MAGMA MIXING AND HYBRIDISM: A PRELIMINARY STUDY FROM SOUTHERN ICELAND

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ABSTRACT

The importance of magma-mixing in the generation of intermediate rock types is discussed in the light of two occurrences of mixed rocks found in the Tindfjallajökull silicic centre, S.-Iceland. The first being a minor mafic part of the large Thorsmörk ignimbrite (Jørgensen, 1980), demonstrates the formation of non-linearly derived hybrids through differential interdiffusion of elements ,in connection with resorption/crystallization of phenocryst phases, demonstrated by the occurrence of abundant xenocrysts of feldspar and pyroxene and new crystallization of pyroxene and magnetite in the hybrids. The

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second occurrence is a mafic lava of benmoreitic composition, containing xenocrysts of acid and basic feldspars and pyroxenes in addition to unresorbed phases in equilibrium with the melt. Several other rocks show disequilibrium features which may indicate mixing of two contrasting magma types, though other rock types contain phases which may be remnants from partial melting of crustal material, as well as of fractional crystallization.

INTRODUCTION

The contemporaneity of acid and basic magmas in Iceland has challenged petrologists since the days of Bunsen, and explanations of the relationship have changed several times. Since the early sixties two contrasting schools of thought have evolved, the first explaining the phenomenon in the terms of fractional crystallization best illustrated by the Thingmuli (Carmichael 1964, 1967) and the Setberg centres (Sigurdsson 1970), or in terms of partial melting of crustal material as proposed by Walker (1966) and further evolved by Grønvold (1973), Sigvaldasson (1974), Johannesson (1975) and recently in a comprehensive model by Oskarsson et al. (in press).

The present study is mainly concerned with the importance of magma-mixing in the formation of intermediate rocks exemplified by the late Pleistocene Tindfjallajökull silicic center in S.-Iceland, and an associated pyroclastic flow deposit, the Thorsmörk ignimbrite.

THE THORSMORK IGNIMBRITE

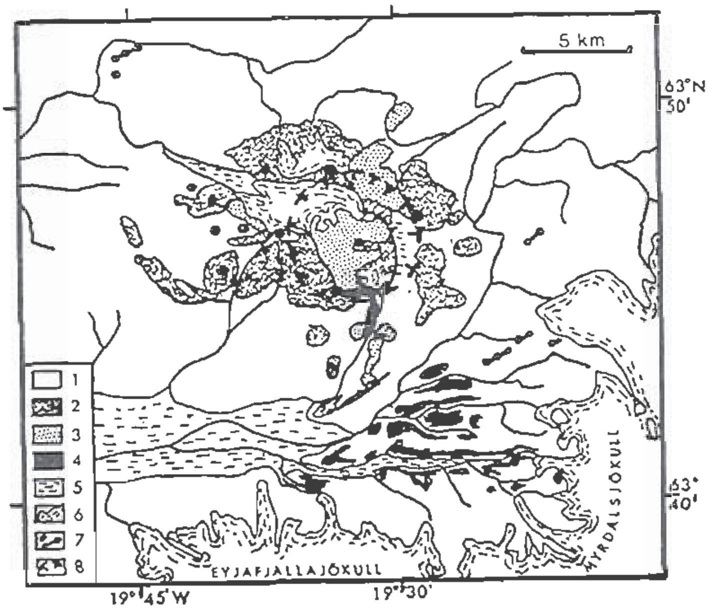

Fig. 1 — Simplified geologic map of the Tindfjallajökull silicic center and surroundings. 1 : basalts undifferentiated. 2 : evolved rock types, basaltic andesites to benmoreites. 3 : rhyolites. 4 : The Thorsmörk ignimbrite. 5 : alluvium. 6 : icefields. 7 : late to postglacial vents. 8 : inferred caldera fault. Rocks of neighbouring centers undifferentiated.

The Thorsmörk ignimbrite (Fig. 1) was originally described by Thorarinsson (1969), and in more detail by Jørgensen (1980a, b). The mapping of the ignimbrite demonstrated that it originated within the caldera-region of the Tindfjallajökull silicic center during the penultimate interglacial of the region (approx. 200.000 years old). It was emplaced as a series of low energy pyroclastic flows which buried the surrounding lowland to a max. depth of > 200 m in a prolonged eruption sequence. The lower part of the ignimbrite is welded and crystallized after emplacement, producing a compound cooling unit. The present outcrop are aof 80 km^2 must have contained an original volume of 6 km^3 ignimbrite (4 km^3 dense rock equivalents) indicating a probable original total volume of the order of 6-8 km^3 dense rock.

Petrologically 95 % of the juvenile material is a rather homogeneous comendite showing small, but significant, variations in the phenocrysts. Variations in the feldspar phenocryst compositions indicate a small, but permanent thermal gradient in the magma-chamber prior to eruption, while trends in the pyroxenes indicate falling fO_2 during crystallization, stabilizing the formation of fayalite in the upper part of the magma-chamber. Exsolution phenomena and large ranges in haematite and ulvøspinel contents in the oxides from the uppermost part of the ignimbrite indicates disequilibrium conditions in the magma-chamber at this stage of the eruption, probably resulting from external heating of the magma-chamber.

In addition to the comendite, the ignimbrite contains a suite of mafic glasses constituting approximately 5 % of the juvenile material. This material ranges in composition from transitional basalt (in the sense of Jakobsson, 1972) through mugearite and benmoreite to subcalcic rhyodacite, spanning the whole silica range from 46 to 71 % SiO_2.

The material occurs as glass shards and lapilli fragments, which are often transparent, especially the more silica rich varieties, but larger clasts are often tachylitised, due to crystallization of a fine web of feathery pyroxene and skeletal magnetite, Fig 2 B.

The material is compositionally rather heterogeneous even within single fragments, Fig. 3. The heterogeneity is often seen as colour banding in the transparent glasse, Fig. 2A, as lighter or darker patches, or various different shades of brown or grey, probably a function of different oxidation ratios. True banded pumices with alternating dark and light bands occur throughout the ignimbrite, but change in character from bottom to top, the mafic bands becoming more siliceous with increasing height in the ignimbrite and interdiffusion becoming more

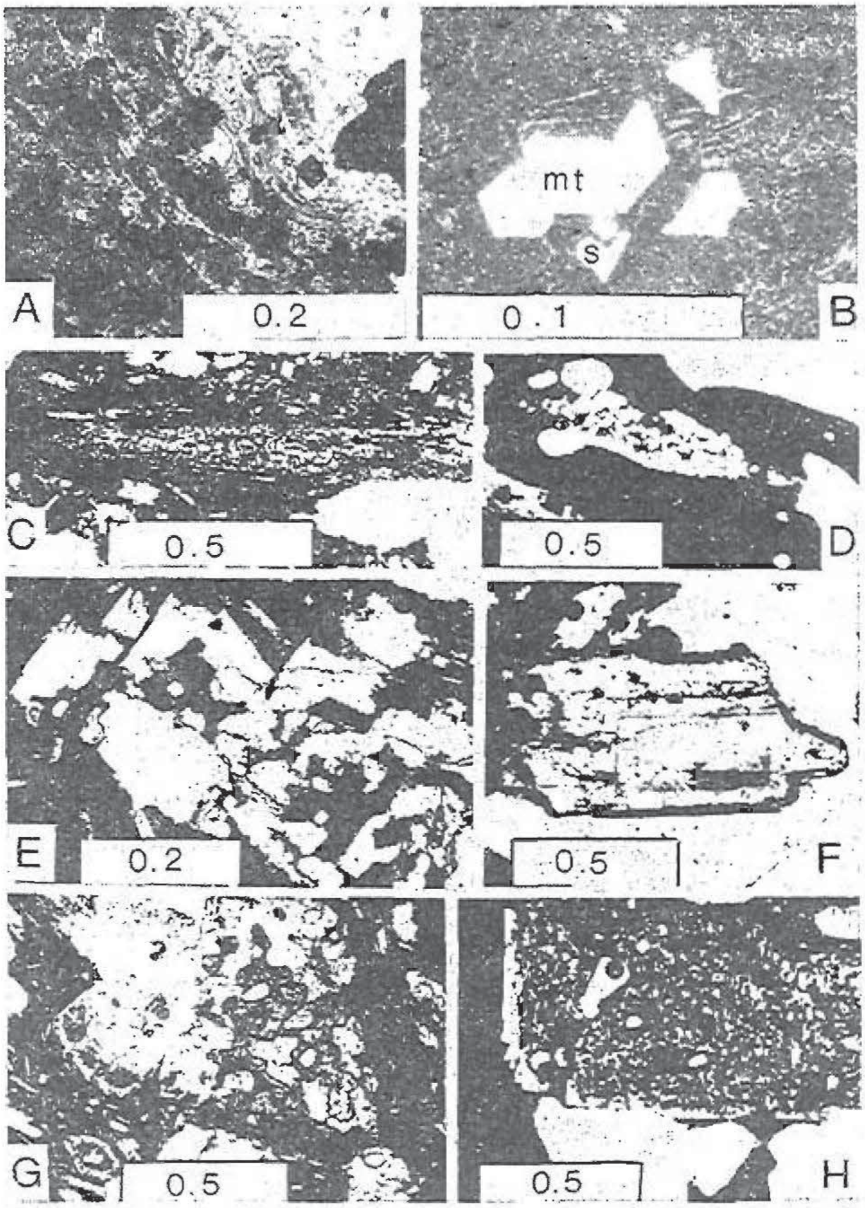

Fig. 2 — Microphotographs from the Thorsmörk ignimbrite and Tf 13.

A. Transition from dark basalt to light basaltic andesite (with magnetite microcryst). Lower part of Thorsmörk ignimbrite.

B. Magnetite (mt) and sulfide globules (s) in matrix of feathery pyroxene and glass of mugearitic composition. Middle part of THI. Reflected light.

C. Fe-hedenbergite with abundant glass inclusions. Tf 13.

D. Fe-hedenbergite with abundant glass inclusions in benmoreitic glass. Uppermost part of THI.

E. Strongly resorbed basic plagioclase. Tf 13.

F. Slightly resorbed oligoclase mantled by anorthoclase in muggearitic glass, Lower part of THI. Partly crossed N.

G. Fingerprint textured anorthoclase with oligoclase rim. Hollow ferrosalite microcryst in lower left. Tf 13. (Dark amoeboid patch in anorthoclase is artifact).

H. Strongly resorbed anorthoclase with oligoclase rim in benmoreite glass. Uppermost part of THI.

Bar scale in mm.

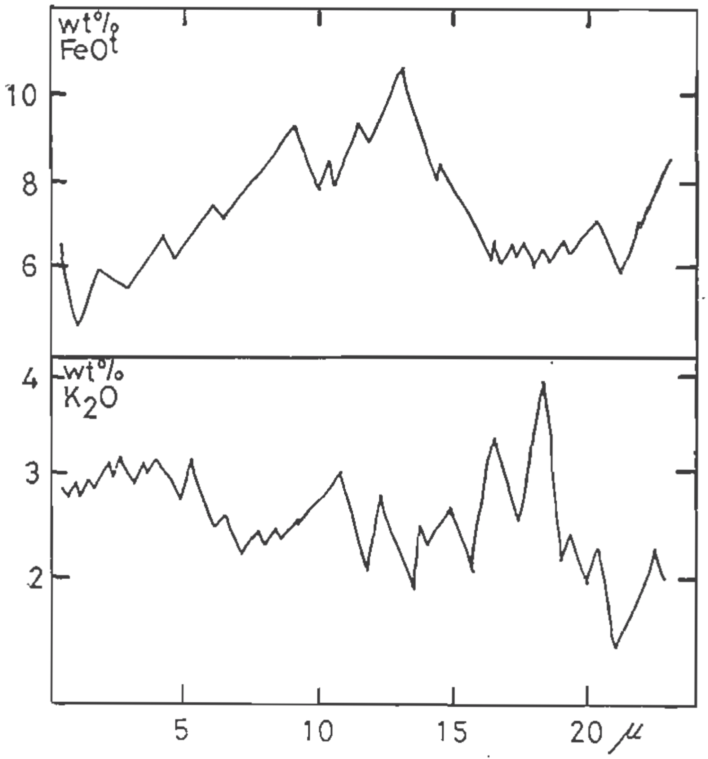

Fig. 3 — Tracings of elemental scans across heterogeneous glass, for Fe and K. Uppermost part of THI.

pronouced. The banded pumices indicate mechanical, incomplete mixing, while large mafic clasts of benmoreitic composition, Table 1 : Th2, represents a much more advanced stage of diffusional mixing where the more acid glasses only occur as occasional small patches more or less digested in the large mass of mafic benmoreite.

The most basic material is homogeneous and may occur as spheres of the type formed during Hawaiian fountaining, Heiken (1972) but is mainly found as shards and subrounded, vesiculated lapilli, of the type mainly found strombolian deposits, Walker and Croasdale (1972). The mugearitic material is mainly found as strongly vesiculated clasts of reticulite type, Heiken (1972). The benmoreitic material is very massive and little vesiculated while more siliceous material becomes increasingly more vesiculated becoming true pumices around 70 % SiO_2.

The mafic glasses contain a number of minerals displaying a wide range of textures. The basic glass apparently contained rare phenocrysts of olivine, augite and labradorite plagioclase, which all occur more or less resorbed. The intermediate glasses crystallized ferrosalitic pyroxenes (Fig. 4), oligoclase plagioclase, magnetite and sulphide globules as phenocrystal phases, while Fe-hedenbergitic pyroxene (Fig. 4), and magnetite occur as microcrystal phases. The phenocrysts are inevitably resorbed (Fig. 2F), but not as much as the abundant xenocrystal phases from the comendite, mainly Fehedenbergite with abundant glass-inclusions (Fig. 2D), and anorthoclase commonly displaying finger-print textures, or even higher degrees of resorption (Fig. 2H).

The mixing apparently took place between the temperature of the comendite, 915° C (Fe-Ti oxide temperature after Buddington and Lindsley, 1964) and 1100° C for the basalt (olivine/liquid temperature after Roeder (1974) and Bender et al. (1978)). The magnetites of the intermediate compositions are very hig in ulvøspinel content indicating rather reduced conditions.

THE TINDFJALLAJOKULL SILICIC CENTER

The Thorsmörk ignimbrite originated within the Tindfjallajökull silicic center, and a major question was then whether intermediate rocks comparable to hybrid compositions found in the ignimbrite, was present as independent rock units within the center.

The Tindfjallajökull silicic center was mapped in detail by Larsen and Jørgensen (personal communication), and initial results show that the center is mainly composed of transitional basalt with abundant sub-calcic to peralkaline rhyolite (Table I), with minor intermediate rocks of mainly basaltic-andesites with

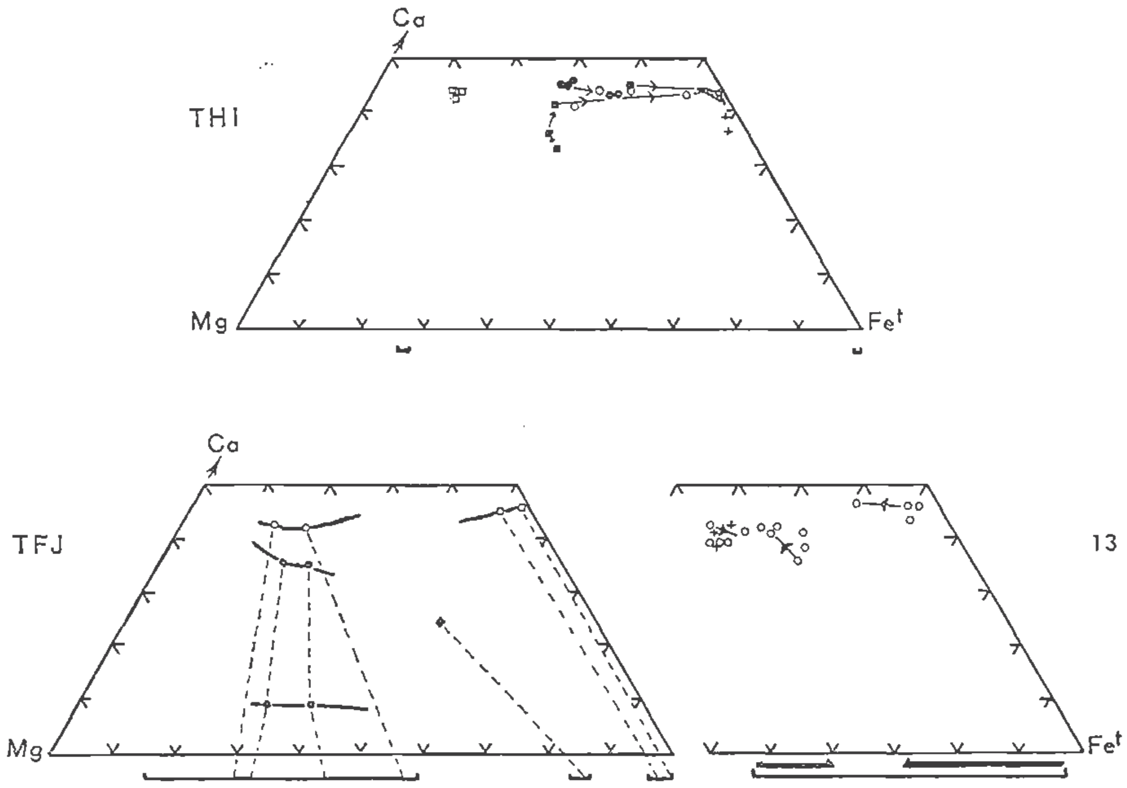

Fig. 4 — Pyroxene quadrilaterals (preliminary) for the Thorsmörk ignimbrite (THI), the Tindfjallajökull igneous suite (TFJ) and sample TF 13 (13). Symbols : *THI.* hatched area : general field of comenditic pyroxenes. Filled squares and circles : zoned pyroxenes. Filled squares and circles : zoned pyroxenes in comendite. Crosses : microcrysts in quenched rhyodacite. Open triangle : microcryst from mugearitic glass. Open circles : phenocrysts from various hybrid glasses. Open squares : phenocrysts in basic glass. Lower bars : associated olivines. *TFJ.* Heavy lines : generalised pyroxene trends for the igneous suite. Dashed lines : connects coexisting cpx, olivine and opx for different assemblages. Open circles : basalt. Closed circles : intermediate rocks. Open squares : acid rocks. Diamond : hornblende bearing rhyolite. *13.* Heavy arrows at bottom : shows direction of zoning in olivines. Crosses : microcrysts in glomerocryst.

marked alkaline affinities (Fig. 5). The intermediate rocks show several complexities, some of them looking very much like ordinary icelandites, while others seem to be true mugearites. One of the rocks, Tf. 13, seemed to be a rather homogeneous

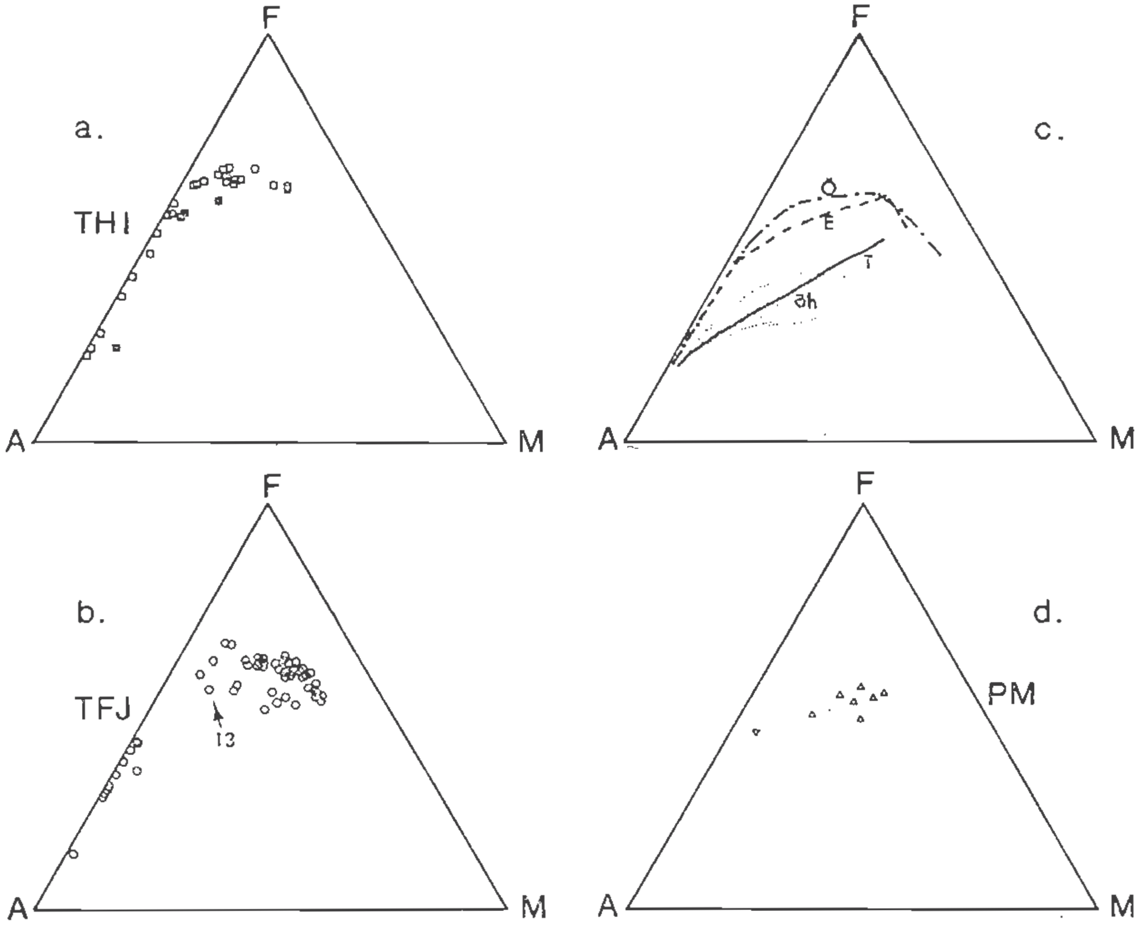

Fig. 5 — Representative AFM diagrams, (wt. % $Na_2O + K_2O - FeO^t - MgO$). *a.* The Thorsmörk ignimbrite suite. Open squares : single spot microprobe analyses. Filled squares : whole rock analyses. *b.* The Tindfjallajökull igneous suite, whole rock analyses. Arrow points to sample Tf 13. *c.* Comparative trends. O : Öræfajökull main trend, (Prestvik, 1980). E : Eyjafjallajökull, (Arney, 1978). T : Torfajökull mixed trend, (Grønvold, 1973). öh : Öræfajökull hybrid field, (Prestvik, 1980). *d.* Partial melts from gabbro-standing triangle) and granophyre (inverted triangle) xenoliths from Tindfjallajökull hyaloclastites, (Larsen, 1979 and personal communication).

benmoreite, but microprobe investigation proved it to be very heterogeneous, containing phenocrysts of both Fe-hedenbergitic and augitic compositions zoned to ferrosalite, while similar trends are found in the olivines, (Fig. 4) and in the feldspars, which show finger-print textures, (Fig. 2G) and strong disintegration (Fig. 2E). Microcrysts in vesicular glomerocrysts have compositions comparable with the most basic pyroxenes, while the microcrysts in the groundmass are ferrosalites. This mineralogic evidence indicates that the rock resulted from mixing of approximately equal amounts of comendite and transitional basalt, and thus is very similar to the benmoreitic compositions found in the Torsmörk ignimbrite. Many other rocks in the Tindfjallajökull centre shows disequilibrium relationships, but many of these are not as readily interpreted as magma-mixing as was the Tf 13. It appears as though two parental basaltic compositions are present, a dominant low magnesium transitional basalt type and a subordinate high magnesium tholeiitic type, (Fig. 5). The transitional basalt type seems to grade continously into rocks of basaltic andesite composition, an evolution most probably resulting from fractional crystallization. More evolved rocks inevitably show disequilibrium features, and in more finegrained varieties two sizegrades commonly appears thouroughly mixed, indicating mixing of two magmas not very different in composition. The comendites only rarely shows disequilibrium features, indeed many of them are only sparsely porfyritic and the minerals present shows only very restricted compositional ranges. The subcalcic rhyolites on the other hand commonly shows disequilibrium features in the shape of resorption of phenocrysts as well as clots of quenched mafic material, even for the most evolved rhyolite, a hornblende-fayalite-ore-allanite-oligoclase-phyric, high silica rhyolite. The tholeiitic basalt type does not seem to have any direct successors, but a scattered selection of rocks falling off the main trend of evolution for the center, (Fig. 5) and generally showing abundant disequilibrium textures, may be more or less associated with this type. The abundance of more or less melted xenoliths of gabbroic or granophyric composition found in the frequent hyaloclastites of the center, Larsen (1979), presents a further complication. Partial melts formed from these, Fig. 5 (Larsen, 1979) plot in the scattered field of compositions described above. The occurrence of pyroxene phenocrysts with partly exsolved orthopyroxene lamellae, characteristic of slowly cooled plutons, in some very plagioclase-rich rocks, seems further evidence of the importance of contamination from wall rocks.

DISCUSSION

The data presented above show that magma-mixing is an important, though not the only, operative proces in the formations of the intermediate rocks of the Tindfjallajökull. One may then question the importance of this observation on the regional scale. Silicic hybrid rocks have recently been described from the Øræfajökull center in SE-Iceland, Prestvik (1980), and many of the features described are comparable with those of the present work. Grønvold (1973) described and gave analyses of hybrid rocks from the Torfajökull silicic center S.-Iceland, and so did Wetzel et al. (1978). The origin of the Hekla andesites have variously been attributed to fractional crystallization of basalt, Baldridge et al. (1973), partial melting of crustal material, Sigvaldasson (1974) and magma-mixing Wetzel et al. (1978). The Eyjafjallajökull igneous series (Arney, 1978), on the other hand was claimed to be solely a product of fractional crystallization, in spite of the occurrence of mechanically mixed lavas and abundant disequilibrium features, Arney (1978). The important difference between the earlier described occurrences of hybrid rocks and those of the present study is, however, the marked deviation from a linear mixing line of the hybrid composition, especially for elements such as Na, Fe, P, Mn (enriched) and Ca, Mg, Ti (depleted). This is a clear indication that processes other than mechanical mixing were operative, of which differential interdiffusion, as observed on a micro-scale, and, resorption/crystallization of phenocrysts, of the type proposed by Aderson (1976), were the most important, while both fractional crystallization and partial melting of crustal material, definitely were important in the formation of several rock types present in the TFJ center. Similar complex processes undoubtedly operated in the formation of rcoks from the neighbourin gsilicic centers described above, though more detailled studies are needed to establish to what degree.

Eichelberger (1978), proposed that thorough mixing of magmas to produce intermediate rocks were characteristic of subduction zone situations, due to thick crust and thus long residence time for magmas in this environment, while rift areas were characterised by scarce intermediate rocks and a pronounced bimodality, due to thin crust and correspondingly short residence time for magmas. The present data corresponds well to this model, the amount of intermediate material being insignificant against the abundant basalts and rhyolites. Further the data presented corresponds extremely well to the model presented for southern Iceland by Oskarsson et al. (in press), the Tindjfjallajökull actually being placed in the middle of their zone most favourable of mixing, the transitional basalt corresponding to their wet alkali basalt, and the tholeiitic type being injected from the Eastern Rift Zone proper, and through mixing/crystallization resulting in the other observed rock types. The melted xenoliths could then be remnants after melting of amphibolite, though amphiboles are extremely rare, even in unmelted samples. The composition of the partial melts is further more similar to tholeiites, but this may not be significant, as it could be a function of very local conditions with the liquid later being modified during collection.

CONCLUSIONS

The present study has demonstrated the importance of magma-mixing in the production of intermediate rocks in the Tindfjallajökull silicic center, suplementary to other petrogenetic processes, and implied this probable importance in the case of several other centers, though the origin of the parental composition remains unresolved. The wide range of compositions present in the Tindfjallajökull center, however, indicates that this center remains a key area to the understanding of the fundamental petrogeentic processes operating in this region, and is thus important to the understanding of oceanic island volcanism in general.

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TABLE I

REPRESENTATIVE ANALYSES

	Tf 1	*Tf A1*	*Th 1*	*Tf 13*	*Th 2*	*Tf 236*	*Th 3*
SiO_2	47.12	45.28	46.15	57.64	61.65	72.29	74.28
Al_2O_3	13.92	14.93	12.70	13.17	12.77	11.51	11.41
TiO_2	2.97	3.96	4.10	1.83	1.31	.23	.17
$FeO.^t$	12.35	14.20	15.66	10.78	10.80	3.36	2.73
MnO	.19	.20	.32	.29	.33	.10	.07
MgO	8.13	6.57	4.98	1.83	.65	.06	.02
CaO	10.57	10.16	9.64	4.87	3.83	.46	.42
Na_2O	2.83	2.92	3.13	5.66	5.42	5.89	4.82
K_2O	.54	.53	.73	1.59	2.41	3.80	4.17
P_2O_5	.35	.38	1.03	.64	.36	.01	.01
Sum	98.97	99.13	98.46	98.30	99.47	97.71	98.10

Explanation :

Tf 1 :basalt from northern part of Tindfjallajökull silicic center
Tf A1 : biotite bearing basalt from SW part of Tfj. center
Tf 13 : mugearite from central part of Tfj. center
Ff 236 : comendite from northern rim of Tfj. caldera
Th 1 : basic shard from middle part of Thorsmörk ignimbrite
Th 2 : benmoreitic shard from uppermost part of THI
Th 3 : average comendite from THI
All Tf : whole rock analyses from G.G.U. Geochemical Lab.
All Th : single point microprobe analyses
All Fe : calculated as FeO for convenience.