factor correction procedure. A total of over 2000 point analyses were compiled and used. All iron is calculated as FeO except where otherwise stated. The precision and accuracy of the microprobe analyses is given in Table 2. One standard deviation on replicate analyses are generally below 0.50 for major elements and 0.10 for minor elements.

TABLE 1 Petrological details of the samples and sample localities. The table indicates the mineral assemblages present within the glass in individual samples

Sample no.	macrophenocrysts			microphenocrysts					Locality	Comments
	pl	cpx	ol	pl	cpx	ol	chr	mt		
Snaefellsnes										
KE			x	x		x	x		Kerlingarfjall	hyaloclastite
KE			x	x		x	x		Kerlingarfjall	hyaloclastite
KE 3A			x	x		x	x		Kerlingarfjall	hyaloclastite1)
KE 3B			x	x		x	x		Kerlingarfjall	hyaloclastite1)
KE 4A			x	x		x	x		Kerlingarfjall	hyaloclastite2)
KE 4B			x	x		x	x		Kerlingarfjall	hyaloclastite2)
GR			x	x		x	x		Grettisbaeli	hyaloclastite
GR		tr	x	x		x	x		Grettisbaeli	hyaloclastite
HI	x		x	xx		x			Klifsgil, Hitarvatn	hyaloclastite
HI 2f	x		x	xx		x			Klifsgil, Hitarvatn	hyaloclastite3)
HI 2c	x		x	xx		x			Klifsgil, Hitarvatn	hyaloclastite3)
EN	x	x	xx	xx	x	x	x		Enni, Olafsvik	hyaloclastite
EN 5	x	x	xx	x	x	x	x		Enni, Olafsvik	hyaloclastite
ST 1	x	x	xx	x		x	x		Stapafell, Stapi	hyaloclastite
ST 2	x	x	x	xx	x	x	x		Stapafell, Stapi	hyaloclastite4)
Vestmannaeyjar										
VE 20	x		x	xx		x			Ellidaey	hyaloclastite4)
VE 46			xx	x		x	x		Brandur	hyaloclastite
VE 49	x		x	x		x			Hellisey	hyaloclastite
VE 76	xx		xx	xx		x	x		Saefell, Heimaey	hyaloclastite4)
VE 112				xx		x		x	Eldfell, Heimaey	tephra5)
VE 156				xx		x		x	Eldfell, Heimaey	tephra6)
SU 19	x		xx	xx		xx	x		NE Surtsey	tephra7)
SY	x		xx	x		x	x		Syrtlingur	tephra8)
Sudurland										
LA				x	x				SW of Laufafell	hyaloclastite9)
LA				x		x			SW of Laufafell	hyaloclastite
RE	x		x	x		x	tr		Reidskard	hyaloclastite
RE 2				x	x	x			Hungurfit, Reidskard	hyaloclastite
RE 4	x		x	x	x	x	tr		Kerlingafjall, Reidskard	hyaloclastite10)
HA 1	x			x	x				Hagafell, S of Laufafell	hyaloclastite
HA 2	x			x	x				Hagafell, S of Laufafell	hyaloclastite
HA 3		tr		x	x			x	Hagafell, S of Laufafell	hyaloclastite4)
HA 4A				tr					Hagafell, S of Laufafell	hyaloclastite4)11)
HA 4B	tr			x	x				Hagafell, S of Laufafell	hyaloclastite11)
HA 5	tr			x	x	x			Hagafell, S of Laufafell	hyaloclastite
HA 6	x			x	x			x	Hagafell, S of Laufafell	hyaloclastite

pl - plagioclase, cpx - clinopyroxene, ol - olivine, chr - chromian spinel, mt - titanomagnetite

x - present, xx - abundant, tr - trace.

1) KE 3A is a coarse-grained relative unconsolidated layer above a fine-grained mineral-rich layer (KE 3B).

2) KE 4A is a coarse-grained rock from the same locality as KE 4B which is a fine-grained rock.

3) HI 2c is a coarse-grained part from the same sample as HI 2f which is from a fine-grained layer.

4) Sample partly altered by palagonitization.

5) Tephra fall Jan. 23, 1973.

6) Tephra fall May 2-3, 1973.

7) Tephra fall Nov. 1963 - Jan. 1964.

8) Tephra fall June 6, 1965.

9) Xenocrysts of silicic glass are occasionally present.

10) Two types of glass and rare xenocrysts of albite.

11) HA 4A is from a light and HA 4B from a dark coloured variety. The difference is due to high concentration of cubic zeolites (analcime?) in the latter.

All samples from Vestmannaeyjar are from the collections at Museum of Natural History, Reykjavik.

TABLE 2. Precision and accuracy of microprobe analyses

	WRAB-4				VG-A99			
		2	3	4	1	2	3	4
SiO_2	47.94	47.95	0.53	0.0	50.90	50.90	0.47	0.0
TiO_2	0.69	0.64	0.07	7.2	4.06	3.79	0.15	6.7
Al_2O_3	17.75	17.91	0.24	0.9	12.97	12.26	0.15	5.5
FeO	8.58	8.46	0.19	1.4	13.18	13.28	0.25	0.6
MnO	0.12	0.17	0.03	41.7	0.19	0.20	0.03	5.3
MgO	9.95	9.83	0.08	1.2	5.18	4.82	0.05	6.9
CaO	11.52	11.59	0.11	0.6	9.38	9.41	0.10	0.3
Na_2O	2.44	2.46	0.04	0.8	2.73	2.59	0.10	5.1
K_2O	0.11	0.09	0.03	18.2	0.80	0.76	0.04	5.0
P_2O_5	0.06	0.06	0.03	0.0	0.41	0.46	0.05	12.2
Total	99.16	99.16			99.80	98.47		

1. Accepted analysis of WRAB-4 (B. Evans, pers. comm.) and VG-A99 (Jarosewich et al. 1979) basaltic glasses.
2. Average of 50 microprobe analyses.
3. One standard deviation.
4. Percentage deviation from accepted analysis.

Types of phenocrysts

The term phenocryst is used to denote all crystals found in the glass samples regardless of their origin. The origin of the various types of phenocrysts will on the other hand be crucial in order to interpret phase relations. To facilitate the discussion a distinction between various phenocryst types is used throughout the paper.

Xenocryst is as used a true non-comagmatic crystal (i.e. likely to have crystallized from a significantly different or more evolved liquid composition then that of the enclosing glass). Micro- and macrophenocrysts were preliminarily classified according to size (0.30 mm). Macrophenocrysts are likely to be comagmatic phases, but might have crystallized from a liquid of a slightly less evolved composition. Microphenocrysts are the phases that most likely crystallized from the enclosing glass. Microlites are only present in a few samples and have generally been avoided due to the possibility of metastable growth or more evolved stages of liquid compositions. Macrophenocrysts and xenocrysts are in general euhedral to subhedral, and may show resorption with embayed grain margins and slight zonation or overgrowth. Microphenocrysts tend to be compositionally homogeneous, euhedral or sometimes skeletal. All types occasionally contain inclusions of glass.

Order of nucleation

Determination of order of nucleation as recorded in the mutual intergrowth of the mineral phases is important for understanding phase equilibria and petrogenesis. Both micro- and macrophenocrysts occur in general as discrete crystals indicating homogeneous nucleation from the melt. Monomineralic clustering, particularly of olivine or clinopyroxene, and more rarely polymineralic clustering between mafic phases and plagioclase, is occasionally observed. A few examples of 'bow-tie' and radiating intergrowth between clinopyroxene or olivine and plagioclase are seen in the Sudurland glasses but rarely in the Snaefellsnes and Vestmannaeyjar glasses. These latter textures can be interpreted as resulting from simultaneous nucleation and crystal growth from a common nucleus (Bryan 1979), whereas glomerocrysts may indicate secondary nucleation upon earlier phenocryst phases (Dowty 1980). In some samples plagioclase occurs as rare minute laths only (KE, Table 1). This may indicate a late nucleation of plagioclase relative to olivine (Jakobsson 1979). Corresponding considerations can be applied to the rare occurrence of olivine in the Fe-Ti glasses from Sudurland (HA).

A close spatial relationship between chromian spinel and olivine points to a dependent nucleation of chromian spinel on olivine growth. Very often chromian spinel is found in clusters included in or closely attached to the olivine phenocrysts. Titanomagnetite occurs as primary discrete phenocrysts in the glass but also as inclusions in olivine and occasionally in plagioclase. The spinel phase is hence an early nucleating phase but with a dependent nucleation of chromian spinel on olivine growth (Thy 1982).

Phenocryst assemblages

Systematic regional changes are recorded in the phenocryst assemblages within and between the various subareas (Table 1). The small size of a thin section makes it questionable whether the macrophenocryst assemblages in Table 1 can be taken as representative for the sample, and the following discussion will for this reason be limited to the microphenocryst assemblages. Also the small number of samples restricts the representativity and further investigations may very well change the general pattern outlined below.

Sneefellsnes Volcanic Zone. Olivine strongly dominates over plagioclase in most samples from Snaefellsnes, whereas clinopyroxene is only found in a few samples (Table 1). Four samples from the western part (ST, EN; Fig. 1) contain microphenocrysts of olivine, plagioclase and clinopyroxene. Chromian spinel are present as euhedral inclusions in olivine, but are also found as discrete crystals in glass adjacent to olivine. Further eastwards (KE) clinopyroxene is not found as a microphenocryst at all and plagioclase occur only as a subordinate microphenocryst. Olivine dominates and chromian spinel is still present. Further east (HI, GR) plagioclase is an abundant phenocryst together with olivine, and chromian spinel is only present in the GR samples.

Previous petrographic and mineralogical work on the alkali basaltic rocks of the Snaefellsnes Volcanic Zone has mainly been concerned with the evolution of volcanic centers from late Tertiary, during Quaternary to Recent times (Sigurdsson 1970b; Johannesson 1975). Sigurdsson (1970b) described alkali basalts from the Setberg area showing evolution to benmorites and possibly alkali rhyolites. In the basalts of this series phenocrysts are olivine and plagioclase but clinopyroxene occurs only in a few samples. Apatite occurs as phenocryst in rocks of mugearitic composition, and rare Ca-poor pyroxenes are found in the groundmass. Johannesson (1975) described transitional and alkali basalts from the extreme eastern part of the Snaefellsnes Volcanic Zone containing phenocrysts of olivine and plagioclase. Clinopyroxene phenocrysts were noted to be rare except in hawaiitic lavas. Additional groundmass phases are Fe-Ti oxides, clinopyroxene and rare Ca-poor pyroxene. The findings in this study are in accordance with those of Sigurdsson (1970b) and Johannesson (1975).

Sudurland Volcanic Zone. The Sudurland glasses show two different types of phenocryst assemblages (Table 1) related to the composition of the glasses. A Fe-Ti basalt glass contains plagioclase, clinopyroxene and rarely olivine. Titanomagnetite is only found as a phenocryst in two of these samples. An alkali basalt glass contains plagioclase, olivine and sometimes clinopyroxene. Only trace amounts of chromian spinal are found (Table 1).

The Sudurland Volcanic Zone was investigated in detail by Jakobsson (1979), who distinguished several Recent volcanic systems with either tholeiitic or transitional alkali compositions. The latter series is referred to in this paper as Fe-Ti basalts. The microphenocryst assemblages in the Recent lavas from Sudurland were suggested by Jakobsson (1979, p.70) to have formed during a near cotectic crystallization of plagioclase, olivine and clinopyroxene at shallow depths. This contrast with the present findings (see a later section on phase relations).

Vestmannaeyjar Volcanic Area. All glasses from Vestmannaeyjar contain olivine and plagioclase as microphenocrysts and in some samples either chromian spinel or titanomagnetite (Table 1). Titanomagnetite is only found in hawaiite and mugearite products of the 1973 Heimaey eruption (Jakobsson et al. 1973; Thorarinsson et al. 1973).

The general geology and petrography of the Vestmannaeyjar has been described by Jakobsson (1968, 1979). The phenocrysts are plagioclase and olivine; groundmass minerals include titanomagnetite, clinopyroxene and apatite. Jakobsson (1968) also described residual pockets and veins with augite zoned towards aegerine-augite and interstitial nepheline (Thy & Jakobsson, unpub. anal.). The Surtsey eruption products were briefly examined by Thorarinsson et al. (1964) and Steinthorsson (1966). The Heimaey eruption products have been described in more detail by Jakobsson et al. (1973), Thorarinsson et al. (1973) and Schau & Gasparrini (1974). The Surtsey lava and tephra contain phenocrysts of olivine, plagioclase and chromian spinal; whereas the hawaiite and mugearite lavas from Heimaey contain plagioclase, olivine and titanomagnetite as phenocrysts, with clinopyroxene occuring in the groundmass only. Ca-poor pyroxenes have not been described as a phenocryst from the Vestmannaeyjar basalts.

GLASS CHEMISTRY

The glass analyses reported in this study reveal differences between the various alkalic provinces in Iceland. The results thus confirm previous conclusions based on bulk lava geochemistry (Jakobsson 1972; Imsland 1978). Representative analyses of the alkali basaltic glasses are listed in Table 3, each being an average of several point analyses. The standard deviation of repeated analyses is in general smaller, or comparable to, the analytical precision (Table 2) and is hence not further considered.

The regional variation in the chemistry is shown in Figs. 2-6. In Fig. 2 the Sudurland glasses can be distinguished from the other provinces by TiO_2 enrichment with values reaching more than 4 wt%. The most "evolved" (i.e. highest FeO/MgO ratios) Sudurland glasses have highest TiO_2 and P_2O_5 contents (Figs. 2 and 3). A K_2O versus TiO_2 diagram clearly discriminates between the three provinces (Fig. 4). The Sudurland glasses have a low K_2O/TiO_2 ratio, Snaefellsnes glasses a high K_2O/TiO_2 ratio, and Vestmannaeyjar glasses an intermediate ratio. A further division for the Sudurland glasses can be based on the TiO_2 content (Fig. 4), which allows two types to be distinguished referred to as Fe-Ti basalt and alkali basalt glasses.

TABLE 3. Averages of microprobe analyses of transitional and alkali basaltic glasses from Iceland

Sample	KE 2	KE 4B	GR 2	HI 1	HI 2c	EN 3	EN 5	ST 1	ST 2	VE 20	VE 46	VE 49	VE 76	VE 112
Anal.[1)]	18	19	20	22	31	16	13	12	12	17	13	18	13	18
SiO_2	48.27	47.89	48.76	48.78	48.96	46.87	47.33	46.51	46.07	46.20	47.35	46.94	47.13	52.13
TiO_2	2.21	1.86	1.64	1.97	1.91	2.70	2.17	2.40	2.44	3.08	2.80	3.07	2.67	2.63
Al_2O_3	14.37	15.19	15.39	14.65	14.98	14.17	14.73	15.11	15.38	15.11	15.92	14.89	15.84	14.30
FeO	9.41	9.55	10.38	11.37	11.76	10.65	10.09	9.53	10.07	13.07	12.22	13.57	12.82	12.48
MnO	0.18	0.18	0.19	0.20	0.21	0.20	0.16	0.17	0.17	0.22	0.19	0.24	0.19	0.33
MgO	6.64	7.07	6.34	5.92	6.22	6.71	6.97	7.26	6.84	5.57	5.86	5.14	5.54	2.67
CaO	12.98	13.26	11.02	10.80	10.82	12.83	13.00	13.32	12.53	10.35	10.28	10.38	10.71	6.91
Na_2O	2.22	2.69	2.96	2.57	2.52	3.01	2.88	3.04	3.00	3.75	3.60	3.95	3.87	5.22
K_2O	0.84	0.73	0.89	0.99	0.96	0.91	0.88	0.89	0.95	0.74	0.75	0.83	0.67	1.94
P_2O_5	0.32	0.28	0.28	0.32	0.32	0.52	0.47	0.41	0.43	0.36	0.38	0.42	0.33	1.10
Total	97.44	98.70	97.85	97.57	98.66	98.57	98.68	98.64	97.88	98.45	99.35	99.43	99.77	99.71
FeO/MgO	1.42	1.35	1.64	1.92	1.89	1.59	1.45	1.31	1.47	2.35	2.09	2.64	2.31	4.67
Olivine phenocryst compositions (mol.% Fo)														
Mi[2)]	85 86-83	85 86-84	83 85-82	80 81-79	80 82-79	86 87-80	86 87-82		81 87-79	77 78-76	80 81-78	78 79-76	78 83-78	60 61-58
Ma[3)]		86 87-86			82 82-79	90 90-85	89 90-85	86 88-85	87 88-84	81 84-80	84 84-80			
Plagioclase phenocryst compositions (mol.% An)														
Mi[2)]	76 78-74	73 74-70	73 76-72	74 81-71	73 77-70	74 75-67	76 77-74	75 76-71	76 77-72	67 70-65	69 71-61	71 78-66	69 72-62	55 61-51
Ma[3)]				79 81-75	78 82-74			82 83-80		70 75-67				

TABLE 3 (continued)

	VE 156	SU 19	LA 1	LA 3	RE 2	HA 1	HA 2	HA 3	HA 4B	HA 5
	25	13	17	15	16	14	16	14	16	16
SiO_2	47.99	47.21	46.64	46.66	46.73	46.59	46.55	46.75	47.53	46.43
TiO_2	3.80	2.41	4.07	2.77	3.17	3.91	4.04	3.92	4.21	3.89
Al_2O_3	13.65	15.58	13.24	14.08	14.17	12.86	12.52	12.91	12.71	12.83
FeO	14.51	11.57	14.61	11.90	12.47	14.27	14.44	14.36	14.29	14.40
MnO	0.26	0.23	0.21	0.20	0.21	0.24	0.23	0.25	0.25	0.22
MgO	3.61	5.84	5.27	6.71	6.44	5.10	5.25	5.13	4.62	5.38
CaO	8.66	10.58	10.32	12.77	13.19	10.69	10.85	10.83	9.58	10.80
Na_2O	4.78	4.04	3.26	2.63	2.60	2.88	2.78	3.22	3.48	2.76
K_2O	1.39	0.67	0.65	0.31	0.39	0.61	0.61	0.61	0.77	0.59
P_2O_5	0.76	0.36	0.56	0.29	0.34	0.48	0.47	0.57	0.76	0.43
Total	99.41	98.59	98.83	98.32	99.71	97.63	97.74	98.55	98.20	97.73
FeO/MgO	4.02	1.98	2.77	1.77	1.94	2.80	2.75	2.80	3.09	2.68
Olivine phenocryst compositions (mol.% Fo)										
Mi 2)	68 70-66	80 85-79		81 82-80	80 81-79					73 75-71
Ma 3)		86 87-79								
Plagioclase phenocryst compositions (mol.% An)										
Mi 2)	61 62-53	75 79-65	63 64-61	76 77-73	72 74-69	65 68-60	66 68-64	57 58-55	57 60-55	64 69-61
Ma 3)									66 67-66	

1) Number of analyses used in each average.

2) Mi - Average composition of microphenocrysts together with total range. Microphenocryst is defined as the composition most likely to have crystallized from the enclosing glass (see text).

3) Ma - Average composition of macrophenocrysts together with total range. See text for discussion and definition.

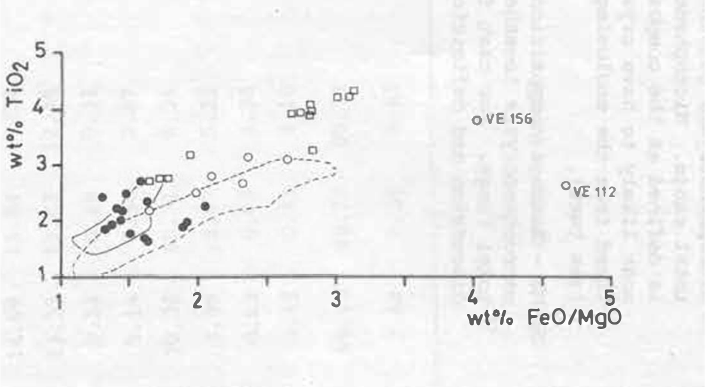

Figure 2. Variation of TiO_2 as a function of FeO/MgO. Iron as total FeO. Dashed line encloses field of tholeiitic glasses from Iceland (Mäkipää 1978) and full line alkali basaltic glasses from the compilation of Melson et al. (1977). ● Snaefellsnes; ○ Vestmannaeyjar; □ Sudurland.

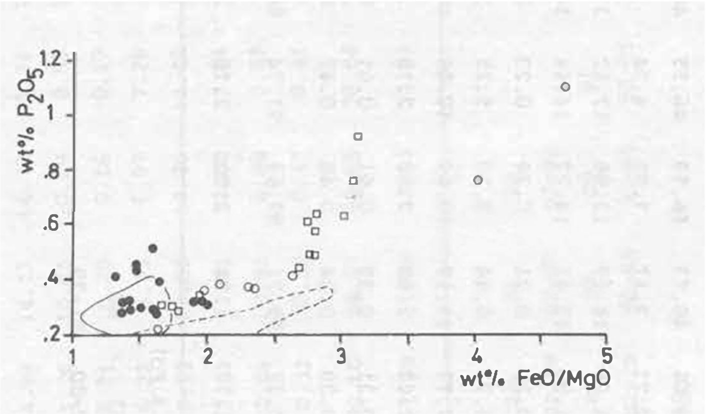

Figure 3. Variation of P_2O_5 as a function of FeO/MgO. Symbols as in Fig. 2.

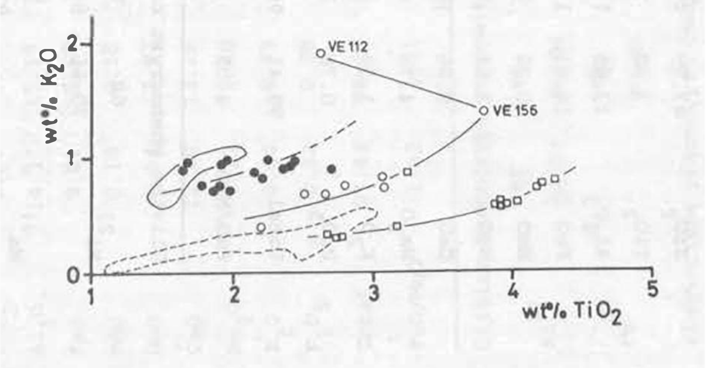

Figure 4. Variation of K_2O as a function of TiO_2. Symbols as in Fig. 2.

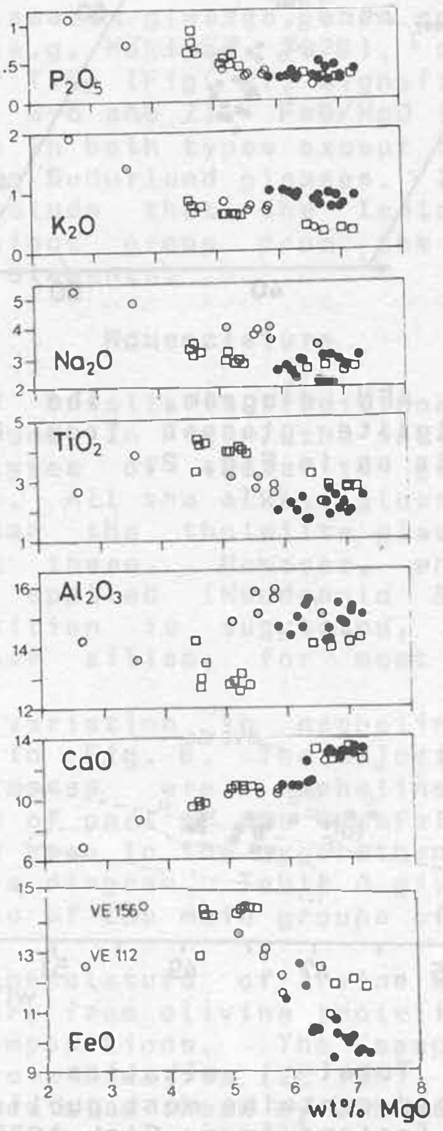

Figure 5. Selected MgO variation diagrams for alkali basaltic glasses from Iceland (Table 3). Symbols as in Fig. 2.

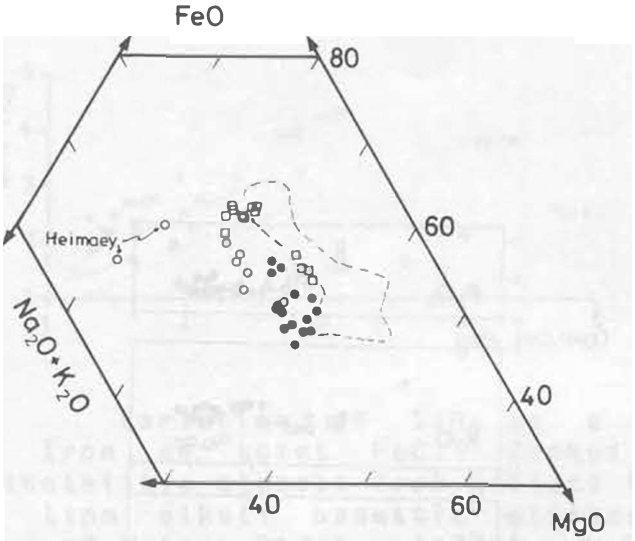

Figure 6. AFM diagram. The field occupied by Icelandic tholeiite glasses from Mäkipää (1978) is shown. Symbols as in Fig. 2.

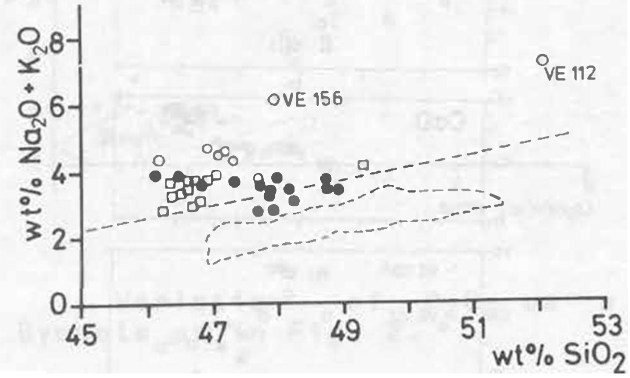

Figure 7. Total alkalies versus silica. Subalkalic field contains most published basaltic glass analyses from Iceland (e.g. Fisk 1978; Mäkipää 1978). Hawaiian dividing line from Macdonald & Katsura (1964). Symbols as in Fig. 2.

The general variation may be summarized on simple variation diagrams (Fig. 5) as parallel trends with decreasing Al_2O_3 and CaO, and increasing FeO, P_2O_5, K_2O, Na_2O and TiO_2, all with decreasing MgO. The mugearite (VE 112) glass from the 1973 Heimaey eruption, however, show departure from the general trends as expected from its more intermediate composition. Fig. 6 shows the analyses plotted in a AFM diagram.

Analyses af alkali basalt glasses are rare in the literature. The compilation of Melson et al. (1977) includes only about 20 analyses, all of which are comparable on an alkali-silica diagram to those in this study (Fig. 7). Most of these are from two localities: hypersthene normative glasses from a aseismic ridge in the Indian Ocean, and nepheline normative glasses from a fracture zone in the Atlantic Ocean. When compared to the present alkali basalt glasses it is, however, clear that the Icelandic glasses have significantly lower values for Al_2O_3 and somewhat higher CaO.

The alkali basalt glasses, when compared to Icelandic tholeiite glasses (e.g. Mäkipää 1978), show only slightly higher values for TiO_2 (Fig. 2), significantly higher P O , Na_2O and K_2O (Figs. 3-5 and 7). FeO/MgO (Fig. 6), Al_2O_3 and CaO is comparable in both types except for a somewhat lower Al_2O_3 content in the Sudurland glasses. It seems therefore reasonable to conclude that the Icelandic alkali basalt glasses form a distinct group from the tholeiite glasses based on the minor elements.

Nomenclature

The alkalinity of basalts is traditionally evaluated in an alkali-silica diagram. In Fig. 7 the analyses are compared to available analyses of tholeiite glasses from Iceland (e.g. Makipaa 1978). All the alkali glasses show a higher alkali content than the tholeiite glasses and are clearly discriminated from these. However, when the Hawaiian dividing line is applied (Macdonald & Katsura 1964) a transitional composition is suggested, as seen in lower alkalies and higher silica, for most of the Sneefellsnes glasses.

The normative variation in nepheline-diopside-olivine-silica is shown in Fig. 8. The majority of the Icelandic alkali basalt glasses are nepheline normative; the transitional nature of part of the Snaefellsnes end Sudurland Fe-Ti glasses, as seen in the hypersthene normative nature, is supported in this diagram. Table 4 gives a CIPW norm of average compositions of the main groups of glasses calculated to 100 %.

Using the nomenclature of Irvine & Baragar (1971) the analysed glasses vary from olivine tholeiite through alkali olivine basalt compositions. The samples from the 1973 Heimaey eruption are a hawaiite (VE 156) and a mugearite (VE 112), which was also shown by Jakobsson et al. (1973). As pointed out by Jakobsson (1979) the classification scheme by Irvine & Baragar (1971) gives inadequate results for the present purpose (i.e. different rock names to related rock series). The classification used in this paper in general follows the proposal by Jakobsson.

It is concluded that the Snaefellsnes and the Sudurland glasses are transitional alkali (Jakobsson 1979) or mildly alkali (Coombs 1963) basalts, whereas the Vestmannaeyjar glasses are alkali basalts. This conclusion is supported by the presence of Ca-poor pyroxene in the groundmass in Snaefellsnes alkali basalts (Sigurdsson 1970b; Johannesson 1975).

TABLE 4. Average composition and CIPW norm of the main glass types (1)

Glass type (2)	West Snaefellsnes	East Snaefellsnes	Vestmannaeyjar	Alkali Sudurland	FeTi basalt Sudurland
SiO_2	46.70	48.11	47.09	46.50	46.79
TiO_2	2.43	1.95	2.72	2.85	4.07
Al_2O_3	14.85	14.91	15.41	14.18	12.95
FeO	10.09	10.49	12.35	12.04	14.37
MnO	0.18	0.18	0.21	0.20	0.24
MgO	6.95	6.52	5.76	6.83	5.01
CaO	12.92	12.03	10.80	12.99	10.30
Na_2O	2.98	2.54	3.77	2.58	3.09
K_2O	0.91	0.86	0.67	0.34	0.67
P_2O_5	0.46	0.31	0.34	0.31	0.60
Total	98.47	97.90	99.12	98.82	98.09
FeO/MgO	1.45	1.61	2.14	1.76	2.87
Or	5.46	5.19	3.99	2.03	4.04
Ab	14.29	21.71	21.04	17.71	26.66
An	24.84	27.32	23.35	26.42	19.87
Ne	6.13	0.13	6.04	2.38	
Di	30.63	26.13	23.76	30.45	23.74
Hy					2.20
Ol	12.89	15.00	15.82	14.82	14.21
Il	4.69	3.78	5.21	5.48	7.88
Ap	1.08	0.73	0.79	0.73	1.42
Ne (3)	5.22		4.93	1.30	
Hy (3)		2.56			6.36

(1) CIPW norm calculated to 100 per cent with all iron as FeO.

(2) Average of groups of analyses (Table 1 and 3). West Snaefellsnes - samples EN and ST. East Snaefellsnes - samples KE, HI and GR. Vestmannaeyjar - samples VE 20, VE 46, VE 49, VE 76, SY and SU 19. Alkali Sudurland - samples LA 3, RE 1, RE 2 and RE 4. FeTi Sudurland - samples LA 1 and HA.

(3) Normative Ne and Hy with a fixed Fe_2O_3/FeO ratio at 0.15.

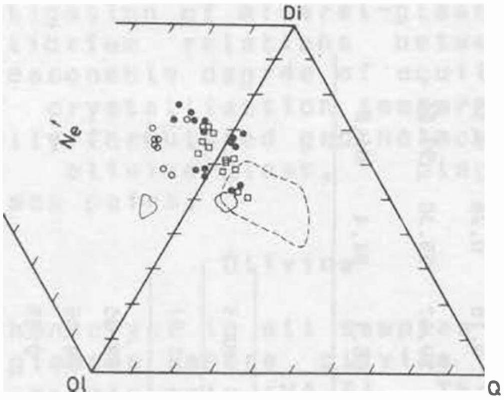

Figure 8. Normative proportions of nepheline-olivine-diopside-silica based on a cation equivalent norm with all iron as FeO and modified from Coombs (1963). Dashed area represent the compositional range of tholeiitic glasses from Iceland. Full line encloses alkali basaltic glasses from Melson et al. (1977). Symbols as in Fig. 2.

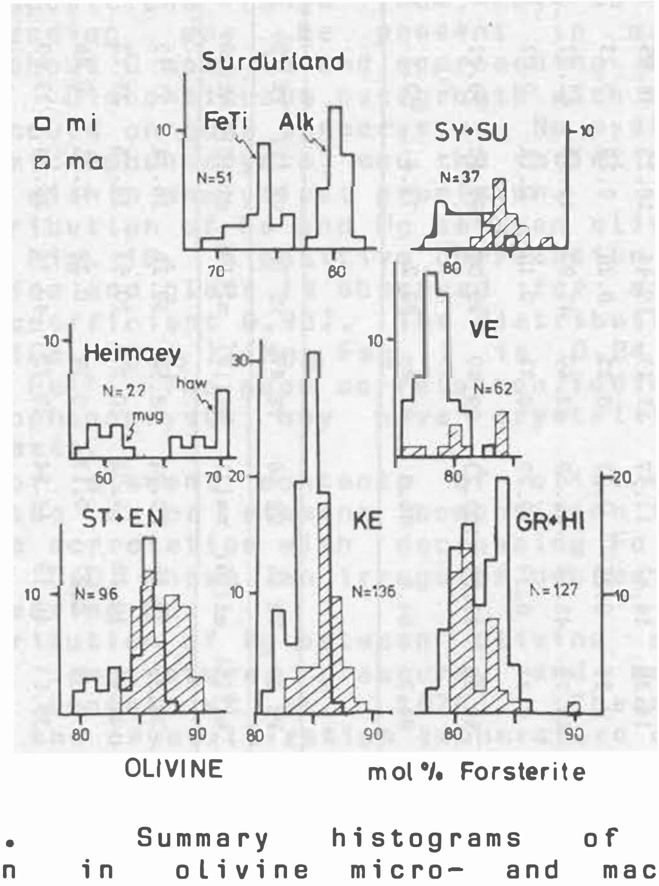

Figure 9. Summary histograms of compositional variation in olivine micro- and macrophenocrysts. Sudurland Volcanic Zone (Fe-Ti, Alk); Surtsey 1963-64 eruption (SY+SU); Heimaey 1973 eruption (VE 112 mugearite, VE 156 hawaiite); Vestmannaeyjar (other VE samples); Snaefellsnes Volcanic Zone (ST+EN, KE, GR+HI).

TABLE 5. Averages of microprobe analyses of olivine micro- and macrophenocrysts from transitional and alkali basaltic glasses from Iceland

Sample	KE 2	KE 4B	KE 4B	GR 2	HI 1	HI 2c	HI 2c	EN 3	EN 3	EN 5	EN 5	ST 1	ST 2	ST 2
Type (1)	mi(18)	mi(15)	ma(12)	mi(19)	mi(21)	mi(15)	ma(5)	mi(18)	ma(10)	mi(8)	ma(12)	ma(21)	mi(4)	ma(13)
SiO_2	40.26	39.62	39.96	40.01	38.35	38.86	39.29	39.71	40.71	39.76	40.43	39.61	39.21	40.00
FeO	14.38	14.47	13.17	15.43	18.44	18.73	16.65	13.43	9.99	13.43	10.59	13.37	17.20	12.83
MnO	0.25	0.25	0.22	0.25	0.26	0.28	0.23	0.24	0.27	0.30	0.24	0.21	0.30	0.22
MgO	44.79	45.16	46.59	43.40	41.93	41.39	42.87	45.26	47.62	45.49	48.04	46.30	42.31	46.42
CaO	0.22	0.39	0.29	0.31	0.10	0.14	0.07	0.19	0.18	0.20	0.18	0.18	0.28	0.19
Total	99.90	99.89	100.23	99.40	99.08	99.40	99.11	98.83	98.77	99.18	99.48	99.67	99.30	99.66
Fo mol.%	84.7	84.8	86.3	83.4	80.2	79.8	82.1	85.7	89.5	85.8	89.0	86.1	81.4	86.6

Sample	VE 20	VE 46	VE 46	VE 49	VE 76	VE 112	VE 156	SU 19	SU 19	LA 3	RE 2	HA 5
Type (1)	mi(15)	mi(16)	ma(3)	mi(15)	mi(10)	mi(10)	mi(12)	mi(15)	ma(5)	mi(4)	mi(8)	mi(8)
SiO_2	38.39	39.48	40.34	38.58	38.28	36.34	37.12	38.70	40.00	38.99	39.14	38.05
FeO	21.65	18.28	15.02	20.29	20.53	34.05	28.12	18.09	13.45	17.46	18.37	24.06
MnO	0.32	0.27	0.17	0.31	0.29	0.66	0.46	0.26	0.19	0.26	0.26	0.35
MgO	39.63	40.19	43.54	39.72	40.74	28.24	33.68	41.49	45.44	41.86	41.44	37.16
CaO	0.14	0.10	0.10	0.09	0.09	0.10	0.06	0.10	0.09	0.26	0.27	0.09
Total	100.13	98.32	99.17	98.99	99.93	99.39	99.44	98.64	99.17	98.83	99.48	99.71
Fo mol.%	76.5	79.7	83.8	77.7	78.0	59.6	68.1	80.3	85.8	81.0	80.1	73.4

(1) mi - microphenocryst; ma - macrophenocryst. Numbers in parentheses are the numbers of analyses used in calculation of average compositions. See text for definition of phenocryst types.

MINERAL CHEMISTRY AND MINERAL-LIQUID EQUILIBRIA

A detailed investigation of mineral-glass relations may throw light on equilibrium relations between phenocrysts and liquids. If a reasonable degree of equilibrium was attained an estimate of crystallization temperature can be inferred from experimentally formulated geothermometers. This will be attempted for olivine-glass, plagioclase-glass and clinopyroxene-glass pairs.

Olivine

Olivine is a phenocryst in ell samples (Table 1) except the Sudurland Fe-Ti glasses where olivine was found as tiny grains in one sample only (HA 5). The olivine phenocrysts often contain inclusions of a brown spinel (Table 1). Representative olivine compositions and total range are listed in Table 3. The total compositional range is Fo_{90-55} (Fig. 9). The total variation in phenocrysts of a single sample generally amounts to from 2 to 4 mol% Fo, but may reach 10 mol% Fo, xenocrysts excluded. In some samples a bimodality in olivine composition is apparent which can be related to the size of the crystals (Fig. 9). Macrophenocrysts generally have a few mol% higher Fo content than microphenocrysts (Table 3 and Fig. 9). Table 5 gives representative analyses of micro- and macrophenocrysts. Xenocryst compositions range from Fo_{77} to Fo_{64}. Slight continuous zoning may be present in macrophenocrysts amounting to about 2 mol% Fo and approaching microphenocryst compositions. Discontinuous overgrowth with microphenocryst composition occurs on some xenocrysts. No systematic zoning is found in microphenocrysts, and the variation in these are in most cases within analytical precision.

The distribution of Fe and Mg between olivine and glass is shown in Fig. 10. A positive correlation between atomic Fe/Mg in olivine and glass is observed for microphenocrysts (correlation coefficient 0.93). The distribution coefficient defined as $(Fe_{ol}\,Mg_{liq})/(Mg_{ol}\,Fe_{liq})$ is 0.24 with all iron calculated as Fe^{2+}. The good correlation indicates that the olivine microphenocrysts may have crystallized from the enclosing glasses.

The minor element contents of olivine show trends related to the major element composition (Fig. 11). MnO shows positive correlation with decreasing Fo ranging from 0.2-0.6 wt%. CaO shows an irregular decrease from 0.2-0.1 wt% with decreasing Fo.

The distribution of Mg between olivine and liquid is dependent on temperature, pressure, and melt composition (Leeman 1978; Longhi et al. 1978). Therefore only an indication of the crystallization temperature can be obtained using geothermometers based on the distribution of Mg between olivine and melt. There is an excellent agreement between the Roeder & Emslie (1970), Roeder (1974) and Leeman & Scheidegger (1977) thermometers indicating temperatures between 1188-1128 °C. The mugearite and hawaiite glasses from the 1973 Heimaey eruption indicate, as expected by their lower Mg content, significantly lower temperatures of 1093-1042 °C. The thermometer calibrated by Fisk et al. (1978) for Icelandic tholeiites tend to give temperatures that are

$20^{o}C$ lower than the above mentioned. The obtained temperature variations are in general within the experimental uncertainties (e.g. Leeman & Scheidegger 1977).

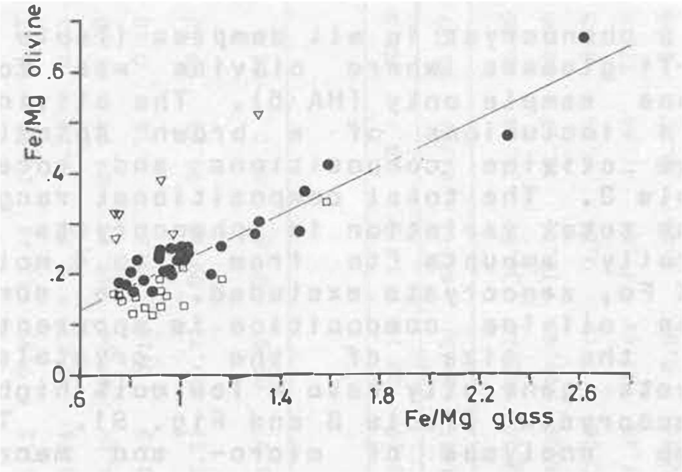

Figure 10. Covariance between atomic Fe/Mg in olivine and glass. Least-squares linear regression for microphenocrysts gives y=0.24x-0.01 (correlation coefficient 0.93).
● microphenocryst; □ macrophenocryst; ▽ xenocryst.

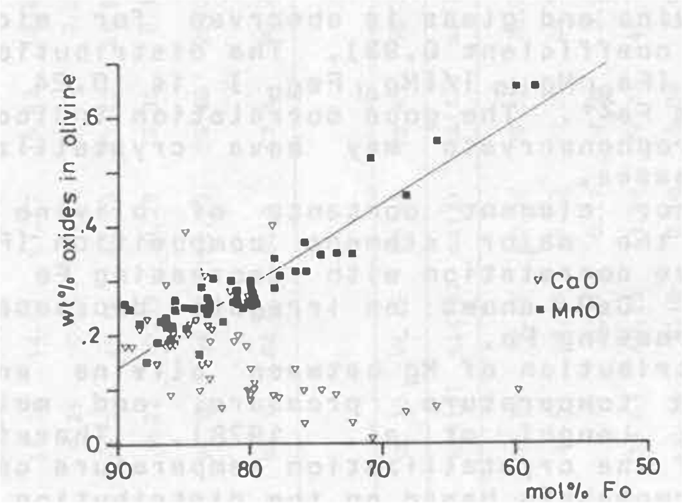

Figure 11. Minor elements in olivine versus mol% Fo. Calculation of the linear regression: MnO=1.52-0.015Fo (correlation coefficient 0.86).

TABLE 6. Averages of microprobe analyses of plagioclase micro- and macrophenocrysts from transitional and alkali basaltic glasses from Iceland

Sample	KE 2	KE 4B	GR 2	HI 1	HI 1	HI 2c	HI 2c	EN 3	EN 5	ST 1	ST 1	ST 2	VE 20	VE 46
Type (1)	mi(7)	mi(3)	mi(8)	mi(18)	ma(19)	mi(24)	ma(17)	mi(1)	mi(10)	mi(4)	ma(4)	mi(9)	mi(15)	mi(10)
SiO_2	48.63	50.24	50.24	48.95	47.52	48.92	47.72	50.47	48.83	48.26	46.93	49.65	50.76	49.80
Al_2O_3	31.90	31.07	30.41	31.88	33.03	31.54	32.33	31.16	32.35	31.12	33.38	31.53	30.50	31.20
FeO	0.68	0.60	0.86	0.79	0.59	0.80	0.62	0.78	0.74	0.73	0.54	0.67	0.70	0.71
MgO								0.19	0.22	0.21	0.11	0.24	0.15	0.11
CaO	15.63	14.88	14.74	14.34	15.33	14.42	16.04	14.90	15.30	15.18	16.51	15.39	13.88	14.24
Na_2O	2.61	2.87	2.94	2.65	2.13	2.88	2.40	2.77	2.59	2.72	1.97	2.61	3.75	3.39
K_2O	0.16	0.19	0.20	0.16	0.12	0.17	0.11	0.15	0.17	0.23	0.12	0.21	0.14	0.11
Total	99.61	99.85	99.39	98.77	98.72	98.73	99.22	100.42	100.20	98.45	99.56	100.30	99.88	99.56
An mol.%	76.1	73.3	72.6	74.2	79.3	72.7	73.2	74.2	75.7	74.5	81.7	75.6	66.6	69.4

TABLE 6 (continued)

Sample	VE 49	VE 76	VE 112	VE 156	SU 19	LA 1	LA 3	RE 2	HA 1	HA 2	HA 3	HA 4B	HA 4B	HA 6
Type (1)	mi(12)	mi(17)	mi(10)	mi(10)	mi(7)	mi(8)	mi(5)	mi(8)	mi(8)	mi(12)	mi(4)	mi(9)	ma(3)	mi(10)
SiO_2	50.16	50.05	54.39	51.91	48.25	52.73	49.84	51.33	52.11	51.97	54.25	54.26	51.50	52.32
Al_2O_3	31.55	31.23	29.13	30.05	32.46	29.06	31.45	31.54	30.89	30.73	29.12	29.82	31.66	29.88
FeO	0.58	0.66	0.57	0.70	0.72	1.10	1.04	0.90	0.94	0.98	1.05	0.98	0.83	1.14
MgO	0.14	0.13	0.08	0.10	0.13	0.17	0.24	0.21	0.15	0.17	0.15	0.15	0.15	0.17
CaO	14.16	13.62	10.84	12.13	14.85	12.35	14.76	14.46	13.01	13.00	11.41	11.33	13.04	12.53
Na_2O	3.15	3.34	4.80	4.14	2.68	3.98	2.59	3.06	3.72	3.64	4.69	4.54	3.57	3.83
K_2O	0.12	0.13	0.22	0.19	0.08	0.15	0.06	0.10	0.14	0.15	0.26	0.24	0.14	0.16
Total	99.86	99.16	100.03	99.22	99.17	99.54	99.98	101.60	100.96	100.64	100.93	101.32	100.89	100.03
An mol.%	70.8	68.7	54.8	61.1	75.0	62.6	75.6	71.9	65.3	65.8	56.5	57.1	66.3	63.8

(1) mi - microphenocryst; ma - macrophenocryst. The numbers in parentheses are the numbers of analyses in the calculation of the average compositions. See text for definition of phenocryst types.

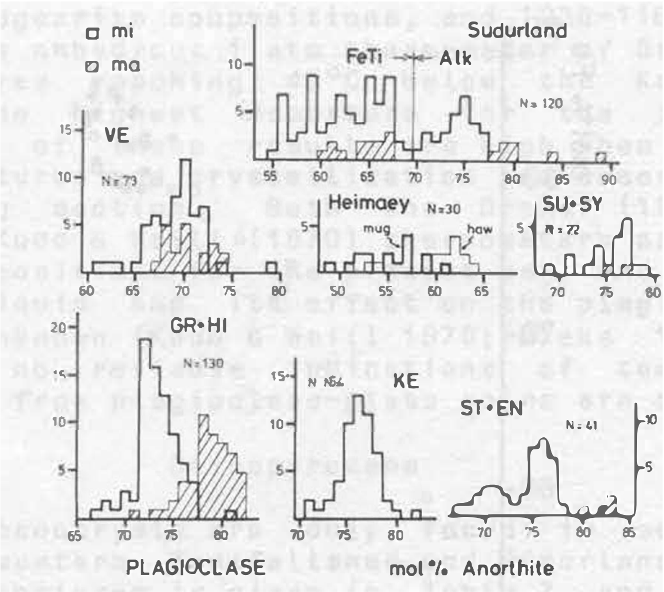

Figure 12. Summary histograms of compositional variation in plagioclase micro- and macrophenocrysts. See text to Fig. 9.

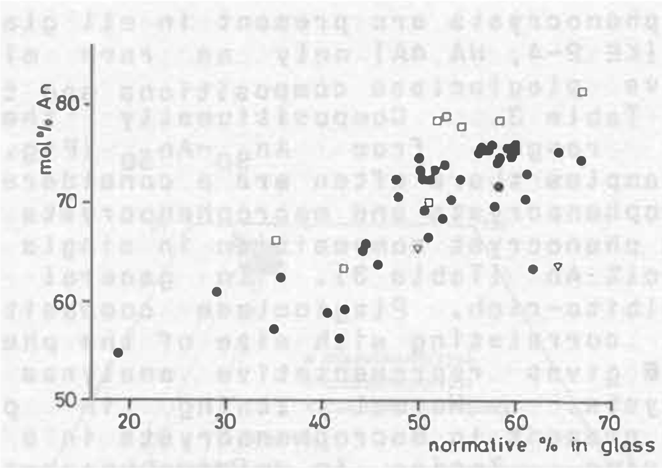

Figure 13. Covariance between mol% An in plagioclase and normative plagioclase composition of glass. Symbols as in Fig. 10.

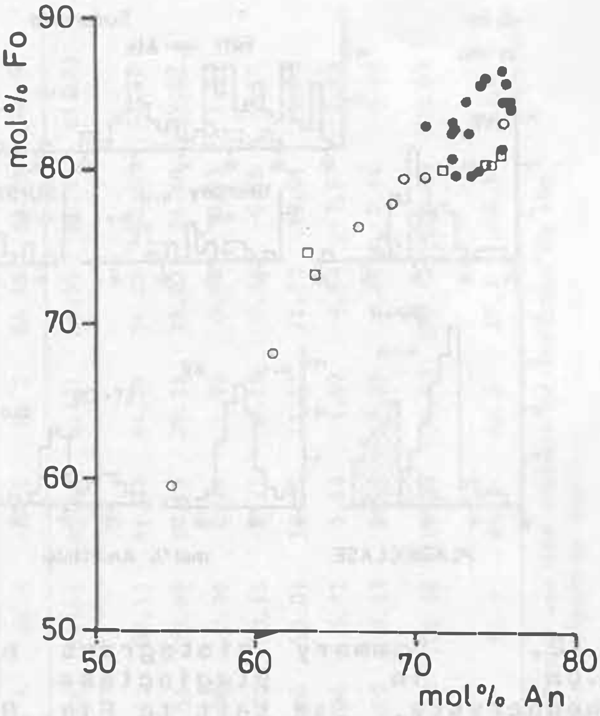

Figure 14. Covariance between mol% Fo in olivine and An in plagioclase for all microphenocryst pairs. ● Snaefellsnes; ○ Vestmannaeyjar; □ Sudurland.

Plagioclase

Plagioclase phenocrysts are present in all glasses (Table 1), but in some (KE 2-4, HA 4A) only as rare microphenocrysts. Representative plagioclase compositions and total ranges are given in Table 3. Compositionally the plagioclase phenocrysts range from An_{90}-An_{50} (Fig. 12). Within individual samples there often are a considerable difference between microphenocrysts and macrophenocrysts (Fig. 12). The variation in phenocryst composition in single samples is from 3 to 12 mol% An (Table 3). In general xenocrysts are relatively albite-rich. Plagioclase compositions sometimes are bimodal correlating with size of the phenocrysts (Table 12). Table 6 gives representative analyses of micro- and macrophenocrysts. Normal zoning in plagioclase is occasionally present in macrophenocrysts in a similar manner as for olivine. Zoning in microphenocrysts has not been detected.

Covariance between normative An in glass and mol% An in plagioclase is shown in Fig. 13. Great scatter is present but nevertheless a positive correlation between mol% An in plagioclase and normative plagioclase in glass (correlation coefficient 0.76) can be seen and points to a certain degree of equilibrium. This is also suggested from the straight line defined by coexisting olivine and plagioclase in Fig. 14.

Two geothermometers based on experimental plagioclase-melt equilibria have been applied. The anhydrous 1 atm Kudo & Weill (1970) thermometer gives temperatures in the range 1330-1258°C for most glasses, but 1226-1178°C for the hawaiite and mugearite compositions, and 1236-1185°C for Fe-Ti glasses. The anhydrous 1 atm thermometer of Drake (1976) give temperatures reaching 40°C below the Kudo & Weill results, with the highest departure for the low FeO/MgO glasses. Most of these results are high when compared to olivine temperatures and crystallization sequences discussed in a foregoing section. Both the Drake (1976) and in particular the Kudo & Weill (1970) thermometers are based on unrealistic compositions for the present use, and further the P_{H_2O} in the liquid and its effect on the plagioclase-melt equilibria is unknown (Kudo & Weill 1970; Drake 1976). For these reasons no reliable indications of temperature of crystallization from plagioclase-glass pairs are obtained.

Clinopyroxene

Clinopyroxene phenocrysts are only found in some of the glasses from western Snaefellsnes and Sudurland (Table 1). Representative analyses is given in Table 7 and the total range are shown in Fig. 15. The analyses show considerable variation in Ca:Mg:Fe (Fig. 15) as well as in Ti:Al (Fig. 16). In general the pyroxenes show a higher Ca content than typical tholeiitic pyroxenes.

Two groups can be identified and correlated with the composition of the glasses (Table 7, Figs. 15 and 18). A low-Fs group (Fs_{9-15}) is present in the Snaefellsnes and Sudurland alkali glasses (Table 7, anal. EN, ST, RE), whereas a high-Fs group (Fs_{15-17}) is present in the Fe-Ti glasses from Sudurland (Table 7, anal. LA, HA). The latter group is identified in thin section by a weak green colour.

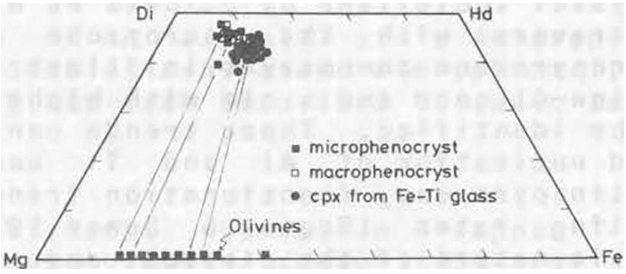

Figure 15. Compositional variation of clinopyroxene and averages of olivine microphenocryst analyses. Examples of tie-lines between coexisting clinopyroxene and olivine are shown.

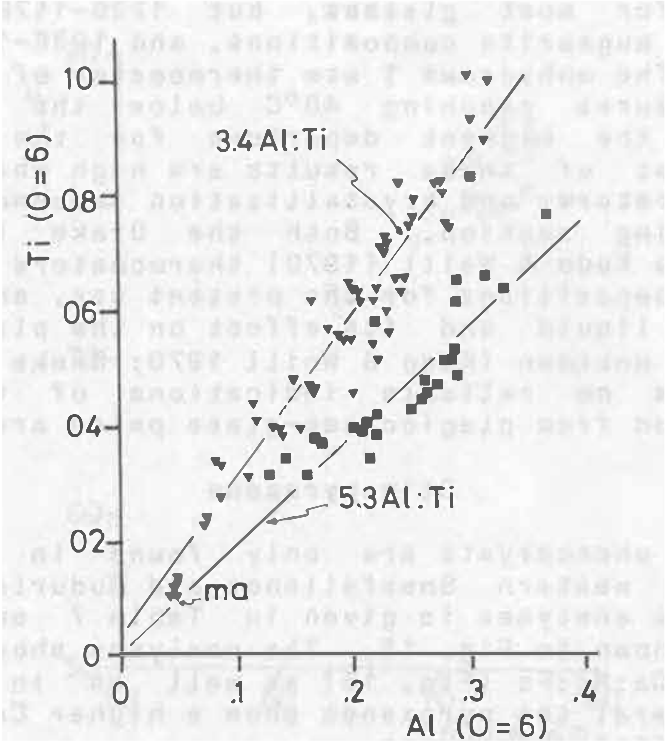

Figure 16. Ti versus Al in clinopyroxene from Sudurland Volcanic Zone calculated to 6 oygens. ■ Sudurland alkali basalt glasses; ▼ Sudurland Fe-Ti basalt glasses; ma - macrophenocryst.

The Ti:Al relations suggest metastable crystallization of the pyroxenes. Particularly the clinopyroxenes from the Sudurland glasses show systematic Ti:Al trends (1:3.4 and 1:5.3; Fig. 16). These trends are broadly similar (1:4) to those in the controlled cooling rate experiments by Walker et al. (1976) and Grove & Bence (1977), and have been observed in natural abyssal tholeiites by Shibata et al. (1979b). An example of a traverse with the microprobe across a zoned euhedral clinopyroxene phenocryst is illustrated in Fig. 17. A low-Ti and low-Al core and a rim with higher but variable values can be identified. These trends can be explained by either delayed nucleation of Al and Ti containing phases relative to clinopyroxene, fractionation trends in the liquid or fast cooling rates (Grove & Bence 1977). Due to the relative aphyric nature of the glasses and the low-Al and low-Ti content of rare macrophenocrysts (Fig. 16) and microphenocryst cores (Fig. 17) a fast cooling rate may be preferred. However, the effect of increasing pressure may be to decrease Al or the Al^4:Al^6 ratio (Wass 1979) consistent with the present data (Table 7, anal. HA 3). The systematic trend in tetrahedral coordinated Al and Ti for the Sudurland glasses may suggest a combined Ca-tschermak and Ca-Ti-tschermak substitution in the clinopyroxene solid solution series. The departures does not, however, account for such a simple 4Al:Ti substitution (Fig. 16). Systematic difference in Ti:Al substitution between the two glass types from the Sudurland Volcanic Zone are likely to be related to differences in the composition of the enclosing glass phase (e.g. Ti and Al). The Al:Ti substitution in clinopyroxene from the Sneefellsnes alkali glasses shows no clear trend.

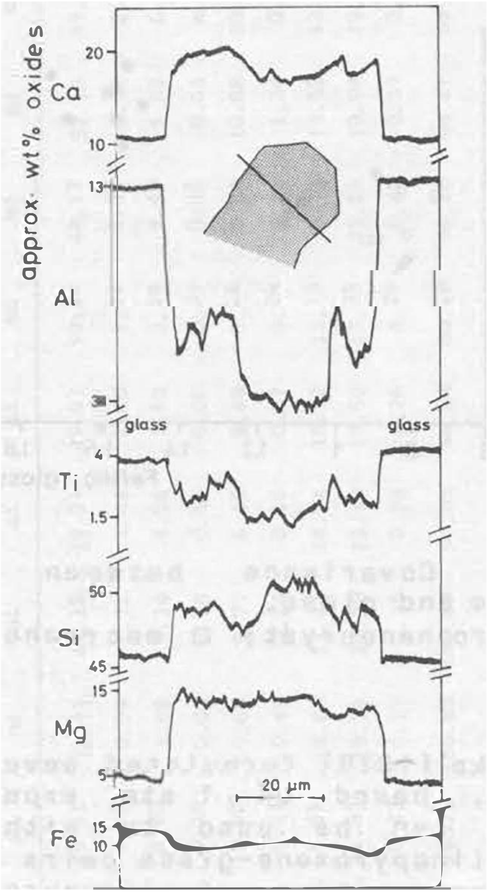

Figure 17. An example of a microprobe traverse across a zoned clinopyroxene microphenocryst from a Fe-Ti basalt glass from Sudurland Volcanic Zone.

The compositional variation impose problems in determining an unambiguous composition for the individual samples in the evaluation of clinopyroxene-glass equilibria. Average values in atomic Fe/Mg ratios for the clinopyroxene analyses are shown in Fig. 18. The two compositional groups can despite the great scatter be identified and related to the composition of the glass showing a positive correlation between Fe/Mg for clinopyroxene and glass.

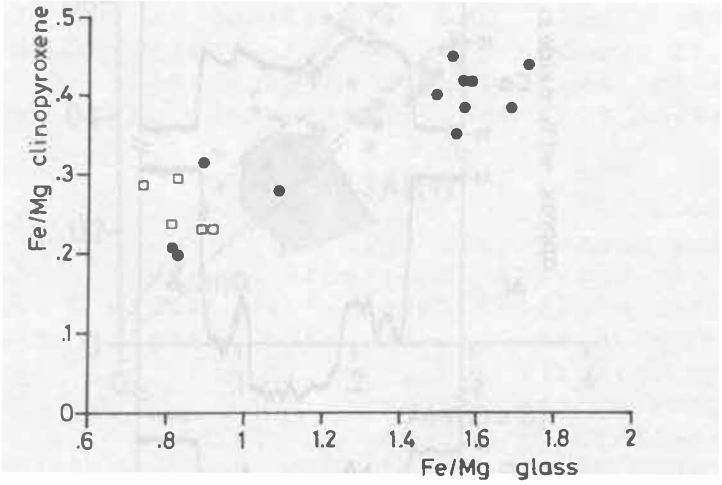

Figure 18. Covariance between atomic Fe/Mg in clinopyroxene and glass.
● microphenocryst; ☐ macrophenocryst.

Nielsen & Drake (1979) formulated several clinopyroxene-melt thermometers, based on 1 atm experiments from the literature, which can be used to either calculate the temperature from clinopyroxene-glass pairs or to predict the temperature and composition of clinopyroxene crystallizing from a melt of known composition. Only the last possibility has been used in this study. It is encouraging that the model of Nielsen & Drake is able to predict (Fs$_{9-16}$ and Fs$_{16-18}$) the composition of the two types of clinopyroxenes found in this study (i.e. Fs$_{9-15}$ and Fs$_{15-17}$), and also give temperatures, assuming all iron as FeO, equal to or slightly below those obtained from olivine-glass pairs, thus confirming that the clinopyroxene microphenocrysts may have crystallized from a melt represented by the composition of the enclosing glass. This conclusion do, however, not relate to the Al:Ti relations in the clinopyroxenes.

TABLE 7. Representative analyses of micro- and macrophenocryst clinopyroxenes from transitional and alkali basalt glasses from Iceland

Sample	EN 3	EN 5	ST 1	ST 2	LA 1	LA 1	RE 2	HA 1	HA 2	HA 3	HA 3	HA 4B	HA 5
Type (1)	mi	ma	ma	mi	mi	mi	mi	mi	mi	mi	ma	mi	mi
SiO_2	49.09	46.87	47.72	49.81	52.41	48.35	49.27	49.97	50.49	48.17	52.18	47.03	46.29
TiO_2	2.09	1.96	2.04	1.29	0.99	2.32	1.44	1.40	1.35	2.30	0.42	2.87	2.65
Al_2O_3	7.97	6.44	5.69	4.90	1.88	5.34	4.94	3.50	3.14	4.40	1.03	6.18	5.59
Cr_2O_3	0.04	0.83	n.d.	0.39	0.03	0.08	0.55	0.06	0.03	0.02	0.03	n.d.	0.07
FeO	7.63	6.13	8.53	5.60	10.65	9.77	6.35	9.49	9.25	9.88	10.68	10.10	10.21
MnO	0.07	0.43	0.22	0.11	0.45	0.24	0.16	0.17	0.24	0.25	1.24	0.26	0.23
MgO	13.39	14.16	13.68	15.55	14.88	13.44	14.74	15.52	15.18	13.73	13.52	12.44	13.28
CaO	18.98	22.35	21.00	21.83	19.26	20.20	22.19	19.52	19.35	20.25	19.94	19.74	19.56
Na_2O	0.54	0.27	0.49	0.23	0.27	0.35	0.28	0.26	0.25	0.40	0.57	0.63	0.36
Total	99.80	99.44	99.37	99.71	100.82	100.09	99.92	99.89	99.28	99.40	99.61	99.25	98.24
$Al_4:Al_6$	1.22	5.48	3.96	2.82	2.57	3.92	3.70	6.70	3.48	9.89	1.88	3.68	7.72
En	42.8	42.1	40.8	45.2	42.9	40.2	43.0	44.5	44.3	40.6	39.9	38.5	40.2
Fs	13.7	10.2	14.3	9.1	17.2	16.4	10.4	15.3	15.1	16.4	17.7	17.5	17.3
Wo	43.6	47.7	45.0	45.6	39.9	43.4	46.6	40.2	40.6	43.0	42.3	43.9	42.5

(1) mi - microphenocryst; ma - macrophenocryst; n.d. - not detected.

Spinel minerals

Spinal minerals are present in some of the glasses (Table 1) either as chromian spinal or titanomagnetite. Chromian spinal occur in variable amounts as clusters of euhedral to rounded octahedra, generally below 100 µm in diameter, included in or closely attached to olivine phenocrysts. Occasional discrete crystals in the glass reach 500 µm in diameter. Titanomagnetite is found as inclusions in the other phenocryst phases but occurs primarily as discrete phenocrysts in the glass.

The occurrence of the two spinal minerals can be broadly correlated with the FeO/MgO ratios in the glasses. Chromian spinel occurs in the Snaefellsnes glasses with low values (1.70) and is missing in the glasses with higher values. For the Vestmannaeyjar glasses chromian spinal is found below about 2.30 and titanomagnetite above 4.00. The occurrence of spinal minerals in the Sudurland glasses is somewhat irregular (Table 1). However, chromian spinal is present in two glasses with FeO/MgO values below 1.70 (alkali) and titanomagnetite is present in two glasses above 2.80 (Fe-Ti).

The chromian spinel is mostly of the titaniferous magnesiochromite type described by Sigurdsson & Schilling (1976) but covers the same range in Cr/(Cr+Al) as chromian spinels in abyssal basalts (Sigurdsson & Schilling 1976; Sigurdsson 1977). A high Ti content (above c. 0.5 wt% TiO_2) seem to be a common feature for Icelandic chromian spinels (Steinthorsson 1972; Fisk 1978). Further information and discussion of the spinal minerals is given in Thy (1982).

Origin of phenocryst types

Micro- and macrophenocrysts were classified on size (0.30 mm measured along the longest axis). It is apparent from Figs. 9 and 12 that in many samples, or groups of samples, the total compositional ranges of the two groups nearly overlap and extend towards the composition of the microlites for both olivine (Fig. 9) and plagioclase (Fig. 12). A bimodality, however, clearly exist for many samples, with a high temperature compositional bias towards the macrophenocrysts. One clear exception is olivine in the GR and HI samples where a size bimodality is observed unrelated to the composition of the phenocryst (Fig. 9). On the other hand plagioclase in the same samples shows the most clear compositional bimodality found (Fig. 12). Jakobsson (1979) in his study of phenocryst assemblages in Recent lavas from the Sudurland Volcanic Zone concluded that macrophenocrysts did have an average diameter above and microphenocrysts below 0.70 mm. This is a far higher value than that used in this study, and some of the compositional overlap may be due to this. For this reason the low temperature extension in macrophenocryst compositions may in part be an artifact of the analytic procedure. It will, nevertheless, be proposed that the compositional spread from macro- to microphenocryst reflects compositional changes in the melt prior to quenching. Unfortunately Jakobsson did not analyse his phenocryst assemblages. An interpretation of the various phenocryst types is summarized below.

Microphenocrysts: The microphenocrysts are interpreted as approaching equilibrium with the enclosing glass. This is supported by the compositional homogeneity of both olivine and plagioclase, and by considerations of mineral-glass relations. Significant Al-Ti zoning in clinopyroxene has, however, been observed, which may reflect either metastable growth or decreasing pressure during ascent of the magma.

Macrophenocrysts: The macrophenocrysts may show variable degree of disequilibrium with the enclosing glass as suggested by chemistry and resorption textures. Occasional continuous marginal zoning towards slightly lower temperature mineral compositions, approaching those of the microphenocryst, points to only a slight disequilibrium for part of the macrophenocrysts. The macrophenocryst assemblages are consequently interpreted as being comagmatic, originating from a slightly less evolved liquid composition. However, in some samples the macrophenocrysts may have crystallized from the enclosing glass.

Fisk (1978) observed in samples from the Reykjanes Ridge and peninsula two compositional types of plagioclase. A high anorthite plagioclase was related to an early stage of plagioclase crystallization, while a low anorthite plagioclase was considered to be an equilibrium phase. Jakobsson (1979) reached a similar conclusion in his study of the size distribution of phenocryst assemblages in Recent lavas from Sudurland, and inferred that the macrophenocrysts had crystallized in a deep-seated position during slow cooling and either been partially lost, or accumulated during transfer to higher levels; thus high amounts of macrophenocrysts may be related to a short time of ascent and consequently poor removal of phenocrysts from the liquid (Jakobsson 1979).

Xenocrysts: The xenocrysts are for chemical reasons clearly out of equilibrium with the enclosing glass. This is also indicated by occasional discontinuous rims of compositions comparable to that of the microphenocrysts. The xenocrysts are interpreted as being derived from plutonic rocks of basic, intermediate or silicic compositions. Partly fused silicic xenoliths (Sigurdsson 1968; Jakobsson 1979) and gabbro nodules (Larsen 1979; Jakobsson 1979) offer an explanation for some mineral and glass xenocrysts. Furthermore, mechanical mixing during eruption with basic to silicic glass is seen (RE 4 contains albite xenocrysts and two types of glass fragments and associated phenocryst assemblages; LA 1 contains rare silicic glass fragments).

PHASE RELATIONS

The composition of the glasses can be recalculated in terms of their normative minerals and projected into experimentally established phase diagrams modelling basaltic compositions. Similarities with, or differences from, expected low pressure phase relations may indicate conditions of crystallization. It will be shown that major discrepancies exist between the observed and the expected phenocryst assemblages.

Phase boundaries

Bryan and co-workers in a sequence of papers (Bryan et al. 1976; Bryan 1979; Thompson et al. 1980) plotted glass compositions in a plagioclase-total pyroxene-olivine ternary. A strong linear trend is shown by many glass series in this diagram with nearly constant plagioclase proportions (Fig. 19), and has been suggested to represent an olivine-plagioclase divariant surface, analogous to the cotectic in the An-Di-Fo system determined by Osborn & Tait (1952). The alkali basalt glasses in this study contrast markedly from tholeiites, revealing two possible trends (Fig. 19). One of these may be related to a plagioclase-olivine, the other to a clinopyroxene-olivine divariant surface. The junction between these two may define a univariant line or invariant point when compared to the analogous synthetic system as determined at 1 atm by Osborn & Tait (1952) and at pressures up to 20 kb by Presnall et al. (1978). This ternary system has also been used to classify abyssal tholeiites as either clinopyroxene, olivine, or plagioclase tholeiites depending on the first phase to crystallize (e.g. Miyashiro et al. 1969; Shido et al. 1971; Bougault & Hekinian 1974), and related to experimentally determined phase relations (Shibata 1976). The grouping together of clinopyroxene and orthopyroxene, however, makes it difficult to compare with phase equilibria in an experimental basalt system. For this reason more appropriate projections will be used.

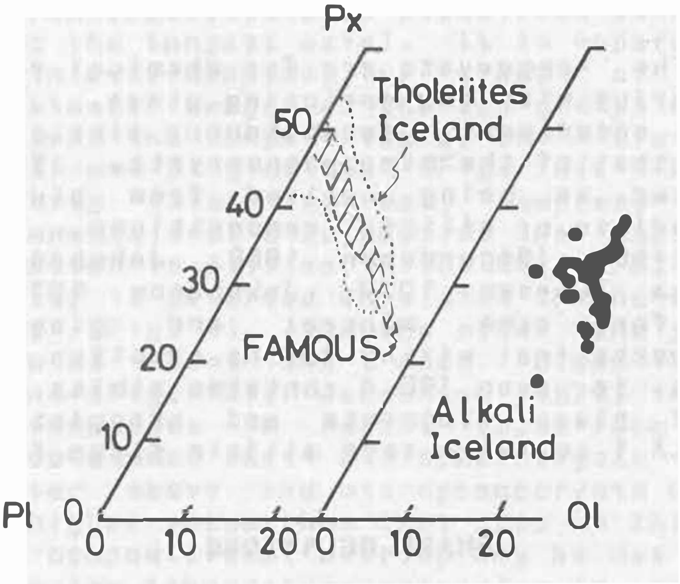

Figure 19. Normative glass composition in the ternary plagioclese(An+Ab)-pyroxene(opx+cpx)-olivine(Fo+Fa). FAMOUS glasses from Bryan (1979) and Icelandic tholeiitic glasses (e.g. Mäkipää 1978) are shown for comparison. A cation equivalent norm with all iron as FeO has been used.

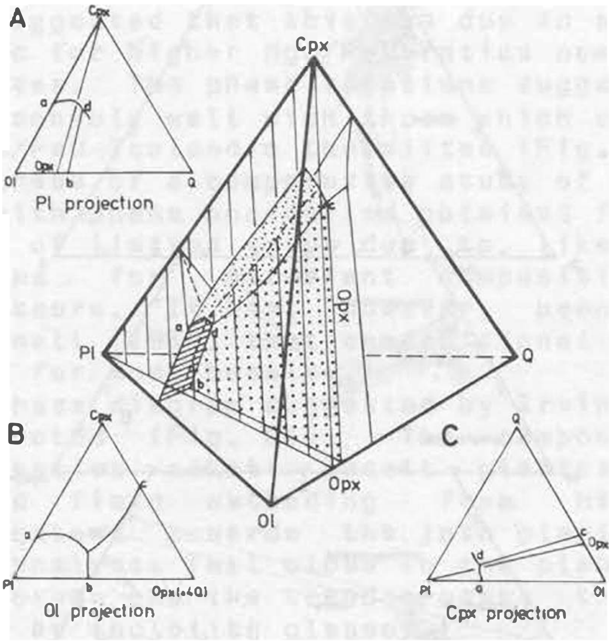

Figure 20. Model of phase relations in the normative clinopyroxena(cpx)-olivine(ol)-plagioclase(pl)-quartz(q) quarternary for subalkalic magmas at 1 atm anhydrous conditions simplified from Irvine (1979). Phase boundaries are based on simple systems and drawn from melting relations of natural basalts. The three projections used in Fig. 21 are given with relevant cotectic relations.

A. Projection from the pl apex onto the plane ol-cpx-q.

B. Projection from the ol apex onto the plane pl-cpx-opx. Quartz normative compositions have been projected using the equation q+3ol=4opx, giving the coordinates cpx:pl:(opx+4q).

C. Projection from the cpx apex onto the plane pl-ol-q.

A cation norm with all iron as FeO has been used. For further information of projection methods and norm conventions the original work by Irvine (1970, 1979) should be consulted.

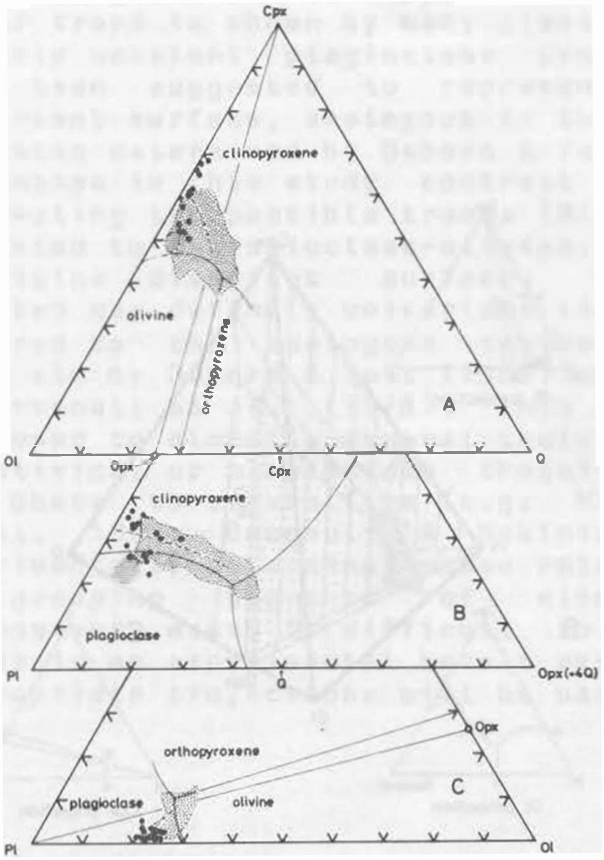

Figure 21. The projections from Fig. 20 in the plagioclase-clinopyroxene-olivine-quartz quarternary and inferred phase relations (light solid lines). Dotted area represent tholeiitic glasses from Iceland and FAMOUS. Horizontal ruled area is approximately 10 hypersthene normative alkali basaltic glasses from the compilation by Melson et al. (1977). Points are hypersthene normative alkali basaltic glasses in this study (Table 3). Broken line are the suggested phase boundaries for abyssal glasses from Irvine (1979). See text to Fig. 20 and Irvine (1970, 1979) for further information.

Experimental melting relations on natural basaltic rocks can be projected into the normative plagioclase-olivine-clinopyroxene-quartz quarternary system, which together with a general knowledge of phase relations in simplified synthetic systems, can be used to model phase relations in natural basaltic systems. This was done by Cox & Bell (1972) for a projection onto the plane plagioclase-olivine-clinopyroxene and by Irvine (1970, 1979) for several projections as shown in Fig. 20. Both these attempts are primarily based on anhydrous 1 atm melting experiments by

Tilley and co-workers at the Carnegie Institution, Washington, covering a wide compositional variation including alkali basalts but, however, centered on alkali enriched Kilauean tholeiites.

The phase diagrams constructed by Irvine (1970, 1979) are used in Fig. 21. Tholeiitic glasses extend from quartz normative compositions around the five phase invariant point ("d" in Fig. 20) into the clinopyroxene field departing from the inferred phase boundaries showing lower olivine content relative to clinopyroxene and plagioclase (Fig. 21). A similar departure was found by Irvine (1979) for abyssal glasses. He suggested that this was due to an expansion of the olivine field for higher MgO/FeO ratios compared to the Kilauean tholeiites. The phase relations suggested by Irvine (1979) agree reasonably well with those which can be inferred from the low MgO/FeO Icelandic tholeiites (Fig. 21).

The usefulness of a comparative study of natural alkali basalt glasses with phase boundaries obtained from tholeiites may obviously be of limited value due to likely shifts in phase boundaries for different compositions, volatile contents and pressure. It has, however, been proposed by O'Donnell & Presnall (1980) that compositional effects are of minor importance for most basalts.

From the phase diagram suggested by Irvine (1979) a few points can be noted (Fig. 21). The composition of the hypersthene normative alkali basalt glasses fall into a narrow elongated field extending from high normative clinopyroxene content towards the join plagioclase-olivine (Fig. 21). All analyses fell close to the plane plagioclase-olivine-clinopyroxene and the trend crosses the four phase cotectic defined by tholeiite glasses.

If nepheline normative compositions are considered in a projection in the nepheline-clinopyroxene-plagioclase-olivine quarternary onto the plane nepheline-clinopyroxene-plagioclase (Fig. 22) a broad field can be inferred extending from the nepheline into the hypersthene volume (Fig. 21). So far it can be concluded that tholeiite glasses from Iceland are related to or situated not far from a four phase cotectic line, but alkali basalt glasses seem not to be related in a simple way to cotectic crystallization.

The clustering of all the alkali glasses near to the plane clinopyroxene-plagioclase-olivine makes useful a projection onto this plane from either the quartz or the nepheline apex, as shown in Fig. 23. All glasses fall not far from the simplified plagioclese-olivine cotectic line in the experiments of Osborn & Tait (1952). If the Icelandic alkali glasses are corrected with the Fe_2O_3/FeO ratio used by Presnall et al. (1979) as a mean for abyssal basalts (0.174) the data points move towards the plagioclase-clinopyroxene join and the 1 atm phase relations for natural basalt compositions drawn by Cox & Bell (1972) (Fig. 23). The data can be interpreted to delineate the plagioclase-olivine and clinopyroxene-olivine phase boundaries. The intersection between these two trends may define a piercing cotectic line in this projection. The Icelandic end FAMOUS tholeiitic glasses closely overlap, and with the same Fe_2O_3/FeO correction, cluster immediately below this point.

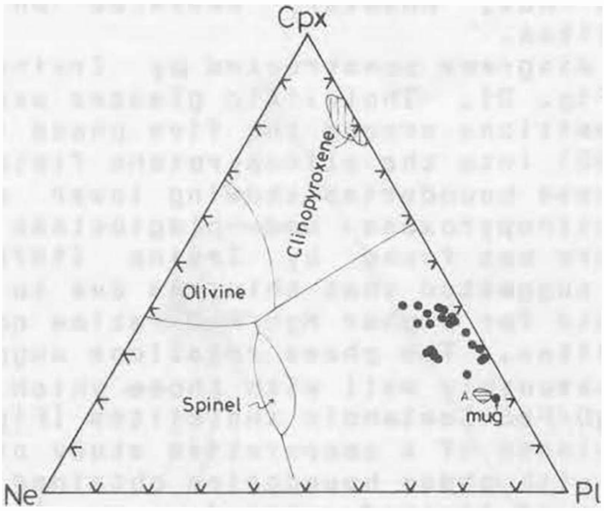

Figure 22. Projection onto the plane clinopyroxene-nepheline-plagioclase in the system clinopyroxene-olivine-plagioclase-nepheline for all nepheline normative glasses (Table 3). Horizontal ruled area ('A') is nepheline normative basaltic glasses from Melson et al. (1977). Vertical ruled area encloses clinopyroxene analyses calculated using the same norm conventions as for the glass analyses. The phase boundaries shown are simplified relations from Schairer et al. (1968).

Phenocryats and phase boundaries

In order to compare the expected phenocryst assemblages with those observed (Table 1), and to avoid the effect of grouping together obviously unrelated glass series, the three provinces are separated and symbols given for phenocryst assemblages in Fig. 24.

The Snaefellsnes glasses are interpreted to follow a olivine-clinopyroxene divariant surface containing plagioclase-olivine-clinopyroxene microphenocrysts, but fall on the olivine-plagioclase divariant surface for glasses containing olivine-plagioclase microphenocrysts (Fig. 24). The variation from high to low normative clinopyroxene generally correlates with increasing FeO/MgO ratio in the glass, and decreasing Fo content of olivine. The observed micrcphenocryst assemblages agree with what is expected, except for the appearance of plagioclase on the olivine-clinopyroxene boundary.

The Vestmannaeyjar glasses all have plagioclase-olivine as microphenocrysts and fall in a similar region as the corresponding Snaefellsnes glasses (Fig. 24). The normative compositions and FeO/MgO ratios of the glasses, together with the Fo content of olivine, closes the gap observed in the Sneefellsnes glasses. Only the 1973 Heimaey mugearite (VE 112) departs significantly by falling well within the plagioclase volume.

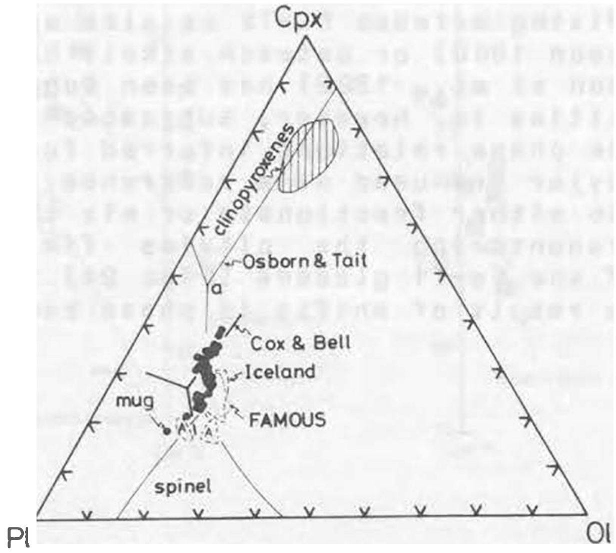

Figure 23. Projection onto the normative plane plagioclase-clinopyroxene-olivine from either the quartz or the nepheline apexes. Simplified 1 atm anhydrous phase relations from Osborn & Tait (1952). The point 'a' is the piercing plagioclase-olivine-clinopyroxene-melt univariant line (also 'a' in Fig. 20). The fields of tholeiitic glasses from Iceland and FAMOUS are outlined. The fields labelled 'A' are alkalic basalts taken from the compilation by Melson et al. (1977). The alkali basaltic glasses in this study (Table 3) are shown as points. Clinopyroxene analyses are indicated calculated with the same norm conventions as for the glass analyses. The experimental phase relations in 1 atm anhydrous natural basaltic systems from Cox & Bell (1972) is shown.

The Sudurland glasses show a complex compositional and microphenocryst variability, which is difficult to interpret in the light of the above phase boundaries. The glass compositions define a straight line nearly parallel to the clinopyroxene-olivine boundary for the Snaefellsnes glasses (Fig. 24). The alkali glasses have high normative clinopyroxene and may be related to a position in the vicinity of a clinopyroxene-olivine boundary or the cotectic. All Fe-Ti glasses show low normative clinopyroxene and are in general hypersthene normative, bearing a microphenocryst assemblage consisting of plagioclase-clinopyroxene and occasionally olivine (Fig. 24). Based on the appearance of clinopyroxene and plagioclase in most glasses a composition not far from a clinopyroxene-plagioclase divariant surface in the quarternary system could be suggested. However, the orientation of the linear trend in Fig. 24 would point to a clinopyroxene-olivine divariant surface. In this case the anomalous appearance of plagioclase, and the rare olivine in the glasses together with an apparent expansion of the clinopyroxene field, remain a riddle. The unsystematic phenocryst assemblages and the strong linear trend in the glasses invites interpretation as a mixed series (Walker et al. 1979). Mixing between Fe-Ti basalts and Mid-Ocean Ridge basalts (Smarason 1980) or between alkali basalts and silicic melts (Oskarsson et al. 1982) has been suggested. Either of these possibilities is, however, suggested from the present data. If the phase relations inferred for the Snaefellsnes and Vestmannaeyjar are used as a reference, it would indeed be difficult to either fractionate or mix the two end-members without entercountering the olivine field. The normative composition of the Fe-Ti glasses (Fig. 24) is perhaps best explained as a result of shifts in phase boundaries.

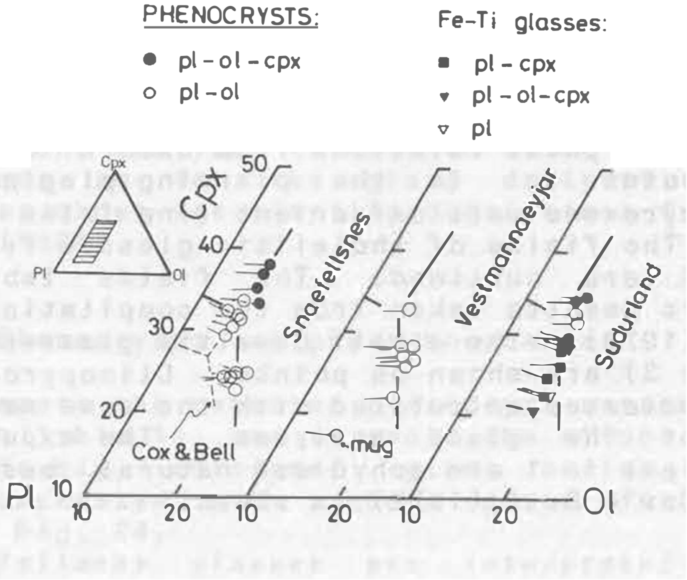

Figure 24. Projection onto the normative plane plagioclase-clinopyroxene-olivine from either the nepheline or the quartz apexes, same as in Fig. 23. The three petrologic subregions are separated into individual projections. Phase boundaries between clinopyroxene, plagioclase and olivine are from Cox & Bell (1972) and as inferred from this study. For further information, projection and norm conventions see text to Fig. 20. All iron is calculated as FeO. Horizontal bars mark the effect of changing the Fe_2O_3/FeO ratio to 0.17. Microphenocryst assemblages as given in Table 1.

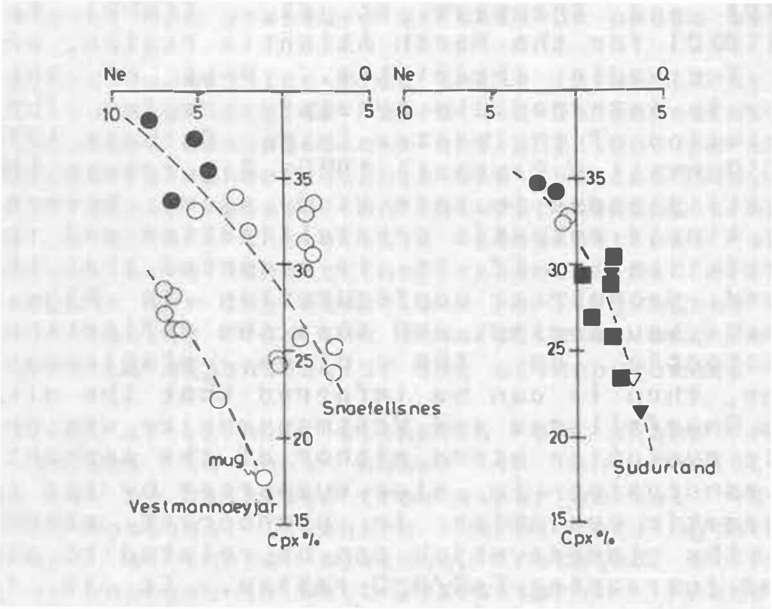

Figure 25. Variability in normative nepheline-quartz-clinopyroxene for the three subareas. Normative hypersthene has been recalculated to quartz and olivine after the equation given in text to Fig. 20. Clinopyroxene are calculated as per cent of total clinopyroxene-olivine-plagioclase. Cation equivalent norm calculated as used by Irvine (1970) but with $Fe_2O_3/FeO=0.17$. Symbols as in Fig. 24.

The relative position to the clinopyroxene-olivine-plagioclase plane in the alkali basalt and the olivine tholeiite volumes are shown in Fig. 25. Trends can be drawn for the Snaefellsnes glasses from nepheline normative clinopyroxene-olivine-plagioclase to hypersthene normative olivine-plagioclase microphenocryst assemblages. A great scatter is, however, apparent and likely to reflect even small analytical errors in e.g. SiO_2 determinations. The Vestmannaeyjar glasses vary from high to low nepheline normative, with low nepheline shown by the 1973 Heimaey mugearite glass. The microphenocryst assemblages in the Sudurland glasses vary from plagioclase-olivine-clinopyroxene to in general plagioclase-clinopyroxene with decreasing nepheline and increasing hypersthene in the norm. The transition from high to low nepheline composition correlates in general with increasing FeO/MgO ratio in the glass and olivine.

To summarize it can be suggested that tholeiitic glasses are related to a plagioclase-olivine-clinopyroxene cotectic line, which projects into a narrow area without major distortions on the plane plagioclase-clinopyroxene-olivine (Fig. 23), and thus reflects the geometric configuration of the tholeiite cotectic within the system. The position of this cotectic line agrees closely with the results of Walker et al. (1979). The compositional variation in tholeiitic glasses can therefore be related to fractional crystallization along or towards the cotectic line. This is consistent with conclusions reached by Bryan et al. (1976), Bryan (1979) and Thompson et al. (1980) for FAMOUS, Sigurdsson (1982) for the North Atlantic region, and Makipaa (1978) for Icelandic tholeiites. Most of these authors suggest a low to intermediate pressure regime (below 3 kb) for the evolution of tholeiites (e.g. Shibata 1976; Fisk et al. 1980; O'Donnell & Presnall 1980; Sigurdsson 1981).

The alkali glasses in this study seem, however, to be unrelated to simple cotectic crystallization and instead show divariant relations. If it is accepted that the observed positions and geometric configuration in Figs. 23 and 24 delineate phase boundaries, and that the deflection marks the piercing cotectic on the plane plagioclase-olivine-clinopyroxene, then it can be inferred that the alkali basalt glasses from Snaefellsnes and Vestmannaeyjar are not related to a cotectic evolution along either of the segments in Fig. 24. This conclusion is also supported by the observation that no systematic evolution in phenocryst assemblages is present in the glasses which can be related to simple phase relations and increasing FeO/MgO ratios. It is interesting to note that the position of the cotectic suggest only a minor shift in phase boundaries relative to that inferred from 1 atm experiments on tholeiites (Fig. 24).

A major anomaly exists for the clinopyroxene containing assemblages as these in addition to olivine also contain plagioclase phenocrysts on an inferred clinopyroxene-olivine divariant surface. It will be suggested that this reflects polybaric origin and evolution of the alkali glasses.

The early 1973 Heimaey glass

The mugearite glass from the 1973 Heimaey eruption departs from general trends in most variation diagrams and phase diagrams. The rapid change from mugeerite to hawaiite during the eruption was interpreted by Jakobsson et al. (1973) to reflect a vertically zoned magma chamber. Reaction between mugearite magma and gabbroic xenoliths to form pargasitic to kaersutitic amphibole was suggested to indicate e relatively high P_{H_2O} in the magma. A gradual change in composition as well as in vapour pressure in the upper part of the magma chamber is likely to have shifted phase boundaries towards the plagioclase volume and consequently affected the liquid composition if equilibrium was maintained. A subsequent sudden release of vapour pressure during eruption would shift phase boundaries and bring the liquid into a supersaturated position well within the plagioclase volume, as suggested by Jakobsson et al. (1973) based on Yoder's (1965) experiments on the join diopside-anorthite. It may be reasonable to suggest that quenching could in part have prevented the liquid-mineral equilibration to low vapour pressure. More advanced stages of solidification from the 1973 Heimaey eruption have been analysed by Schau & Gasparrini (1974). Except for unexplained high normative nepheline, their analyses support a strong contraction of the plagioclase volume likely to be caused by high P_{H_2O} (Yoder 1965).

DISCUSSION AND PETROGENESIS

Compositional and pressure effects on phase boundaries

Shifts in phase boundaries from those inferred by Cox & Bell (1972) and Irvine (1979) were to be expected, reflecting different chemical compositions and physical parameters. The phase relations for Snaefellsnes end Vestmannaeyjar glasses compared to those based on natural compositions and 1 atm experiments on mainly tholeiitic compositions show only a slight contraction of the clinopyroxene field (Fig. 24). The phase relations for the Sudurland Fe-Ti glasses do, however, differ significantly from the Snaefellsnes and Vestmannaeyjar relations with an expansion of the clinopyrcxene field (Fig. 24).

The effect of minor elements on phase relations in basaltic systems is not known in any detail. Only some indications can be obtained from experimental investigations on simplified systems. Kushiro (1975), adding minor elements to simplified silicate systems, related shifts in phase boundaries to changes in melt structure. Phase boundaries between two crystalline phases having different degrees of polymerization (e.g. olivine and pyroxenes) will be shifted towards the silica-rich side upon adding monovalent cations (e.g. H, K, Na) and towards the silica-poor side adding polyvalent cations (Ti, C, P). The expected effect of alkalies on the phase relations is therefore to expand the liquidus volumes of olivine and clinopyroxene at the expense of plagioclase (Yoder 1976; Biggar & Humphries 1981). This effect may, however, be counteracted by Ti and P. Considering the high consentrations used by Kushiro (1975) and Biggar & Humphries (1981) it might be reasonable to suggest that the small variation in minor elements observed in this study is insufficent to cause major shifts in phase relations. This would also be supported by the only minor shift in phase boundaries observed between 1 atm experiments on a natural basalt (Walker et al. 1979) and a simplified system (Presnall et al. 1979; O'Donnell & Presnall 1980).

The effect of increasing FeO/MgO in the liquid is to expand the plagioclase volume relative to the olivine and clinopyroxene volumes (Longhi 1977; Lipin 1978). The relative positions of the alkali (FeO/MgO $\simeq$ 1.8) and Fe-Ti (FeO/MgO $\simeq$ 2.9) glasses from Sudurland in Fig. 24 can therefore not be explained as an effect of difference in FeO/MgO ratios. The shift in the position of the cotectic observed for the Snaefellsnes and Vestmannaeyjar glasses is also not likely to be an effect of higher FeO/MgO ratios compared to tholeiite glasses (e.g. Fig. 6).

The volatile content of natural basaltic liquids has been considered too low to cause significant shifts in phase boundaries at low or high pressures (Presnall et al. 1978; Wyllie 1979). This is supported from the present results for the main part of the alkali glasses. However, there are some indications for relatively higher water contents for the Fe-Ti glasses from Sudurland. A higher Fe_2O_3/FeO ratio of 0.17 in Fe-Ti basalt lavas compared to 0.15 from the Vestmannaeyjar have been reported (Jakobsson 1979, fig. 34). Chromian spinel in the Sudurland alkali glasses show an anomalously high Fe^{3+} content compared to spinel from the other glasses (Thy 1982). The appearance of titanomagnetite, when compared to Fe-Ti glasses from Snaefellsnes, does however not support this (Thy 1982).

The most important factor is likely to be pressure with or without volatiles. High pressure, water saturated conditions will cause a major shift (Kushiro 1969). There is no evidence to suggest water saturation for the alkali glasses in this study. The effect of P is to expand the olivine and clinopyroxene volumes at the expense of plagioclase (Yoder 1965; Kushiro 1975), while CO_2 has the opposite effect (Eggler 1974). A relatively higher P_{H_2O} for the Sudurland Fe-Ti glasses would therefore explain the observed shift in phase boundaries. Increasing anhydrous pressure will cause the clinopyroxene volume to expand relatively to the plagioclase and olivine volumes (Merrill & Williams 1975; Longhi 1978; Presnall et al. 1978). This has also been experimentally demonstrated for natural basalts (e.g. Thompson 1974; Bender et al. 1978). Again the position of the Fe-Ti basalts could be explained as a result of high anhydrous pressure.

The effects of intensive, extensive and compositional parameters on phase boundaries are very difficult to evaluate in a multivariate natural system. The shift observed for the Snaefellsnes and Vestmannaeyjar glasses compared to tholeiites is likely to reflect the overall compositional difference between the tholeiite liquids and the alkali liquids. It will be suggested below that the inferred position of the cotectic for the alkali glasses is actually a high pressure position. For this reason a more significant expansion of the plagioclase volume must be seen when both the alkali glasses and the tholeiites is refered to 1 atm. The shift observed for the Sudurland Fe-Ti glasses can be an effect of high pressure (with or without volatiles). The latter could imply that the Fe-Ti basalts are either a high pressure primary or evolved liquid. This would contrast to the shallow level crystal fractionation models suggested by Clague & Bunch (1976) for the origin of ferrobasalt at East Pacific Mid-Ocean spreading centers.

Polybaric origin of phenocryst assemblages

The experimental work by Presnall et el. (1978) on the plane forsterite-anorthite-diopside demonstrates a significant expansion of the clinopyroxene volume at even moderate pressures. A liquid composition close to a clinopyroxene-olivine-plegioclase-liquid four phase point below 7 kb (Presnall et al. 1978, fig. 4a) will, if pressure is lowered, obtain a position within the plagioclase volume (Presnall et al. 1978, fig. 5). Subsequent plagioclase fractionation would drive the liquid towards a plagioclase-olivine cotectic surface (Fig. 26). Fast ascent of the magma from a high pressure region and quenching upon extrusion may prevent reequilibriation to a shrinking clinopyroxene field with falling pressure and liquidus temperature (e.g. O'Donnell & Presnall 1980). Disequilibrium textures of the phenocrysts and superheating of the liquid would be a consequence. Several features suggest an intermediate pressure residence or slower transfer to the surface in order to allow the liquid temperature to reach the plagioclase liquidus. This intermediate pressure regime must have been of relatively short duration to account for the failure of most glasses to reach equilibrium composition before final ascent and quenching.

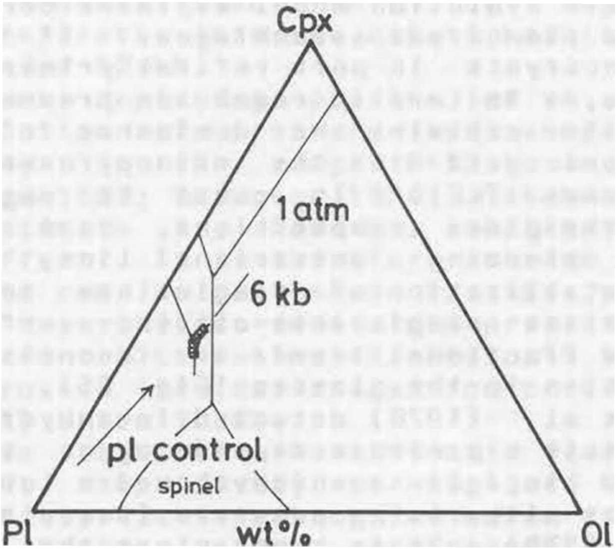

Figure 26. Tentative model for the ploybaric evolution of glasses and phenocryst assemblages. Phase boundaries based on Presnall et al. (1978, fig. 5). The development of a spinel field is not considered. The arrow indicates the expected plagioclase fractionation control line on glass composition towards low pressure phase relations (see text).

The assemblage olivine-plagioclase-clinopyroxene in the Snaefellsnes glasses can hence be interpreted es polybaric crystallization of clinopyroxene-olivine at high pressure. Crystallization of plagioclase occurred at an intermediate pressure without equilibrium being reached. The olivine-plagioclase assemblages from the Snaefellsnes and Vestmanneeyjar glasses also failed to reach lower pressure equilibrium relations, and the phenocrysts in these glasses can from the model be interpreted to be in the main part of a high pressure origin.

The above model also applies to the alkali basalt glasses from Sudurland. The expansion of the clinopyroxene field for the Fe-Ti glasses and their plagioclase-clinopyroxene phenocryst assemblages were interpreted as a pressure effect. It follows that the composition is inherited from higher pressure than seen for the Snaefellsnes and Vestmannaeyjar glasses. A high pressure position related to a clinopyroxene-plagioclase divariant boundary not far from univariant relations with possible minor lower pressure crystallization of plagioclase is suggested from the phenocryst assemblages. A consequence of this interpretation is that the alkali basalts and Fe-Ti basalts from the Sudurland Volcanic Zone cannot be genetically related to isobaric fractional crystallization.

The model proposed indicates different tectonic and magmatic evolution stories between and within the Sudurland, Vestmannaeyjar and Snaefellsnes Volcanic Zones, in particular regarding medium to low pressure residences during ascent of magmas.

A polybaric evolution model explains certain additional features in the phenocryst assemblages. If it is assumed that the phenocrysts in part reflect primary high pressure phase relations, a failure to reach low pressure equilibrium relations will explain the dominance of olivine over plagioclase phenocrysts in the clinopyroxene-free samples from Snaefellsnes (KE). It could be suggested that the deflection in the glass compositions, here interpreted as marking the piercing univariant line, simply reflect fractional crystallization of plagioclase towards a lower pressure divariant plagioclase-olivine surface (Fig. 26). However, such a fractional trend is inconsistent with the chemical evolution in the glasses (Fig. 25).

Bender et al. (1978) detected in anhydrous experiments on a FAMOUS basalt a pressure dependency on the composition of olivine and plagioclase which showed a lowering in Fo and An mol.% content with rising pressure (see also Green 1969; Longhi et al. 1978). It is hence clear that a high pressure origin of macrophenocryst assemblages (higher Fo and An) relative to the microphenocrysts cannot be suggested. The observed bimodality in the composition of phenocrysts will for this reason be related to fractional crystallization in a high pressure regime, and it will be suggested that the main part of the phenocrysts is actually of high to intermediate pressure origin. This would explain the completely missing reverse zoning in phenocrysts which is a consequence of decreasing pressure during crystallization (O'Donnell & Presnall 1980).

Estimate of pressures

It was suggested that the observed compositional variation in glass chemistry is inherited from higher pressure residence in the mantle or crust, modified only to minor extent by later mineral-liquid fractionation.

It is generally held on the basis of Sr-isotopes that alkali basalts are produced by initial melting of a primitive mantle source (e.g. O'Nions et al. 1973; O'Nions & Grönvold 1973; Sun & Hanson 1975; Frey et al. 1978). The work by Kushiro (1972) showed that high pressure (20 kb) initial melts produced from a garnet lherzolite was nepheline normative but hypersthene normative at lower pressure (10 kb). The initial melt produced at 20 kb was nepheline normative and changed to hypersthene normative compositions at higher degree of partial melting (Mysen & Kushiro 1977). The initial liquids produced by partial melting of a peridotite in the presence of small amounts of volatiles at 13.5 kb was determined by Olafsson (1980, fig. 6) to be nepheline normative and changing to quartz normative with increasing degrees of melting.

High pressure anhydrous experiments on basalts of alkali compositions support this pressure range. Alkali basalts are generally multi-saturated with olivine, orthopyroxene and clinopyroxene at pressures between 20-10 kb (Green & Ringwood 1967; Thompson 1974; Takahashi 1980). In the experiments by Thompson and Takahashi orthopyroxene appears as a liquidus phase about 15 kb. This confirms that alkali basalts may be partial melts from a lherzolite mantle source. Presnall et al. (1978) substantiated this by suggesting that orthopyroxene penetrates into the alkali basalt volume at a minimum pressure of 12 kb.

Clinopyroxene replacing olivine as a first liquidus phase as a function of pressure and composition. This transition occurs in the range 9-17 kb in alkali basalts (Green & Ringwood 1967; Thompson 1974; Takahashi 1980). A quantitative estimate is, however, complicated by a strong compositional effect. It is therefore unknown to what extent these experiments can be extended to the present alkali compositions. Nevertheless a minimum pressure of formation in a mantle source can be estimated about 15 kb, while the olivine-clinopyroxene liquidus transition occurred at a lower pressure probably below 10 kb.

At least two stages of mineral-liquid equilibration have been postulated, respectively at high and moderate to low pressure conditions. It is unknown to which extent the high pressure equilibration stage corresponds to an initial melting and segregation stage or to higher level residence in magma chambers in the crust. The moderate to low pressure equilibration stage is likely to be confined to low level magma chambers in the crust.

Oskarsson et al. (1982) suggested that melting of a amphibole-bearing oceanic crust would be able to produce a melt of a nepheline normative alkali basalt composition. The present findings do not rule out this possibility which, however, would change the high pressure estimates.

CONCLUSIONS

The major element variation in alkali basalt glasses from Iceland is interpreted as representing mantle derived magma batches of primary liquids modified to minor degrees by processes during ascent and residence in magma chambers. A complex story is recorded in phenocryst assemblages and phase relations. The glass chemistry has been modified by high and medium to low pressure crystal fractionation towards equilibrium phase relations. Furthermore distinctive stories are recorded within the various provinces.

The Sudurland glasses show complex phenocryst assemblages and phase relations. A marked depression of the plagioclase or expansion of the clinopyroxene volumes is suggested to be a relict high pressure feature with only minor superimposed fractional crystallization towards medium-low pressure phase relations.

The glasses from western Snaefellsnes show phenocryst assemblages attributed to a high pressure clinopyroxene-olivine divariant surface and subsequent crystal fractionation towards lower pressure olivine-plagioclase divariant phase relations. A deflection in normative glass composition is seen in a clinopyroxene-olivine-plagioclase projection. This is suggested to mark the position of the cotectic clinopyroxene-olivine-plagioclase at high pressure, but still lower than that inferred for the Sudurland glasses.

The Vestmannaeyjar glasses fill a compositional gap present in the Snaefellsnes series and are interpreted to be related to the same plagioclase-olivine divariant surface.

Different stories of evolution are hence recorded for the Sudurland and the Snaefellsnes and Vestmannaeyjar Volcanic Zones. In the latter residence in high level magma chambers is suggested from the preserved medium pressure phase relations, while in the Sudurland Volcanic Zone no long low level residence is recorded. This may imply that these latter magmas were brought to the surface relatively fast preventing crystallization towards lower pressure phase relations.

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