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Degassing and differentiation in subglacial volcanoes, Iceland

James G. Moore and Lewis C. Calk

U.S. Geological Survey, Menlo Park, CA 94025, USA

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ABSTRACT

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Within the neovolcanic zones of Iceland many volcanoes grew upward through icecaps that have subsequently melted. These steep-walled and flat-topped basaltic subglacial volcanoes, called tuyas, are composed of a lower sequence of subaqueously erupted, pillowed lavas overlain by breccias and hyaloclastites produced by phreatomagmatic explosions in shallow water, capped by a subaerially erupted lava plateau. Glass and whole-rock analyses of samples collected from six tuyas indicate systematic variations in major elements showing that the individual volcanoes are monogenetic, and that commonly the tholeiitic magmas differentiated and became more evolved through the course of the eruption that built the tuya. At Herdubreid, the most extensively studies tuya, the upward change in composition indicates that more than 50 wt.% of the first erupted lavas need crystallize over a range of 60°C to produce the last erupted lavas. The S content of glass commonly decreases upward in the tuyas from an average of about 0.08 wt.% at the base to < 0.02 wt.% in the subaerially erupted lava at the top, and is a measure of the depth of water (or ice) above the eruptive vent. The extensive subsurface crystallization that generates the more evolved, lower-temperature melts during the growth of the tuyas, apparently results from cooling and degassing of magma contained in shallow magma chambers and feeders beneath the volcanoes. Cooling may result from percolation of meltwater down cracks, vaporization, and cycling in a hydrothermal circulation. Degassing occurs when progressively lower pressure eruption (as the volcanic vent grows above the ice/water surface) lowers the volatile vapour pressure of subsurface melt, thus elevating the temperature of the liquidus and hastening liquid–crystal differentiation.

Introduction

The exposed subglacial volcanoes of Iceland which formed by eruption of tholeiitic basaltic lava beneath pre-existing icecaps (Noe-Nygaard, 1940; Kjartansson, 1943; van Bemmelen and Rutten, 1955; Einarsson, 1960; Jones, 1966, 1969, 1970; Sigvaldason, 1968) provide an opportunity to investigate the chemical changes that occur in lavas during the transition from subaqueous to subaerial eruption. These subglacial volcanoes have been termed tuyas (Mathews, 1947), and also tablemountains, referring to the capping plateau of subaerial lava formed after emergence above the ice. In this work the term tuya will be used.

The initial eruptions beneath the ice apparently melted an intraglacial, water-filled vault within which pillow lava built a steep-sided edifice that probably banked against the ice walls. When the upward growing pillow pile reached a shallow level in the ice, the roof of the water-filled vault melted through to form a lake. Shallow-water phreatic explosive activity then occurred when the water depth was less than a few tens of meters, and a layer of glassy tephra was laid down on top of the pillows until the volcano emerged above water level. Phreatic explosions ceased when the

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vent was effectively sealed from water ingress and eruption of fluid lava flows permitted subaerial lava to cap the sequence. The initial subaerial plateau commonly enlarged as lava flowed across the shoreline into the meltwater lake where degassed hyaloclastites, flow-foot breccias, and pillow lavas formed and draped the slope. The characteristic steep-sided tuya shape exposed upon melting of the icecap results from the sequence of steep-sided pillow lava and hyaloclastite formed below the water level, capped by a plateau of flat-lying subaerial lava flows.

Many tuyas appear to have been formed in a single eruptive episode which is believed to have occurred over a period of years or decades as is common for contemporary eruptions of comparable size on the volcanic rift zones of Iceland. They are steep-sided, and samples collected from base to summit contain the record of structural and chemical evolution of the volcano during much of its history. Tuyas provide a unique site to study the change in eruptive style and release of volatiles during the reduction in confining pressure that occurs as the basaltic volcano grows upward from beneath several hundred meters of ice (or water) to conclude activity as a subaerial volcano.

Present work

Six upper Pleistocene tuyas were investigated in this study (Figs. 1, 2). Sample traverses up these volcanoes were on steep slopes and in gullies, and samples were collected from bedrock at known elevation (determined by map inspection and aneroid barometer). The outer rims of pillows and the margins of lava flows were sampled so as to obtain glassy material for microprobe analyses.

All samples were broken from outcrops, but it is possible that lavas and breccias moved downslope from their site of degassing and/or quenching. Such downslope movement may result from: (1) flow of lava during volcanic activity from the vent, which may be subaerial, so that the flows would cross the meltwater-lake shoreline, develop pillows or breccia below the water level, and move down the subaqueous slope as fluid lava, fragmental lava, or sediment; or (2), slumping or sliding of material ranging in size from talus to large landslide blocks at any stage in the volcano's history (Jones, 1969).

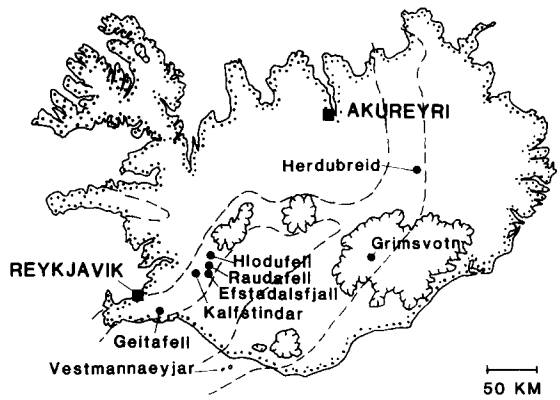

Fig. 1. Index map of Iceland showing localities investigated. Neovolcanic zones are bounded by dashed lines, and icecaps are hachured.

The water level of the meltwater pond commonly fluctuated during tuya growth. Where the level rose, subaqueous pillowed lavas are sandwiched between subaerial flows. Where the level fell, subaerial flows drape, and may obscure, the earlier subaqueous lavas. The generalized water level of each tuya is taken as the lowest boundary between subaerial lava overlying subaqueous lava. The subaerial lava is identified by its throughgoing character and generally greater thickness of cooling units (2–10 m), red, oxidized character, regular columnar joints, and presence of associated red-coloured underlying cinders. Subaqueous flows are marked by pillowed structure, abundant glass, lack of red-coloured material, laterally discontinuous cooling units, and irregular, small columnar joints.

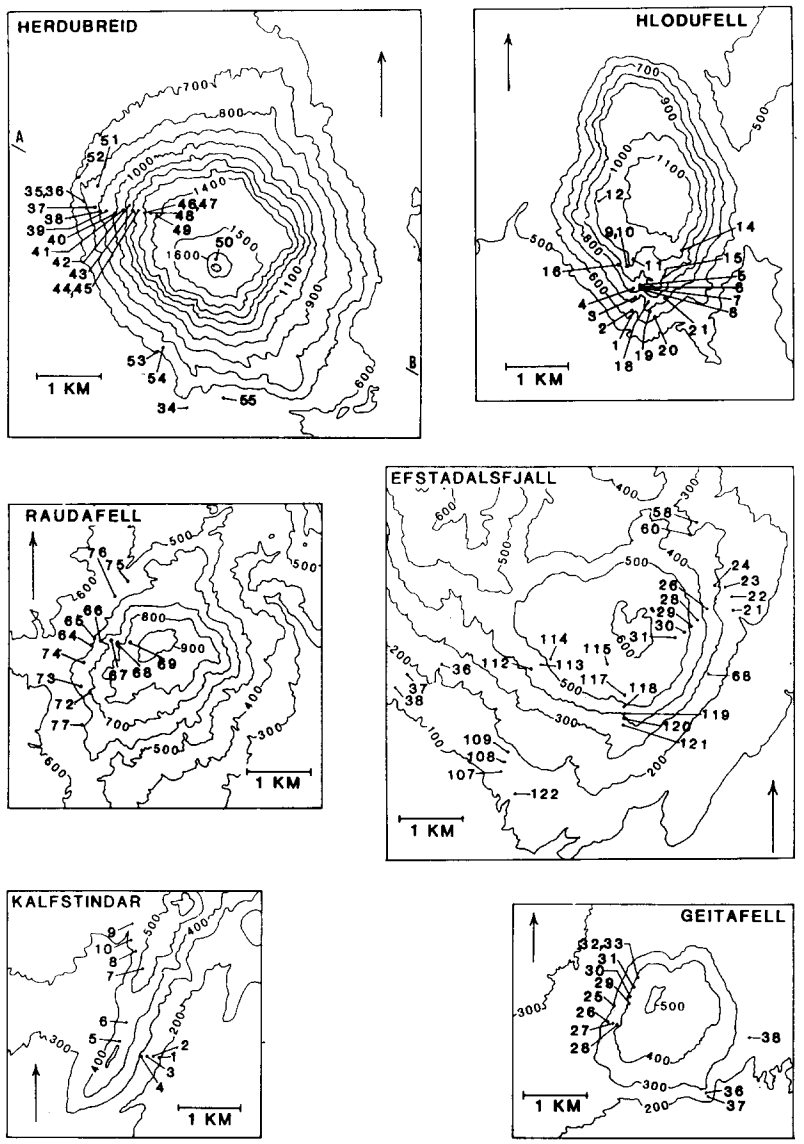

Fig. 2. Sample localities at Herdubreid, Hlodufell, Raudafell, Efstadalsfjall, Kalfstindar, and Geitafell tuyas. Because of space limitations sample numbers have been shortened; insert a "88I-3" before Herdubreid and Raudafell numbers; "85T" before Geitafell and Hlodufell numbers; "9I" before Kalfstindar numbers; and "9I" before Efstadalsfjall numbers below 68 and "88I" before Efstadalsfjall numbers above 100. Analyses of these samples are shown in Tables 3–9.

Electron microprobe analyses of major elements and S were made on from one to four glass chips from each sample (Tables 2–8) on an ARL SEMQ microprobe equipped with three wavelength dispersive crystal spectrometers and six monochromators. An accelerating voltage of 15 kV was used and the electron beam was slightly defocused (about 10 microns) to minimize mobilization of Na and S. Most often, a minimum of four 20 second counts were averaged to obtain an analysis of each chip. USNM standard VG-2, a basaltic glass from the Juan de Fuca, Ridge was used as a standard for Si, Al, Fe, Mg, Ca, and Na.

TABLE 1

Tuyas sampled

Name	Lat./long.	No. of samples	Elevation (m)			Volume (km^3)
			Summit	Base	Water-level	
Herdubreid	65°10′/16°21′	22	1650	520–660	1250, 1310, 1400	8
Hlodufell	64°26′/20°33′	19	1188	500–530	856, 966	4
Raudafell	64°19′/20°35′	12	920	350–600	840	1.5
Efstadalsfjall	64°15′/20°36′	30	627	100–380	570	3
Kalfstindar	64°54′/20°14′	10	600+	200–380	700	>0.6
Geitafell	63°56′/21°31′	12	509	170–240	422, 432	0.9

TABLE 2

Comparison of wet chemical and microprobe analyses of glass standards

Standard No.:	A-99 [1]	A-99 [2] n = 25	A-99 [2] S.D.	VG-2 [1]	VG-2 [2] n = 63	VG-2 [2] S.D.
SiO_2	50.94	50.92	0.27	50.81	50.33	0.25
Al_2O_3	12.49	12.59	0.21	14.06	13.89	0.25
FeO*	13.30	13.34	0.10	11.84	11.68	0.07
MgO	5.08	5.09	0.05	6.71	6.95	0.04
CaO	9.30	9.08	0.06	11.12	10.88	0.06
Na_2O	2.66	2.66	0.06	2.62	2.75	0.02
K_2O	0.82	0.84	0.02	0.19	0.19	0.01
TiO_2	4.06	3.99	0.05	1.85	1.82	0.02
P_2O_5	n.a.	0.49	0.03	n.a.	0.24	0.02
MnO	0.15	0.19	0.01	0.20	0.20	0.01
S	n.a.	0.013	0.004	n.a.	0.126	0.008
Total	98.80	99.20		99.40	99.06	

[1] wet chemical analysis.
[2] mean microprobe analysis.
n.a. = not analyzed.

NIST glass standard N201 was used for K; apatite for P; TiO_2 for Ti; Mn_2O_3 for Mn; and barite for S. The analytical precision and accuracy can be assessed from the analyses of Smithsonian Institution glass standards A-99 and VG-2 (Table 2) which were frequently repeated during the period that the basalt glasses were analyzed.

Major-element analyses by XRF and chemical methods (Table 9) were made on whole-rock samples from a small subset of the samples analyzed by microprobe. Modal analyses of Herdubreid rocks were made by counting more than 1000 points per thin sections.

The general features of the six tablemountains investigated follow.

Herdubreid

Herdubreid (van Bemmelen and Rutten, 1955; Sigvaldason, 1968) located about 100 km southeast of Akureyri on the eastern volcanic zone is one of the largest and most magnificent of Iceland's tuyas (Table 1, Figs. 1, 2, 3). It rises about 1000 m above its base to 1650 m, the summit plateau is 2 km in diameter, and volume of the edifice is about 8 km^3. Eighteen analyzed samples were collected on the climbing route up the west side, and an additional 4 samples were analyzed from the south base of the volcano (Tables 3, 9).

The lower part of the mountain (660 to 900 m elevation) is underlain primarily by coher-

Fig. 3. Herdubreid from the east showing lower gullied slopes of pillow lava overlain by subaerial lava flows of the summit plateau. Cliffs between are developed from interbedded breccias and lava flows in zone of fluctuating water (ice) level at 1250, 1310, and 1400 m elevation. Field sketch by W.B. Bryan.

ent pillowed lavas (Sigvaldason, 1968). Within this section lenses of hyaloclastitic breccia tens of meters thick occur in a few places; some of these lenses contain layers of coherent pillowed lavas. The bottom of a 50-m-thick layer of coarse, angular pillow breccia containing abundant pillow joint blocks crops out at 1185 m. The first continuous lava flow (about 2 m thick) occurs at 1250 m, and the initial water level is taken at this elevation. This normally magnetized flow grades downward to a pillowed base and is overlain by discontinuous pillowed lava and hyaloclastite. The pillow lava overlying this thin flow continues up to 1310 m where it is overlain by red scoriaceous cinders that merge into a base of a relatively continuous lava flow. This flow is overlain by scoriaceous black pillow-like masses that continue up to about 1400 m. Hence, second and third water levels occur at 1310 and 1400 m. Above 1400 m subaerial lava flows form the base for a small lava cone rising to 1650 m. The lava cone contains a central crater about 150 m in diameter with a partly frozen lake within.

Herdubreid lavas all contain small glomeroporphyritic clots 1–2 mm in size. These clots are composed of 10–20 microphenocrysts of plagioclase and olivine with plagioclase greatly predominating. In the lower part of the mountain the pl/ol volume ratio is about 3, and this ratio increases to about 7 in the upper subaerial sequence. Clinopyroxene phenocrysts are virtually absent in the lower subaqueous lavas, and are present, but uncommon in the upper subaerial lavas (Table 3).

Hlodufell

Hlodufell (Kjartansson, 1943; Jones, 1969) is about 80 km northeast of Reykjavik in the western volcanic zone (Figs. 1, 2). The tuya rises nearly 700 m above its base and has a volume of about 4 km^3. Glass analyses were made of 19 samples (Table 4) and whole-rock analyses were made of two (Table 9).

The lower part of the tuya is composed primarily of pillowed lava, but interbedded layers of hyaloclastite and pillow breccia persist up to the first subaerial lavas. From 600 to 820 m elevation discontinuous fragmental layers composed of pillow joint blocks, lapilli, and sand-sized fragments are common, and are overlain by pillowed lavas up to 856 m elevation where the first relatively continuous lava flows, ranging from 0.2 to 2 m thick, mark the lowermost subaerial lavas. This subaerial sequence extends up to 875 m, where it is overlain by vesicular pillows, which in turn are overlain by a second lava sequence at 966 m. The lower lava flows in this subaerial sequence are thin (0.5–1.2 m thick) and show pahoehoe surface features in places. The flows thicken upward, commonly to 3–5 m thick, and comprise the rest of the section up to the summit plateau.

The double subaerial lava sequence is reflected in the topography by a broad step on the north side of the tuya that averages 940 m in height and is built on the lower subaerial lava layer (856–875 m) as exposed on the west side of the mountain. Apparently during growth the volcano breached the surface of the water that covered it at least twice. Dur-

TABLE 3

Glass and modal analyses * from Herdubreid

Sample No. 88I:	355	334	353	352	354	335	336	337	351	338	339
Elevation (m):	580	622	675	710	725	760	790	810	860	900	925
No. in average:	4	3	2	3	2	3	3	5	3	3	3
SiO_2	48.7	49.0	48.9	48.8	48.7	49.0	48.8	48.6	48.8	48.4	48.6
Al_2O_3	15.4	14.7	14.8	14.6	14.9	15.2	15.1	15.6	14.8	16.0	15.3
FeO*	10.7	12.5	10.9	11.0	10.8	11.1	11.1	10.7	11.1	10.6	11.1
MgO	8.23	7.19	8.01	8.01	8.16	7.86	7.91	8.37	7.89	8.42	7.98
CaO	12.8	12.2	12.6	12.6	12.6	12.7	12.6	12.7	12.7	12.7	12.6
Na_2O	2.08	1.34	2.10	2.09	2.08	2.12	2.09	2.06	2.07	2.06	2.12
K_2O	0.13	0.43	0.17	0.17	0.17	0.18	0.18	0.13	0.18	0.14	0.18
TiO_2	1.38	2.19	1.49	1.51	1.46	1.52	1.53	1.34	1.52	1.31	1.48
P_2O_5	0.16	0.33	0.14	0.15	0.17	0.23	0.22	0.19	0.16	0.21	0.22
MnO	0.18	0.20	0.19	0.19	0.18	0.18	0.18	0.17	0.19	0.17	0.19
S	0.076	0.075	0.064	0.066	0.071	0.068	0.063	0.065	0.056	0.067	0.062
Total	99.62	100.10	99.41	99.27	99.32	100.15	99.78	100.05	99.48	100.08	99.81
Glass	92.1		89.9			93.6	92.2		91.3		92.6
Plagioclase	5.2		8.0			4.9	7.0		7.4		6.1
Olivine	2.7		2.1			1.2	0.6		1.3		1.3
Clinopyroxene											
Vesicle	5.4		3.8			3.8	0.2		1.0		1.2

Sample No. 88I:	340	341	342	343	344	345	346	347	348	349	350
Elevation (m):	975	1045	1150	1160	1235	1250	1300	1310	1355	1395	1650
No. in average:	3	3	3	3	4	3	1	2	2	2	2
SiO_2	48.5	48.3	48.5	48.9	48.9	49.0	48.9	49.4	48.9	48.8	48.7
Al_2O_3	13.6	13.6	14.1	13.0	13.7	13.7	13.8	13.7	13.4	13.3	13.2
FeO*	13.4	13.4	12.6	12.7	12.4	12.5	12.4	12.9	13.1	13.0	13.4
MgO	6.25	6.26	6.74	6.69	6.96	6.81	6.92	6.70	6.49	6.54	6.17
CaO	11.1	11.1	11.5	11.6	11.6	11.7	11.6	11.9	11.3	11.4	11.1
Na_2O	2.79	2.76	2.59	2.68	2.59	2.58	2.59	2.58	2.77	2.75	2.78
K_2O	0.46	0.45	0.38	0.39	0.36	0.37	0.36	0.33	0.43	0.41	0.45
TiO_2	2.92	2.95	2.55	2.69	2.51	2.55	2.53	2.65	2.91	2.91	2.96
P_2O_5	0.36	0.36	0.35	0.27	0.25	0.28	0.27	0.28	0.27	0.29	0.32
MnO	0.22	0.21	0.20	0.22	0.21	0.22	0.22	0.22	0.21	0.21	0.22
S	0.012	0.011	0.006	0.009	0.005	0.005	0.004	0.004	0.002	0.004	0.003
Total	99.59	99.45	99.55	99.08	99.52	99.70	99.64	100.58	99.78	99.61	99.25
Glass	73.6	82.1	78.2	81.2	76.8	80.2	81.4		77.2		
Plagioclase	24.2	16.2	18.8	16.8	19.9	18.2	16.7		18.0		
Olivine	2.2	1.8	2.9	2.0	3.3	1.6	1.9		4.8		
Clinopyroxene	tr	tr	tr	tr	tr	tr	tr		tr		
Vesicle	1.5	1.3	1.4	1.5	1.7	28.6	36.0		22.5		

* Modal analyses in vol.%; more than 1000 points counted per thin section. Constituents other than vesicles calculated vesicle-free; glass may include microlites and aphanitic groundmass; minerals are phenocrysts and microphenocrysts.

ing the first emergence it grew several tens of m above the water-level at 856 m. Then after the water level rose 110 m and drowned the early subaerial plateau, continued subaqueous growth produced a second emergence, at 966 m elevation, after which the volcano grew 222 m higher to its present elevation of 1188 m.

The petrologic aspect of Hlodufell lavas does not change notably from bottom to top.

TABLE 4

Glass analyses from Hlodufell

Sample No.:	85T1	85T2	85T18	85T19	85T21	85T3	85T20	85T5	85T6	85T7
Elevation (m):	568	600	622	691	721	747	757	843	850	856
No. in average:	1	1	1	1	1	1	1	1	1	1
SiO_2	48.9	48.9	48.7	48.8	48.9	49.2	48.9	49.3	49.1	50.0
Al_2O_3	14.8	15.1	14.6	14.2	14.3	14.0	15.1	15.1	14.4	14.1
FeO*	11.7	11.6	11.9	12.2	11.9	12.6	11.5	11.5	12.3	12.2
MgO	7.48	7.85	7.51	7.29	7.56	7.01	7.57	6.64	7.18	7.05
CaO	12.2	12.2	12.2	12.3	12.2	12.3	12.4	12.6	12.4	12.6
Na_2O	2.27	2.21	2.30	2.30	2.26	2.26	2.22	2.34	2.29	2.32
K_2O	0.18	0.17	0.18	0.19	0.18	0.19	0.17	0.19	0.19	0.18
TiO_2	1.61	1.59	1.63	1.71	1.66	1.87	1.55	1.68	1.83	1.78
P_2O_5	0.13	0.14	0.13	0.14	0.13	0.16	0.14	0.15	0.16	0.15
MnO	0.22	0.22	0.21	0.22	0.22	0.22	0.20	0.20	0.21	0.22
S	0.028	0.020	0.020	0.028	0.028	0.012	0.024	0.008	0.008	0.004
Total	99.55	99.94	99.34	99.35	99.30	99.70	99.77	99.65	100.09	100.56

Sample No.:	85T4	85T8	85T16	85T15	85T9	85T10	85T11	85T14	85T12
Elevation (m):	862	875	882	920	965	966	1023	1060	1062
No. in average:	1	1	1	1	1	1	1	1	1
SiO_2	49.1	49.8	48.5	49.5	49.1	49.8	49.8	49.3	49.5
Al_2O_3	15.3	14.3	14.3	14.7	13.5	13.9	13.5	13.4	13.1
FeO	11.2	12.7	12.3	12.1	13.5	13.7	13.6	13.8	14.4
MgO	7.21	6.98	7.39	6.87	6.51	6.26	6.43	6.39	6.47
CaO	12.6	12.7	12.0	12.6	11.4	11.6	11.6	11.4	11.9
Na_2O	2.30	2.15	2.33	2.20	2.61	2.68	2.65	2.53	2.57
K_2O	0.16	0.15	0.19	0.12	0.25	0.27	0.13	0.27	0.17
TiO_2	1.56	1.86	1.70	1.75	2.16	2.18	2.23	2.17	2.13
P_2O_5	0.16	0.16	0.13	0.17	0.19	0.21	0.17	0.20	0.20
MnO	0.20	0.23	0.23	0.22	0.23	0.24	0.25	0.25	0.25
S	0.012	0.008	0.016	0.008	0.016	0.020	0.020	0.020	0.020
Total	99.74	101.05	99.09	100.18	99.42	100.83	100.42	99.60	100.70

Plagioclase is the predominant phenocryst phase and makes up about 15% of the rock. It occurs commonly in clots 1–2 mm in size. Olivine phenocrysts comprise about 10% of the rock and clinopyroxene microphenocryst are much less abundant.

Raudafell

Raudafell is on the western volcanic zone 10 km south of Hlodufell. It is partly built on the northeast side of the older, lower Middalsfjall tuya (Jones, 1969). On its west side Raudafell rises 320 m from Middalsfjall to its summit at 920 m elevation; the east flank descends 570 m to the plain drained by the Bruara River. Approximately 1.5 km^3 of lavas are related to the Raudafell vent. Samples were collected up the west side (Fig. 2) and glass analyses were made of 12 samples (Table 5), two of which were also analyzed for whole rock elemental abundance (Table 9).

Glassy clastic rocks are particularly abundant on the lower slopes of Raudafell. Thin layers of pillowed flows are interbedded between hyaloclastites and pillow breccias. The thickest sequence of pillows occurs from 600 to 665 m elevation. It is overlain by hyaloclastite breccias up to 840 m where a thin layer of reddish cinders underlies the first continuous lava flow and marks the water-level. The lowest subaerial lava flow is 2–3 m

TABLE 5

Glass analyses from Raudafell

Sample No. 88I-:	376	375	377	364	365	374	373	366	372	367	368	369
Elevation (m):	515	520	525	585	610	640	643	665	672	735	782	820
No. in average:	3	2	2	2	3	2	3	3	2	2	2	3
SiO_2	48.5	48.2	48.0	48.4	48.8	48.6	48.5	48.5	48.4	48.5	48.6	48.5
Al_2O_3	15.0	15.6	15.3	15.3	15.1	15.1	14.7	15.3	14.5	15.3	14.9	13.9
FeO*	11.4	11.3	11.7	11.3	11.5	11.4	11.4	11.3	11.5	11.2	11.2	12.1
MgO	7.72	7.78	7.61	7.98	7.66	7.76	7.62	7.86	7.66	7.99	7.84	7.44
CaO	12.2	12.0	11.6	12.1	12.4	12.2	12.2	12.3	12.2	12.3	12.4	12.3
Na_2O	2.20	2.23	2.27	2.21	2.22	2.19	2.21	2.22	2.21	2.17	2.20	2.25
K_2O	0.28	0.27	0.28	0.26	0.28	0.28	0.28	0.27	0.28	0.27	0.27	0.31
TiO_2	1.76	1.75	1.85	1.75	1.73	1.76	1.77	1.66	1.76	1.67	1.67	1.94
P_2O_5	0.18	0.21	0.22	0.25	0.25	0.20	0.21	0.23	0.22	0.21	0.22	0.23
MnO	0.20	0.20	0.21	0.19	0.19	0.20	0.21	0.19	0.22	0.19	0.20	0.20
S	0.029	0.056	0.056	0.037	0.025	0.023	0.024	0.023	0.023	0.013	0.011	0.013
Total	99.49	99.49	99.11	99.78	100.12	99.64	99.08	99.81	98.93	99.81	99.47	99.17

thick. It is overlain by up to 80 m of somewhat thicker flows, glaciated on their surface, that comprise the subaerial lava capping of the tuya.

The rock contains abundant phenocrysts of olivine and plagioclase with olivine commonly attaining several mm in size. Clinopyroxene phenocrysts are restricted to one or two per thin section.

Efstadalsfjall

Efstadalsfjall (Figs. 1, 2) is a broad tuya with a volume of about 3 km^3 on the southeast side of a cluster of subglacial volcanoes that include Raudafell and Kalfstindar. It is 627 m in elevation and rises about 500 m above the plane to the south and about 200 m above a contiguous older tuya, Vatnsheidi, on the north (Jones, 1969). Glassy lavas were collected on traverses on the northeast, south, and southwest sides (Fig. 2) and a total of 30 samples were analyzed (Table 6).

On the southwest side coherent pillowed flows are generally confined to the lower slopes generally below 200 m in elevation. Above are fragmental rocks, primarily pillow breccias admixed with glassy tuffs, containing layers up to 30 m thick of waterworked, poorly sorted tuffs. The capping, subaerial lava overlies these clastic rocks at 570 m. On the northeast side dominant pillowed flows, with minor interbeds of hyaloclastite, occur up to about 350 m, where they are overlain by pillow breccias that contain lenses of coherent pillows from 10 to 30 m thick. The breccias are overlain by capping subaerial lava flows also at 570 m, which marks the elevation of the only identified water level on the tuya.

Kalfstindar

Unlike the other tuyas studied, Kalfstindar is an elongate ridge 24 km in length that was built above a subglacial fissure paralleling the neovolcanic zone about 60 km northeast of Reykjavik (Jones, 1969, 1970). The southern 4 km of the ridge has a volume of about 0.6 km^3. Only the south end of the ridge was sampled (Fig. 2) where the crest at 500 m elevation is about 300 m above its east base. Ten samples were analyzed (Table 7) and all of the material examined was apparently erupted subaqueously. To the north, the ridge crest rises to 826 m where a sequence of subaerial lava flows indicates that the water level there was at about 700 m elevation (Jones, 1970).

TABLE 6

Glass analyses from Efstadalsfjall

Sample No.:	88I-122	88I-107	88I-108	9I-38	9I-37	88I-109	9I-36	9I-68	9I-21	9I-58
Elevation (m):	102	120	135	137	142	175	196	226	228	230
No. in average:	3	3	3	3	3	3	4	3	2	3
SiO_2	48.4	48.4	48.4	48.0	47.9	48.3	48.3	48.1	47.6	47.6
Al_2O_3	14.3	14.1	13.7	14.4	14.5	14.1	14.1	14.7	14.8	15.6
FeO*	11.8	11.8	11.9	11.6	11.5	11.8	11.9	11.7	12.2	11.2
MgO	7.81	7.65	7.50	7.67	7.99	7.56	7.45	7.87	7.76	8.62
CaO	12.8	13.0	13.0	12.9	12.9	13.0	12.8	12.8	11.9	12.2
Na_2O	2.12	2.15	2.19	2.17	2.14	2.28	2.15	2.11	2.28	2.08
K_2O	0.15	0.15	0.16	0.16	0.15	0.16	0.16	0.14	0.17	0.17
TiO_2	1.80	1.81	1.85	1.81	1.73	1.83	1.84	1.76	2.06	1.68
P_2O_5	0.22	0.23	0.21	0.23	0.22	0.22	0.22	0.23	0.29	0.20
MnO	0.21	0.20	0.21	0.18	0.18	0.20	0.19	0.19	0.19	0.20
S	0.044	0.075	0.084	0.091	0.088	0.082	0.098	0.083	0.100	0.071
Total	99.71	99.53	99.30	99.25	99.28	99.49	99.17	99.58	99.45	99.76

Sample No.:	9I-22	9I-23	9I-60	9I-24	9I-26	88I-121	88I-120	88I-112	88I-119	9I-28
Elevation (m):	242	274	295	304	346	372	405	405	432	454
No. in average:	2	2	2	2	2	2	2	2	4	3
SiO_2	47.4	47.5	47.6	47.5	48.1	47.8	48.2	48.5	48.0	47.9
Al_2O_3	14.8	14.7	15.4	14.8	14.5	14.7	13.8	14.2	14.6	14.3
FeO*	12.2	12.2	11.6	12.4	11.9	11.7	12.2	11.7	11.6	12.3
MgO	7.77	7.76	8.15	7.57	7.53	7.68	7.35	7.76	8.00	7.56
CaO	12.0	11.9	12.3	11.9	12.5	12.4	12.8	12.9	12.4	12.0
Na_2O	2.26	2.27	2.11	2.30	2.28	2.19	2.16	2.16	2.17	2.29
K_2O	0.17	0.16	0.17	0.17	0.20	0.18	0.17	0.17	0.18	0.18
TiO_2	2.07	2.06	1.76	2.20	1.89	1.84	1.97	1.85	1.81	2.10
P_2O_5	0.26	0.29	0.21	0.29	0.24	0.21	0.23	0.25	0.23	0.25
MnO	0.20	0.19	0.20	0.18	0.19	0.20	0.22	0.20	0.20	0.20
S	0.096	0.097	0.078	0.065	0.069	0.060	0.036	0.030	0.069	0.082
Total	99.33	99.11	99.48	99.39	99.33	98.95	99.13	99.68	99.20	99.19

Sample No.:	88I-118	88I-113	9I-29	88I-105	9I-30	88I-117	88I-114	9I-31	88I-115	88I-106
Elevation (m):	460	462	493	495	518	520	523	563	568	640
No. in average:	3	3	2	3	3	1	3	2	3	4
SiO_2	48.0	48.5	47.9	48.0	48.0	48.8	48.6	48.2	48.5	48.3
Al_2O_3	14.2	14.0	14.4	13.5	14.3	15.4	14.1	14.0	14.1	13.9
FeO*	11.8	11.8	12.4	13.7	12.3	11.7	12.1	12.2	12.1	13.6
MgO	7.96	7.75	7.33	6.68	7.50	7.60	7.79	7.41	7.53	6.84
CaO	12.6	13.0	12.4	11.6	12.5	12.8	12.9	12.8	12.9	11.7
Na_2O	2.10	2.13	2.26	2.45	2.23	2.31	2.15	2.22	2.16	2.44
K_2O	0.16	0.16	0.17	0.32	0.17	0.16	0.17	0.21	0.17	0.32
TiO_2	1.85	1.82	2.13	2.80	2.04	1.73	1.91	2.07	1.92	2.66
P_2O_5	0.21	0.20	0.25	0.28	0.25	0.23	0.23	0.27	0.25	0.27
MnO	0.22	0.22	0.19	0.22	0.20	0.22	0.22	0.19	0.21	0.22
S	0.045	0.025	0.075	0.011	0.083	0.021	0.026	0.030	0.027	0.014
Total	99.20	99.50	99.60	99.62	99.49	101.02	100.24	99.59	99.87	100.22

Exceptionally well-exposed pillow lavas on the east flank of the ridge occur up to 300 m elevation, and continuous pillow lavas are found up to about 400 m on the west flank. Above, to the highest areas investigated at 530 m, pillow breccias and interbedded glassy

TABLE 7

Glass analyses from Kalfstindar

Sample No.:	9I-1	9I-2	9I-3	9I-4	9I-10	9I-6	9I-9	9I-8A	9I-5	9I-7
Elevation (m):	162	168	182	215	360	382	382	395	436	502
No. in average:	3	7	3	3	2	3	3	4	4	4
SiO_2	47.8	47.8	47.9	48.0	47.7	47.8	47.9	47.9	47.8	48.1
Al_2O_3	16.0	15.9	16.0	16.0	16.1	15.9	16.1	15.9	15.9	15.7
FeO*	10.6	10.6	10.6	10.6	10.7	10.6	10.8	10.7	10.8	10.8
MgO	8.56	8.79	8.74	8.72	8.46	8.70	8.39	8.64	8.62	8.40
CaO	12.3	12.2	12.3	12.2	12.4	12.3	12.4	12.3	12.2	12.4
Na_2O	2.17	2.17	2.20	2.19	2.23	2.18	2.24	2.17	2.20	2.19
K_2O	0.13	0.13	0.12	0.13	0.13	0.12	0.13	0.12	0.12	0.12
TiO_2	1.40	1.36	1.36	1.34	1.42	1.36	1.40	1.35	1.40	1.41
P_2O_5	0.13	0.14	0.14	0.13	0.14	0.12	0.13	0.12	0.13	0.14
MnO	0.17	0.17	0.17	0.17	0.17	0.16	0.17	0.16	0.17	0.16
S	0.062	0.057	0.059	0.060	0.044	0.041	0.048	0.039	0.046	0.029
Total	99.35	99.35	99.53	99.56	99.51	99.27	99.59	99.35	99.35	99.48

TABLE 8

Glass analyses from Geitafell

Sample No.:	85T37	85T38	85T36	85T25	85T26	85T27	85T28	85T29	85T33	85T32	85T30	85T31
Elevation (m):	210	238	248	312	326	345	380	420	421	422	431	432
No. in average:	1	2	1	1	1	1	1	2	1	1	1	1
SiO_2	49.0	48.9	49.0	48.7	48.5	48.8	48.8	48.7	49.0	48.5	48.8	48.7
Al_2O_3	13.7	13.7	13.5	14.0	14.1	15.0	14.5	14.1	13.3	13.0	13.4	14.0
FeO*	12.9	12.9	13.4	12.2	12.2	12.1	12.4	13.6	13.8	13.9	12.8	13.4
MgO	6.40	6.54	6.41	6.72	6.92	6.87	6.98	5.96	5.82	5.91	6.32	6.40
CaO	11.6	11.7	11.5	11.4	11.8	11.8	11.7	11.3	11.2	11.0	11.4	11.5
Na_2O	2.64	2.63	2.62	2.60	2.50	2.58	2.62	2.84	2.73	2.73	2.66	2.67
K_2O	0.40	0.39	0.41	0.42	0.36	0.36	0.38	0.44	0.54	0.54	0.48	0.48
TiO_2	2.48	2.47	2.61	2.32	2.13	2.21	2.23	2.70	3.09	2.96	2.70	2.79
P_2O_5	0.30	0.33	0.30	0.32	0.26	0.29	0.26	0.34	0.41	0.37	0.36	0.37
MnO	0.23	0.23	0.24	0.21	0.23	0.23	0.22	0.24	0.25	0.25	0.23	0.24
S	0.020	0.022	0.012	0.036	0.032	0.036	0.020	0.030	0.016	0.012	0.008	0.012
Total	99.66	99.72	99.97	98.81	99.02	100.33	100.15	100.24	100.10	99.18	99.11	100.56

tuffs are more abundant than interbedded coherent pillowed flows.

Geitafell

Geitafell (Einarsson, 1960), the smallest tuya studied (0.9 km^3) occurs on a post-glacial lava plane about 25 km southeast of Reykjavik. The 509 m high tuya rises about 270–340 m above its base (Fig. 2), with the uppermost 90 m composed of subaerially erupted basalt. The steepest slopes, as well as the best gully exposures occur on the west side where coherent pillowed flows crop out in the lowermost 70 m interrupted by a few thin (1–4 m thick) layers of fragmental, partially water-worked, pillow debris and hyaloclastite. The lowest continuous lava flow occurs at 422 m. It is relatively thin (about 2 m thick), finely jointed, and overlain by semi-continuous flows made up of large, tabular, mattress-shaped pillows that extend upward to 432 m where they are scoriaceous and contain 30–40% vesicles. Upward, the lava flows

TABLE 9

Whole-rock chemical analyses of tuya lavas

Tuya:	Hlo	Hlo	Geit	Geit	Her	Her	Her	Her
Sample No:	85T3	85T12	85T31	85T37	88I336	88I338	88I347	88I350
Elevation (m):	747	1062	432	210	790	900	1320	1650
SiO_2	45.6	48.2	46.7	47.5	48.5	47.6	48.3	48.3
Al_2O_3	15.4	15.8	14.1	14.9	15.4	15.9	16.6	13.9
Fe_2O_3	4.38	2.88	4.08	2.26	2.07	1.81	2.93	2.83
FeO	7.22	9.20	9.29	10.30	8.85	8.45	7.98	10.50
MgO	8.52	6.16	9.35	7.91	8.41	9.18	7.01	6.13
CaO	10.6	12.5	10.5	11.5	13.0	12.9	12.5	11.7
Na_2O	1.57	2.22	2.15	2.24	1.90	1.80	2.24	2.29
K_2O	0.17	0.18	0.33	0.27	0.16	0.10	0.28	0.38
H_2O^+	2.59	0.52	0.89	0.59	0.39	0.55	0.21	0.43
H_2O^-	2.85	0.20	0.73	0.46	0.10	0.20	0.08	0.19
TiO_2	1.44	1.76	2.29	2.18	1.47	1.23	2.05	2.96
P_2O_5	0.12	0.17	0.32	0.28	0.13	0.11	0.20	0.28
MnO	0.19	0.20	0.22	0.21	0.18	0.17	0.18	0.22
CO_2	0.23	0.51	0.18	0.03	0.03	0.09	0.08	0.01
Total	100.88	100.50	101.13	100.63	100.59	100.09	100.64	100.12

Major elements in wt.%; FeO, H_2O and CO_2 by chemical methods (analyst: K. Lewis); other majors by XRF (analysts: J. Taggert, A. Bartel, and D.Siems).

are thicker (4–5 m), and become more laterally continuous.

Glass was analyzed from 12 samples 9 of which came from the west section and three from low on the southeast and east flanks (Fig. 2, Table 8), and whole-rock analyses were done on two samples (Table 9). Geitafell lavas contain about 25% microphenocrysts of olivine and plagioclase with olivine predominating. Pyroxene is rare as a phenocryst phase.

Major-element trends

The major elements in Herdubreid glass analyses show an overall coherence with a marked gap and trend change at about 7.5 wt.% MgO (Fig. 4). Above 7.5 wt.% MgO, as MgO decreases the glasses are enriched in SiO_2, FeO, K_2O, TiO_2 and perhaps P_2O_5, whereas CaO and Na_2O remain constant, and only one oxide, Al_2O_3, decreases. Below 7.5 wt.% MgO as MgO decreases, the glasses are enriched in FeO, K_2O, TiO_2, and to a lesser extent Na_2O and P_2O_5, and SiO_2, Al_2O_3, and CaO are depleted. Whole-rock trends are similar. The "hump" in the SiO_2 versus MgO trend (Fig. 4) indicates the removal of a crystal assemblage richer in SiO_2 than the melt below 7.5 wt.% MgO. This change marks the beginning of clinopyroxene fractionation.

The importance of plagioclase crystallization through the entire sequence is emphasized by comparison of whole-rock and glass compositions. Above 7.5 wt.% MgO, the whole rock has more CaO and MgO and about the same Al_2O_3 as the glass whereas all other elements are depleted. Below 7.5 wt.% MgO, the whole rock has more CaO and Al_2O_3 and about the same MgO than the glass, and all other elements are depleted. Changes in slope of the glass trends indicate that the crystal assemblage below 7.5 wt.% MgO relative to that above has more SiO_2 and CaO, about the same Al_2O_3 and P_2O_5, and less Na_2O, K_2O, TiO_2, and FeO. Similarities in the whole-rock and the glass trends indicate that the chemical changes are not simply the result of more complete crystallization so as to produce more evolved glasses, but

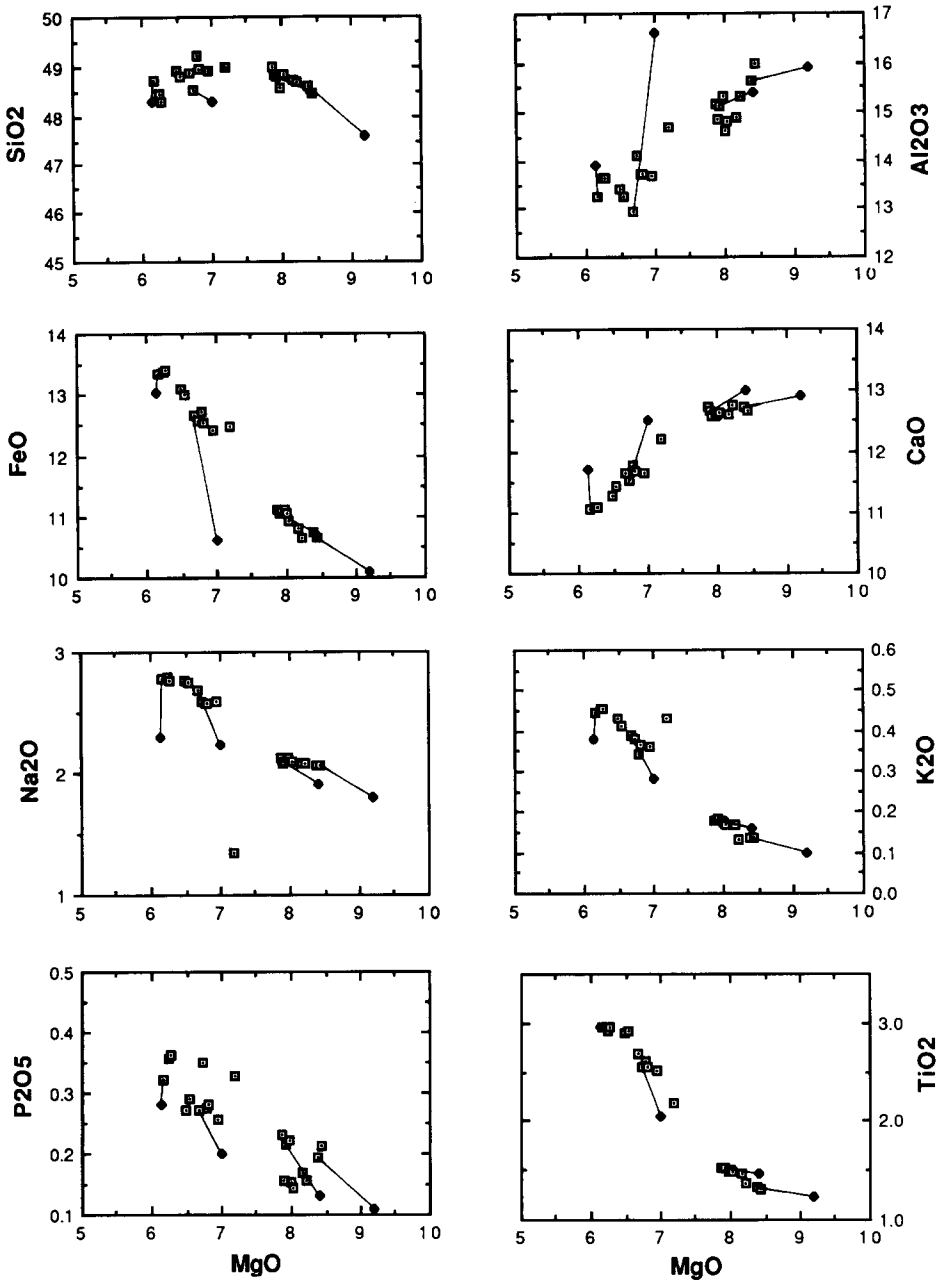

Fig. 4. MgO-diagrams for samples from Herdubreid. Glass analyses are shown by square, and whole-rock analyses by solid diamond.

that crystals were removed from the evolved lavas before eruption.

Glass compositional trends at the other five table moutains (Fig. 5) show similarities to those at Herdubreid, although compositions are commonly more restricted in MgO content, and scatter is commonly greater in the data arrays. At Hlodufell, as MgO decreases, all elements increase exept for CaO and Al_2O_3, both of which decrease. At Raudafell, as MgO decreases (which only ranges 0.6 in weight percent), all elements increase except

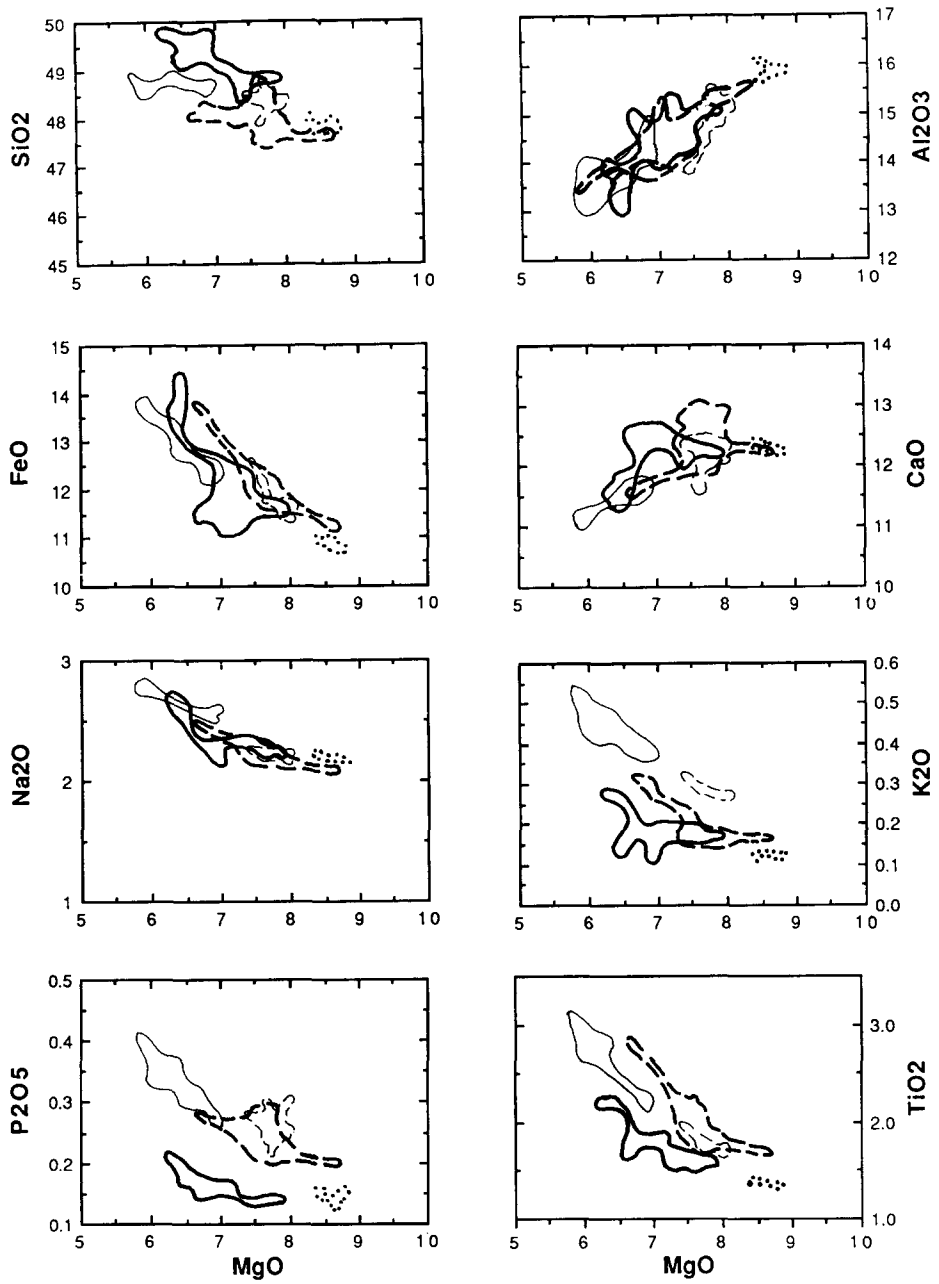

Fig. 5. MgO-diagrams showing glass analysis fields for five tuyas: Hlodufell (heavy solid line), Efstadalsfjall (heavy dashed line), Raudafell (light dashed line), Kalfstindar (dotted line), and Geitafell (light solid line).

for Al_2O_3 which decreases, and CaO, SiO_2, and P_2O_5 which remain about constant. At Efstadalsfjell, as MgO decreases, all elements increase except for CaO and Al_2O_3 which decrease. SiO_2 shows some scatter with a poorly defined maxima at about 7.5 wt.% MgO. At Kalfstindar, glasses (all collected considerably below the water-level) are restricted in MgO content, 8.4–8.7 wt.%, and are the most primitive analyzed. At Geitafall, as MgO de-

creases, all elements increase, except for CaO and Al_2O_3 which decrease, and SiO_2 which remains about constant. Geitafell contains the most evolved glasses analyzed with MgO < 6 wt.% in 25% of the samples.

The temperature of the magma can be estimated from various mineral-glass analyses including the distribution of FeO and MgO between olivine and glass. From a study of such data, coupled with experimental measurements, an empirical method has been developed for estimating the temperature of Icelandic melts from glass analyses alone (Gronvold and Makipaa, 1978). At Herdubreid (which has the greatest compositional range of the tuyas studied) the FeO*/(FeO*+MgO) glass weight ratio ranges from 0.56 to 0.68 which indicates temperatures of 1228 to 1168°C. Hence the melt temperature decreased only about 60°C during the growth of Herdubreid.

In summary, the lavas and glasses from each of the tuyas display coherent chemical trends that suggest a single cycle of fractionation. Hence each tuya was probably built in a single eruptive sequence. During tuya growth, chemical trends indicate that plagioclase and olivine removal controls glass chemistry down to about 7–7.5 wt.% MgO, and that clinopyroxene was also removed from the more evolved rocks. Temperature variations corresponding to these compositional changes are generally less than 60°C.

Major-element changes from base to top of tuyas

Samples collected from the base to the summit of the tuyas are believed to generally represent a time sequence of eruption with oldest near the bottom, proceeding to youngest at the capping lavas of the summit. This sequence is locally obscured by landsliding and draping by younger materials (including pillowed lavas) on the flanks of the edifice.

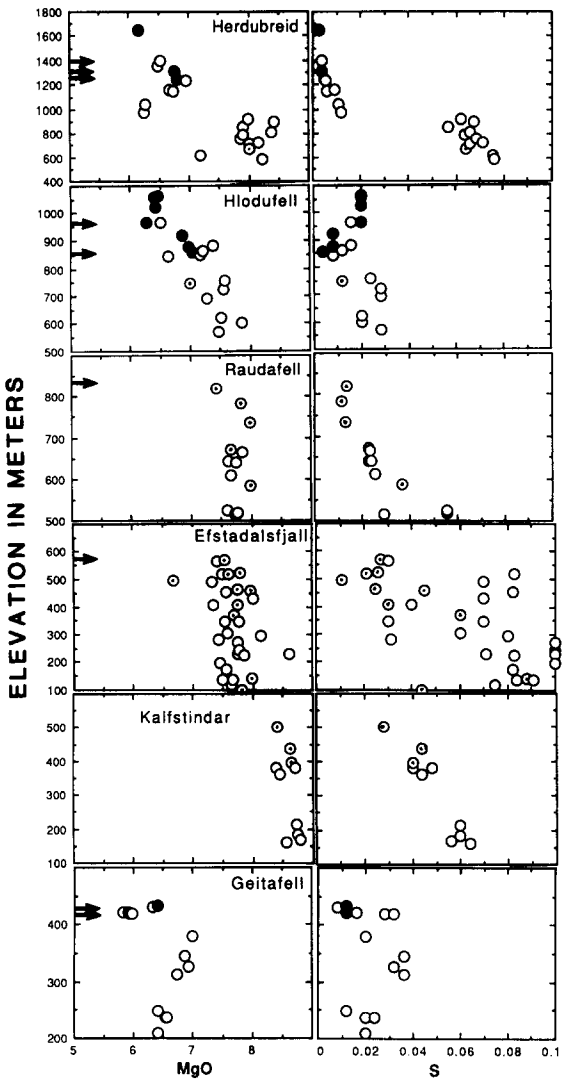

Fig. 6. Weight percent of MgO and S of glass and the elevation of collection at the six tuyas studied. Rock types are pillows (open circle), breccia, hyaloclastite, or tuff (dotted circle), and lava flow (solid circle); arrows indicate field-determined elevations of water level; water level at Kalfstindar is about 700 m.

The largest variation in lava composition from base to top occurs at Herdubreid. Here MgO decreases systematically upward (Fig. 6). Hence, the trends of the other oxides relative to MgO (Fig. 4) also reflect trends upward in the tuya and therefore trends through the course of the eruption that built the volcano.

Hlodufell, Efstadalsfjall, and Kalfstindar, show the same trends as Herdubreid with MgO decreasing upward (Fig. 6), but the trend at Kalfstindar is faint since the MgO range is small. Geitafell shows an irregular trend with the more primitive (high MgO) glasses just beneath the subaerial cap, but the most evolved glasses near the summit. Only the Raudafell glasses show no trend of MgO with elevation, but the total range of MgO is 0.6%, less than that for the other tuyas except for Kalfstindar.

In summary, three of the six tuyas show glasses and lavas that clearly become more evolved (lower in MgO) upward, and one other shows possibly such a trend. Moreover, the tuya farthest below water-level (Kalfstindar) has the most primitive glasses, and the tuya erupted beneath the thinnest ice (Geitafell) has the most evolved glasses. This change in composition is apparently produced by removal of crystallized phases from the melt during volcano growth. The general uniformity of this trend in four of the six tuyas studied supports the notion based on the regular compositional trends at each tuya that the volcanoes are monogenetic, and were built during a single eruptive sequence lasting a relatively short time, perhaps years or decades.

Control of glass sulfur content by eruptive process

The sulfur content of basalt glass provides a basis for estimating the position of a volcanic vent relative to water-level. The volatile elements (including S) dissolved in subaqueously erupted lavas are contained by hydrostatic pressure whereas they escape by exsolution from subaerially erupted lava.

Fresh submarine lava dredged from the axis of the Reykjanes Ridge south of Iceland below a depth of 200 m contains an average of 0.084 wt.% sulfur, whereas that collected between 200 and 43 m depth, contains 0.043–0.064 wt.% (Moore and Schilling, 1973). Likewise, lava erupted below sea level from Mauna Loa, Hawaii, during 1877 at 690 m depth contains 0.10–0.12 wt.% S, whereas lava from the same eruption extruded at 122–133 m depth contains 0.040–0.044 wt.% S (Moore et al., 1985). Sulfur in the glass from 28 subaerially erupted Hawaiian lava flows that flowed into the sea and were collected underwater was largely lost (average of 0.0089 wt.% S, Moore and Clague, 1987). The glassy margins of three samples of Surtsey subaerially erupted pahoehoe lava flows average 0.027 wt.% S.

Hence, analyses from several sources indicate that basalt glass erupted below about 200 m water depth retains most of its S (> 0.08 wt.%) and that erupted subaerially loses a significant amount (< 0.03 wt.%). This pattern may be modified in places where magma feeding subaqueous eruptions moved through horizontally-directed conduits into regions of reduced confining pressure before final eruption (such as the submarine east rift zone of Kilauea, Hawaii. D. Clague, written commun., 1990), but such feeding systems are considered unlikely along Iceland's rift zones.

These data are in general agreement with calculations on the exsolution of H_2O, CO_2, and S from Kilauean tholeiitic magma based on volatile solubilities that indicate that vigorous exsolution occurs when confining pressure is less than 30 bars, equivalent to a water depth less than 300 m (Gerlach, 1986). Analyses of Icelandic subaqueous lava indicate that initial S content is variable, but probably somewhat closer to 0.1 wt.% than the 0.07 wt.% used by Gerlach in his calculations for Kilauean lava. Hence, 0.1 wt.% S, 0.27 wt.% H_2O, and 0.05 wt.% CO_2 are used for the initial volatile content of Icelandic tholeiitic basalt in calculations of the S remaining in the melt upon reduction of pressure (Fig. 8).

Basalt glass quenched during phreatomagmatic eruptions, where erupting lava comes

TABLE 10

Sulfur content of phreatomagmatic tuff and ash glass

Volcano	Samples	Analyses	S (wt.%)	S.D.
Surtsey	9	22	0.053	0.0082
Bjarnarey	6	16	0.064	0.0063
Ellidaey	5	12	0.064	0.0103
Storhofdi	2	10	0.057	0.0042
Grimsvotn *	1	3	0.076	0.0039

* From May 1983 eruption, north ash fan, 100 m north of the lake (sample Mus. Nat. His. no. 9169) coll. by Hrefna Kristmannsdottir).

in contact with groundwater or shallow water, and causes steam explosions, retains some S because of the dynamic, non-equilibrium style of eruption and quenching. The average sulfur content of glasses from each of four Vestmannaeyjar (Fig. 1) phreatomagmatic cones (Surtsey, Ellidaey, Bjarnarey, and Storhofdi), range from 0.053 to 0.064 wt.% S (Table 10). Hence, the glassy tuff of phreatomagmatic cones contains elevated S contents compared to subaerial lava flows because water flooding the vent has quenched the lava so rapidly that loss of S by vesiculation is curtailed.

Currently the most active subglacial volcano in Iceland is Grimsvotn beneath the Vatnajokull icecap (Fig. 1). The volcano is almost totally ice-covered, and an ice shelf about 200 m thick covers a lake within an 8-km-diameter sag in the ice believed to be a caldera. Although the subglacial volcanic system is apparently larger than the volcanoes studied, it is interesting to compare the composition of its recent ejecta with that of the tuyas described herein. The eruption of May–June 1983 (Gronvold and Johannesson, 1984) built a small ash cone above the surface of the crater lake melted in the ice shelf. Phreatomagmatic explosions produced black ash-bearing clouds that rose 4500 m in height and deposited ash fans downwind on the ice. The content of S in this glassy ash (0.076 wt.%, Table 9), is somewhat higher than that of other phreatomagmatic tephra, indicating that rapid quenching has severely inhibited S loss.

In summary, both analyses of lava quenched under different conditions and calculations based on volatile solubility indicate that subaqueously erupted lava degasses progressively more vigorously in shallower water, and that the S content will decrease accordingly. Calculations indicate that about 20 wt.% of the S will degas at 300 m depth, and 40% at 100 m depth (Gerlach 1986; Fig. 8). In addition non-equilibrium venting and quenching processes, as in the case of phreatomagmatic eruptions, may inhibit exsolution so that S is retained.

Sulfur content of tuya lavas

Glass samples from Herdubreid show an inverse relation of S content to elevation (Fig. 6). From the base of the tuya at about 600 m elevation to 900 m, S is relatively high and decreases slightly upward from about 0.075 to 0.06 wt.%. At 900 m, a notable gap in S content occurs that corresponds statigraphically to the 7.5 wt.% MgO discontinuity discussed previously which separates two regimes of major-element differentiation trends. Both this discontinuity, and the S gap, occur 350 m below the apparent water level at the time of eruption of the upper part of the tuya. Above 900 m elevation, S remains low and declines slightly from about 0.01 to $<$ 0.005 wt.% at 1620 m elevation.

Slump-induced unconformities no doubt have removed considerable portions of the lavas and breccias erupted close to the water level (Fig. 7) and could account for the compositional gap at 0.01–0.06 wt.% S.

The effect of normal downslope flow of lava and flow-foot breccia from the vent, as opposed to major slumping, is a factor that can be assessed by assuming a moderate slope of 10° on which materials flowed from the vent (as located beneath the summit crater)

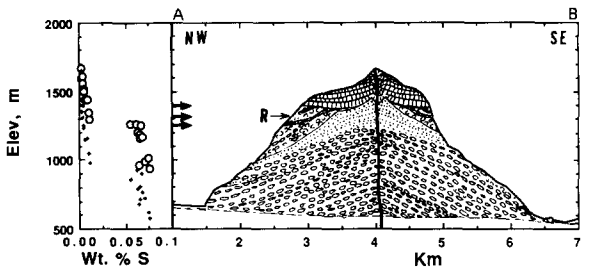

Fig. 7. Geologic section, and sulfur content of glass, at Herdubreid tuya. Lowermost red cinders (*R*), and water levels (arrows) of glacial-contained lake are shown. Section line shown in Figure 2; twofold vertical exaggeration. Sulfur content at elevation of collection shown by crosses, and at calculated elevation of vent shown by circles (assuming a 10° slope from collection site to vent).

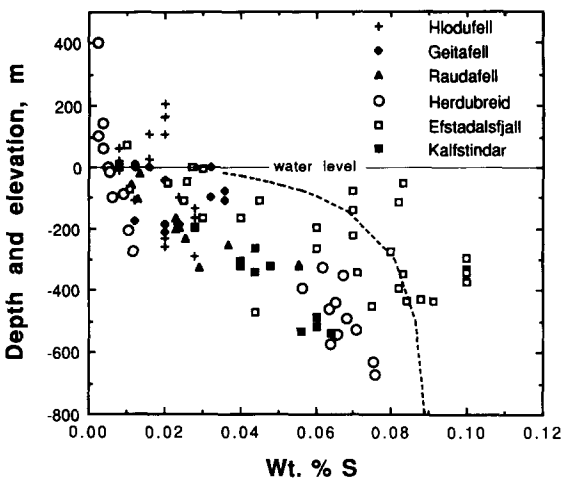

Fig. 8. Sulfur content of glass from the six sampled tuyas relative to the lowest water level measured at each. Exsolution curve of S is calculated assuming 0.1 wt.% S, 0.27 wt.% H_2O, and 0.05 wt.% CO_2 for the initial volatile content (Gerlach, 1986).

to the sample site (Fig. 7). In this simulation the samples farthest from the vent at the base of the mountain would have erupted (and degassed) about 300 m above their present elevation. Such a model can account for the fact that the elevation of the sharp S decrease of samples is 300 m below the lowest water level of the tuya as determined by the lowest subaerial lavas.

At Hlodufell, the S content of lava is relatively low (< 0.03 wt.%) even though the lowest samples are 300 m below the water level (Fig. 6). Apparently, the downslope movement of partly degassed pillowed lava flows (as at Herdubreid) has covered undegassed lava at the base of the tuya. The S content of glass shows a slight tendency to decrease upward, and above the water level it is 0.02 wt.% or less.

At Raudafell, S in glassy samples decreases upward from 0.055 wt.% 300 m below the water-level to less than 0.015 wt.% just below the capping lavas which were not analyzed because no glassy samples were collected (Fig. 6). Comparison with expected S degassing (Fig. 8) suggests that quenched lava moved downhill about 200 m from the eruptive vent where degassing occurred.

At Efstadalsfjall, the S versus elevation data array is broad, and S generally decreases upward (Fig. 6). The S content of glass from lava and breccia averages about 0.09 wt.% 400 m below the water level and declines to < 0.03 wt.% just below it. However, Efstadalsfjall is the only tuya with glass samples containing more S than expected from the degassing curve (Fig. 8). The high-S pillow lavas that occur high on the tuya may have erupted when the water-level stood 200 to 300 m higher than the 570 m elevation at the base of the subaerial lava cap. Such a higher ice surface is reasonable, since Raudafell (5 km north) recorded an ice-level at 840 m elevation. Subsequent to the eruption of the S-rich pillows near the top of the present tuya, the water-level fell to the level at the base of the subaerial lavas. This fall could have resulted from draining of the meltwater lake which, if rapid enough, could have produced a glacial outburst flood (jokulhlaup) sometimes associated with present-day Icelandic subglacial eruptions.

At Kalfstindar, despite a small range in MgO, and the fact that the highest samples are still 200 m below the water-level at 700

m, S declines upward from about 0.06 to 0.03 wt.% from 500 to 200 m below the water-level respectively (Fig. 6).

At Geitafell S is relatively low (< 0.04 wt.%) in all samples analyzed, and no obvious trend with elevation is apparent except that the two samples from subaerial flows contain among the lowest S contents (Fig. 6).

When the glass S content of all the tuya samples is compared with the sample distance above or below the lowest water-level at each tuya (Table 1), a broad trend of increasing S with increasing water depth is apparent (Fig. 8). All samples but one collected deeper than 400 m below the water-level contain more than 0.05 wt.% S, and all samples collected above water-level contain 0.02 or less wt.% S. The samples from each tuya trace a somewhat different trend because of the processes discussed including downslope movement of material from its eruptive vent, fluctuations in water-level, and perhaps original differences in magma sulfur contents.

Both MgO and S generally decrease upward in the tuya glasses (Fig. 6). The relatively undegassed glasses, those above 0.04 wt.% S, have MgO higher than 7.2 wt.%. Below 0.04% S, the MgO decreases markedly down to somewhat less than 6% MgO. However, a group of degassed samples (< 0.04 wt.% S) do contain MgO above 7.2 wt.%.

The variations in MgO and S result from separate processes. MgO decreases upward because fractionation of magma stored in shallow chambers apparently accompanies growth of the volcano. Sulfur decreases upward because degassing during eruption occurs under progressively lower pressure.

In summary the upward decrease in the glass S content of tuya lavas results primarily from degassing under progressively reduced confining pressure as the vent orifice grows upward through shallower water to emerge above the water-surface. The deviations of the glass S content of samples at a given depth below the water-level, from that predicted from volatile solubility data, probably result largely from the downslope movement of eruptive products from vent to sample site. The general deviation of the data array from the degassing curve suggest an average downslope movement of 200 m. In addition the deviations may result from the rise or fall of the water-level from the time of eruption of a given sample to the time that the vent emerged above water-level, and also from original differences in the S content of undegassed lava. The downslope movement causes lava to have less S than predicted, and a fall of the water-level causes lava to have more S than predicted.

Sulfide spherules in vesicles

Sulphur loss from the melt results in the formation of iron sulfide spherules in vesicles in the glassy margins of pillows and flows (Fig. 9). These spherules occur only in lavas that are quenched under pressure, and hence contain elevated S. The spherules form by reaction of S in the exsolved volatile phase in the vesicle with iron in the melt of the vesicle walls (Moore and Calk, 1971).

The sulfide spherules are commonly about 0.4 microns in diameter, and extend half way into the glass vesicle wall so that when they come loose from the glass, a hemispherical socket is exposed (Fig. 9C). Examination of many glassy tuya samples for which glass S analyses are available indicates that the sulfide spherules occur in vesicles only where glass S content is greater than about 0.04 wt.%. Glass with lower S concentrations contains vesicles with smooth, undecorated walls (Fig. 9A). These relations indicate that the low-S glasses high in the tuyas lost S by the loss of vesicles (degassing), and that information on the cooling environment of basaltic glass, and its S content, can be deduced from the nature of its vesicle walls.

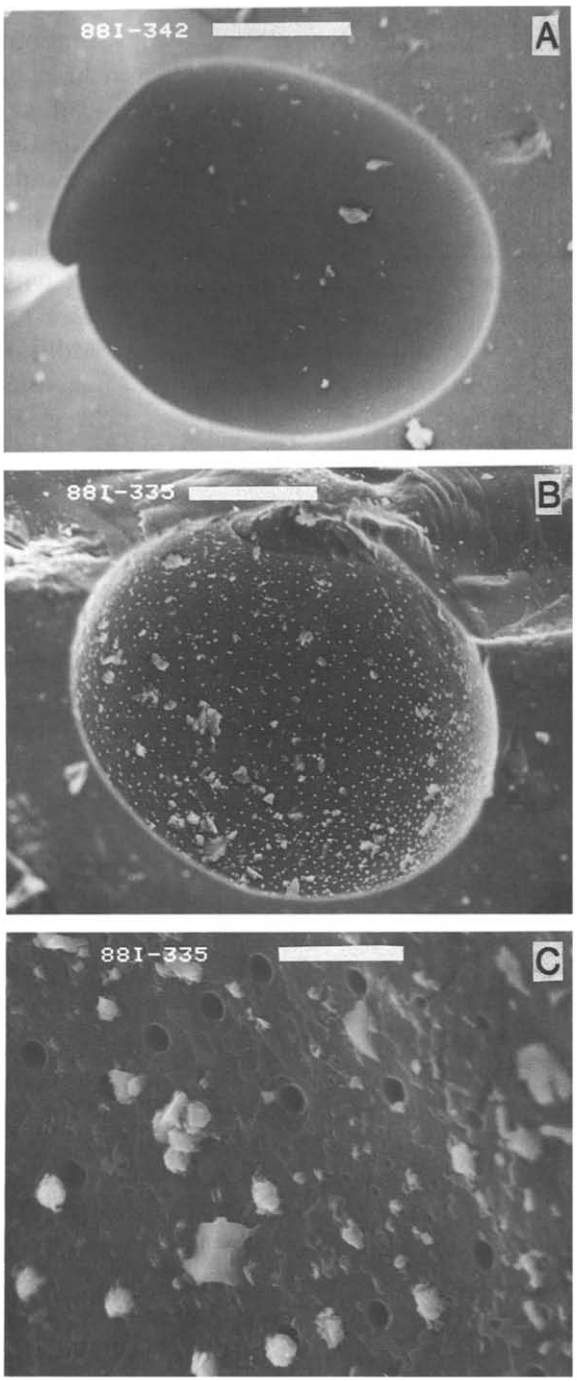

Fig. 9. Scanning electron microscope photographs of vesicles in glass from numbered samples from Herdubreid showing presence of sulfide spherules in glass of high S content. (A) 88I-342, S=0.006 wt.%, scale 40 microns long; (B) 88I-335, S=0.68 wt.%, scale 40 microns long; (C) enlargement of upper right of B showing sulfide spherules (white) and sockets in which they normally rest. Note smaller sockets on right, scale 4 microns long.

Crystal fractionation at Herdubreid

In addition to the glass and whole-rock trends at Herdubreid already discussed, modal analyses indicate that plagioclase and olivine comprise the chief phenocryst assemblage in all the rocks, but rare clinopyroxene phenocrysts occur in the upper subaerial sequence.

Plagioclase is the dominant phenocryst phase, and shows a marked increase in size, abundance, and in albite content upward in the tuya (Table 3 and Fig. 10). The plagioclase phenocrysts occur in glomeroporphyritic clots with olivine, and textural relations suggest that the two minerals grew about simultane-

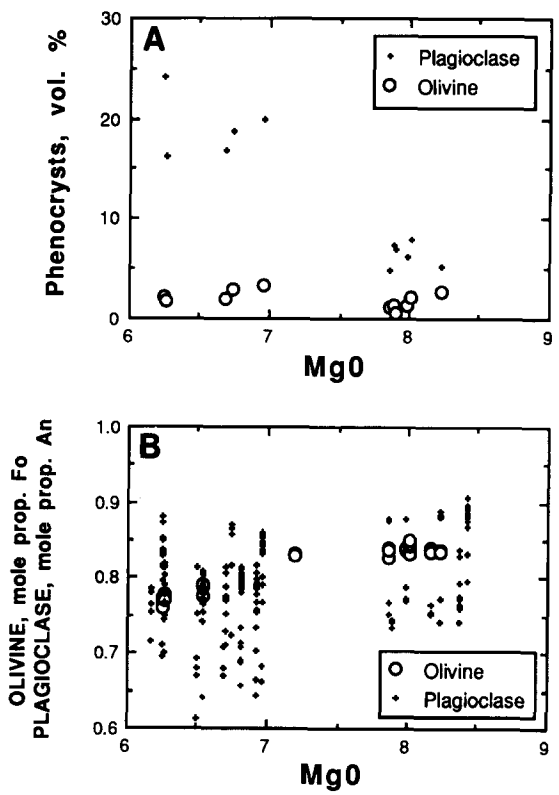

Fig. 10. A. Volume percent of phenocrysts versus glass MgO weight percent for lavas from Herdubreid. B. Composition of plagioclase and olivine phenocrysts versus glass MgO content for lavas from Herdubreid. The range of plagioclase compositions reflects extensive phenocryst zoning; the crystal rim compositions are toward bottom of plot.

ously. The plagioclase phenocrysts are zoned, but only those in the upper (subaerial) part of the tuya show intricate, oscillatory zoning.

Plagioclase in the lower, (subaqueous) region ranges from An_{90} cores to about An_{75} rims and microlites. That in the upper (subaerial) region ranges from An_{88} cores to about An_{65} rims and microlites (Fig. 10). The abundance of plagioclase phenocrysts increases abruptly from 5–8 vol.% in the lower part of the tuya to 16–24 vol.% in the upper part. The average composition of plagioclase phenocrysts decreases from about An_{83} to An_{75} from base to summit (Fig. 10).

Olivine in the lower sequence ranges from Fo_{82-85}, and that in the upper from Fo_{76-78} (Fig. 10). Average olivine content may slightly increase upward, from about 2 to 2.5 vol.% (Fig. 10). The plagioclase/olivine ratio increases upward from about 3 to 8.

The clinopyroxene phenocrysts in the subaerial sequence, like plagioclase, show complex oscillatory zoning; Mg, Fe, and Si is concentrated in the core and Ca, Ti, Al, and Cr in the quenched rim. Clinopyroxene core compositions were utilized in fractionation modeling (Table 11).

Mass balance calculations (Geist et al., 1989) making use of glass, whole-rock, and phenocryst compositions (Table 11) indicate that major-element changes from the base to the top of Herdubreid cannot be modeled in a single step by removal of plagioclase, olivine, and clinopyroxene with compositions similar to those found as phenocrysts in the lavas. Reasonable fractionation solutions were obtained using 3 steps as suggested by the prominent compositional gap and change in trends of the oxides as shown on variation diagrams (Fig. 4, Table 12). Step 1 models the trend of subaqueous, undegassed lavas at the base of the tuya (samples 88I-338 to 336), step 2 is the unsampled gap between the subaqueous and subaerial trends (samples 336 to 347), and step 3 is the trend of the subaerial, degassed samples (samples 347 to 350).

For step 1 both glass and whole-rock modeling is compatible with removal of about 3 wt.% olivine and 7 wt.% plagioclase of the composition found within the lower sequence. Step 2 requires removal of substantial clinopyroxene in addition to plagioclase and olivine; total crystals removed are 29 wt.% from the glass with plagioclase predominating, and 10 wt.% from the whole rock with clinopyroxene predominating. Step 3 also requires removal of clinopyroxene in addition to plagioclase and small amounts of olivine; total crystals removed from the glass is 13 wt.% with clinopyroxene predominating, and 32 wt.% from the whole rock with plagioclase predominating.

To account for the entire shift in composition of either the whole rock or of the glass from the base to the summit of Herdubreid requires the crystallization and removal of more than half by weight from material comparable to that which first erupted at the base of the tuya. Apparently, extensive crystallization occurred in the magma chamber and conduits underlying the subglacial volcano in the relatively short time of growth of the tuya, and most of it occurred after the tuya vent reached water level and vented at one atmosphere pressure.

The weight ratio of minerals apparently removed from the initial lavas to produce the final capping lavas is about 1 olivine: 2 clinopyroxene: 4 plagioclase. Hence the mass balance calculations require removal of a proportion of clinopyroxene that is much larger (relative to the other phenocryst phases) than that present in the lavas. We can only surmise that the clinopyroxene has been in some way more efficiently removed from the melt than olivine or plagioclase. Perhaps the earlier crystallization of olivine and plagioclase promoted their mutual intergrowth so that the olivine tended to be buoyed up in the melt by the lower-density plagioclase, thus preserving them both in the eruptive products, whereas clinopyroxene sank, or

TABLE 11

Microprobe analyses of Herdubreid phenocrysts

Mineral *:	Plagioclase	Plagioclase	Olivine	Olivine	Clinopyroxene
Position:	upper	lower	upper	lower	88I-340
No. in average:	11	7	3	5	1
SiO_2	48.85	48.01	38.15	38.86	51.98
Al_2O_3	31.65	32.07	n.a.	n.a.	2.26
FeO*	0.84	0.96	20.66	15.09	9.52
MgO	0.26	0.46	40.10	44.36	18.10
CaO	15.29	15.95	0.43	12.37	16.60
Na_2O	2.71	2.19	n.a.	n.a.	0.19
K_2O	0.07	0.04	n.a.	n.a.	n.a.
TiO_2	n.a.	n.a.	n.a.	n.a.	0.87
MnO	n.a.	n.a.	0.35	0.26	0.26
NiO	n.a.	n.a.	0.20	0.26	n.a.
Total	99.76	99.75	99.90	98.25	99.13

* Upper plagioclase contains 0.09% SrO and lower, 0.07% SrO, and clinopyroxene contains 0.28% Cr_2O_3. n.a., not analyzed.

TABLE 12

Herdubreid glass and rock fractionation solutions

Step:	1-2	2-3	3-4	1-2	2-3	3-4
Material:	glass	glass	glass	rock	rock	rock
Samples 88I-:	338-336	336-347	347-350	338-336	336-347	347-350
Parent	1.00	1.00	1.00	1.00	1.00	1.00
Olivine, lower	−0.027			−0.038		
Olivine, upper		−0.038	−0.002		−0.015	−0.042
Plagioclase, lower	−0.069	−0.162		−0.074	−0.020	
Plagioclase, upper			−0.047			−0.218
Clinopyroxene		−0.087	−0.055		−0.092	−0.058
Daughter	0.904	0.713	0.896	0.888	0.873	0.682
R^2	0.11	0.55	0.11	0.12	0.41	0.15

was accreted to the walls of chambers and conduits.

Origin of major-element variation

Modelling of trends of glass and whole-rock major-element compositions at Herdubreid suggests that crystal differentiation produced progressively more evolved, lower-temperature melts during the growth of the tuya. The change in glass composition from bottom to top corresponds to a temperature drop of about 60°C. At Herdubreid, the progression from the subaqueous to the subaerial eruptive mode was accompanied by a marked change in the eruptive products: (1) S content decreased 7-fold as a result of nearly complete degassing; (2) phenocrystic plagioclase increased 3-fold, developed oscillatory zoning, and shifted to a more albitic average composition; (3) clinopyroxene phenocrysts (with oscillatory zoning) first appeared; (4) olivine phenocrysts increased slightly in abundance and became more fayalitic in composition; and (5) the overall composition of the whole rock and the glass became markedly more evolved suggesting crystallization and removal of more than half of the melt. Detailed mineralogic studies have not been made on lavas from the other subglacial vol-

canoes, but somewhat similar major element compositional changes are present at 4 of the 6 tuyas examined.

These changes could have resulted from cooling of the magma in a shallow holding chamber or in fissures feeding the volcano during the course of the eruption so that progressively more evolved melt was produced and tapped. Such cooling would be favored because of the locus of tuya growth directly beneath an extensive ice sheet. Percolation of glacial meltwater down cracks where it would be heated and converted to steam to rise and feed a hydrothermal system could effectively extract heat from the melt stored in shallow subvolcanic chambers. However, the cooling processes operating beneath an ice sheet would probably not be much more effective than those at submarine volcanoes.

In addition to this cooling process, the relation between magma compositional changes and magma degassing suggests that subvolcanic crystallization may be promoted by the partial degassing of the magma chamber as the vent progresses upward to regions of lower confining pressure. When the vent emerges above water-level, and is eventually sealed from ingress of surface-water, the freer venting of magmatic gasses would reduce the effective vapour pressure of volatiles dissolved in the melt within feeding pipes and shallow parts of the magma chamber system. This process would be particularly effective if vigorous degassing kept the vent open to considerable depth so that fluid/vapour pressures were lowered below lithostatic pressure and volatile exsolution at depth was favoured. The reduction of H_2O, and possibly other volatiles, in the melt would raise the temperature of the liquidus (Yoder and Tilley, 1962) and cause extensive crystallization due to undercooling.

During the 20-day 1984 Mauna Loa eruption microphenocryst content of lavas sampled at the vent increased from 0.5 to 30 vol.% (Lipman et al., 1985). This dramatic increase in crystallinity of the erupted lava has been attributed to magma undercooling caused by loss of volatiles from subsurface reservoirs through the erupting vent. Such undercooling and resulting precipitation of crystals may result from the exsolution of S as well as H_2O (Lipman et al., 1985).

The extreme shifts in eruptive and degassing behaviour when the volcanic vent is close to the fluctuating water-level at the top of the ice cap will cause abrupt changes in volatile vapour pressure in the melt that may account for the presence of pronounced oscillatory zoning in plagioclase and clinopyroxene phenocrysts that is most prominent in degassed, subaerially erupted lavas. Individual, oscillatory zoned layers in plagioclase phenocrysts from the 1982 lavas of El Chichon volcano, Mexico have been attributed to previous eruptions which caused fluctuations in vapour pressure affecting phenocryst growth within holding chambers beneath the volcano (McGee et al., 1987). Hence, the effects on subvolcanic crystallization of volatile venting at or near the surface may modify the composition, and also the texture, of erupted material.

Conclusions

(1) Most tuyas studied show systematic variations in major-element content of basaltic glass and whole-rock compositions indicating they are monogenetic, and that plagioclase and olivine dominate differentiation above about 7–7.5% MgO and clinopyroxene joins the other phases at lower MgO content.

(2) Glass and whole-rock compositions in tuyas commonly decrease in MgO upwards, indicating that the magmas differentiated and became more evolved though the course of the eruption that built the volcanoes. The decrease in the MgO content of glass is as much as 2.3%, corresponding to a temperature decrease of about 60°C. At Herdubreid more than 50 wt.% of the lava as erupted at the

base of the volcano must crystallize and fractionate to produce the lava erupted at the top.

(3) Sulfur content of basalt glass commonly decreases upward in the tuyas, and is a measure of the change in depth of water (or ice) cover at the eruptive vent. The maximum S content averages about 0.8 wt.% and the S content of subaerially erupted lava is < 0.02 wt.%. Refinement of the relationship of depth versus S content of glass is conditioned by uncertainties in the vertical distances that material has moved from vent to sampling site, and in the fluctuations of water level during the course of the eruptions. Sulfide spherules only appear in vesicles in glass when glass S content exceeds about 0.04 percent; consequently the character of vesicles provides information on the nature of eruptive activity.

(4) The crystal differentiation responsible for the increasing production of more evolved, lower temperature, melts during the growth of the tuyas may result from cooling and crystallization within shallow magma chambers and feeders beneath the volcanoes. Additionally, subsurface crystallization may be favoured by partial degassing of chambers and feeders beneath the volcano through eruptive vents when they grow above water-level. Reduction of volatiles within the subsurface basaltic melt will elevate the temperature of the liquidus and cause increased crystallization and fractionation.

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