MAGMA MIXING IN ICELAND

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ABSTRACT

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Magma mixing is evaluated as a process in the Icelandic crust. Two general types of magma mixing are thought to occur: the mixing between silicic and mafic magmas and the mixing between individual mafic magmas.

The mixing processes between a silicic and mafic magma are evaluated for the Austurhorn and Vesturhorn Intrusions located in Southeastern Iceland. Simple mechanical mixing processes are thought to predominate in these complexes, although diffusional processes probably play a minor role. The interaction of mafic and silicic magmas in the Icelandic crust may have many important ramifications on both silicic and intermediate eruptive products, the eruption mechanics of silicic magmas, and control the evolution of the central volcanic complexes.

Many examples of intermediate compositions occur in these silicic-mafic complexes and in those found in other magma mixing localities elsewhere in Iceland. A comparison of the intermediate compositions found in these known examples of silicic-mafic magma mixing with the intermediate lava variation in Iceland indicates that many similarities are found between groups. This suggests that intermediate lavas are the result of silicic-mafic magma mixing processes. Simple fractional crystallization models are not consistent with the observed trace element ratios (e.g., (Ce/Yb)N, (La/Lu)N, (Ce/Lu)N) and the abundances of intermediate and silicic rocks.

Mafic magma evolution (i.e., high magnesia basalt through ferrobasalt) is most consistent with a modified open system model. The open system model is modified from the terace element model of O'Hara (1977) because it is proposed that major element changes are occurring in the magma chamber and the system is non-steady state. Open system processes can account for the range of trace element ratios observed [e.g., (Ce/Yb)N, (La/Lu)N, (Ce/Lu)N], the distribution in K_2O, TiO_2, P_2O_5 and TiO_2/P_2O_5 ratio with volume of eruptive products, and the aerial distribution of lavas observed. Simple fractional crystallization, partial melting models, and mantle heterogeneity models cannot account for all the variation observed.

Mafic magmas effected by modified open system processes may mix at any point in their evolution with silicic magmas and form intermediate compositions. Silicic magmas are most likely generated by the partial melting of a hydrated basaltic crust.

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GENERAL INTRODUCTION: PART I

The Austurhorn and Vesturhorn silicic intrusions, located in Southeastern Iceland, have associated with them silicic and mafic complexes. The silicic and mafic complexes consist of pillow-like bodies of mafic rock entirely surrounded by silicic rock. The mafic pillow-like bodies have highly cuspate boundaries in contact with the silicic rock. Many pillowed bodies have chilled and sharp cuspate boundaries while others have gradational boundaries in contact with the silicic rock. These gradational zones are intermediate in composition. The presence of rare swallow-tailed plagioclase in the chilled margins of the mafic pillows confirm a liquid-liquid relationship between a silicic and a mafic magma and thus present a unique opportunity to observe the interaction of mafic magma and silicic magma at high levels in the crust (< 2 km). Many silicic and mafic complexes are probably mistaken for intrusion breccias or solid xenoliths.

A model of commingling of magmas with "limited" magma mixing is best supported by the data. Mixing is "limited' because large volumes of a throughly mixed magma have not been produced. The visible scale of mixing is of the same order of magnitude as the size of the pillows enclosed within the silicic rock. Mechanical mixing processes are thought to predominate at the margins of pillows with gradational boundaries. Models involving silicate-liquid immiscibility can be strongly rejected based upon the liquidus temperature differences between the silicic and mafic magmas (i.e., quenched margins) and the trace element data.

As a result of mixing, intermediate compositions are produced, some of which are similar to intermediate compositions found as lavas in Iceland (e.g., basaltic andesite and Icelandite) whereas other intermediate compositions occur which have no or only a rare volcanic equivalent.

The silicic rocks at these two intrusions were likely superheated because many of the mafic pillows lack chilled boundaries on all of the pillow or only on part of a pillow margin. If superheating of silicic magmas is common in the Icelandic crust, then this may have many important ramifications on the possibility and extent of mixing between mafic and silicic magmas (i.e., large amounts of mafic magma may mix with small amounts of silicic magma but not vice versa) and thus the hybridization of mafic and silicic magmas and the production of intermediate compositions. The eruption potential of silicic magmas is enhanced if they are superheated.

In Iceland volcanism occurs in the form of overlapping en echelon overlapping en echelon eruptive lenses in time. The central portion of each lens contains the thickest accommulation of erupted lavas and usually has one or more central volcanic complex(es). The central volcanic complexes are almost exclusively associated with the more evolved basalts, intermediates and silicic rock types, and the occurrences of silicic and mafic complexes. This suggests that the evolution of all of these rock types and the silicic and mafic complexes are related.

The interaction of mafic and silicic liquids in crustal level magma chambers, in Iceland, is manifest by the numerous occurrences of silicic and mafic complexes or net-veined complexes. The silicic and mafic complexes may be the only evidence remaining of the interaction of mafic and silicic magmas at high-levels of the the Icelandic crust before the magma chamber is emptied and erupted at a central volcanic complex. In general, Smith's model for evolution of high-level silicic magma chambers is supported by field and chemical relationships found at two Tertiary silicic and mafic complexes in Iceland.

PART I: THE INTERACTION OF MAFIC AND SILICIC MAGMAS AT TWO INTRUSIONS

INTRODUCTION

The coexistence of silicic and mafic magmas may have been a characteristic of the North Atlantic Tertiary Province (Harker, 1904; Blake et al., 1965; Thompson, 1980) and may be a general feature of high-level silicic magma chambers (Smith, 1979). A major portion of these small volume silicic magma systems have been erupted as pyroclastics (Smith, 1979) and these have either been lost to surfacial processes or have not been the subject of extensive study. An exception to this has been the 1875 Askja eruption which has been studied in detail (Sigvaldason, 1979; Sparks et al., 1981; Sigurdsson and Sparks, 1981). This eruption contained many silicic pyroclastics as well as many intermediate, mafic, and "mixed" ejecta compositions. A study of the silicic and mafic complexes may reveal the processes that have effected these high-level silicic intrusions and ultimately their erupted products, such as those found in the Askja eruption.

In Iceland volcanism occurs in overlapping eruptive lenses, spatially and temporally arranged in en echelon arrays (e.g., Gibson, 1966; Gibson and Piper, 1972; Jakobsson et al., 1978). The central portion of each lens contains the thickest accumulation of erupted lavas and usually one or more central volcanic complex(es) (e.g., Walker, 1963, 1966, 1975; Gibson, 1969; Sigvaldason, 1974; Palmason and Saemundsson, 1974). The central volcanic complexes are almost exclusively associated with the more evolved basalts, intermediate and silicic rock types and the occurrences of the silicic and mafic complexes (e.g., Walker, 1962, 1964, 1966; Blake, 1966, 1969; Blake et al., 1965; Sigurdsson, 1971; O'Nions and Gronvold, 1973; Wood, 1976; Sigvaldason, 1979). This suggests that the

evolution of all of these rock types and the occurrences of the silicic and mafic complexes are related.

Two models can account for the coexistence of silicic and mafic magmas (e.g., Holmes, 1936; Vogel and Wilband, 1978). The first has been termed commingling (Chapman, 1962) and is the failure of two potentially miscible magmas to mix due to viscosity and temperature differences (i.e., rapid crystallization of the mafic magma upon coming into contact with cooler silicic magma). The second model is silicate-liquid immiscibility, whereby a homogeneous magma unmixes to form two thermodynamically stable liquids of a highly contrasting nature, one liquid essentially mafic and the other silicic.

The main objectives of this paper are to evaluate these two models and to suggest mechanisms of formation of the silicic and mafic complexes consistent with the petrographic, major element and trace element data obtained from these complexes. In Part I of this paper the unequivocal liquid-liquid nature of the silicic and mafic complexes will be established and an evaluation of the two models proposed above will be presented. Silicate liquid immiscibility will be shown to be a untenable process based upon the field and chemical data. A commingling model with limited magma mixing between silicic and mafic magmas is the model most strongly supported. Documentation of a complex series of events in these magma chambers will also be presented. In Part II of this paper a comparison of the chemical variation observed in the known mixed rocks in Iceland with the chemical variation observed in the lavas of Iceland will be presented in order to evaluate the significance of magma mixing between mafic and silicic magmas in the Icelandic environment.

A close association of silicic and mafic rocks has been reported from a number of tectonic settings, on a variety of scales, and in both plutonic and volcanic regimes (For example: Harker, 1904; Holmes, 1931; Wilcox, 1944; Wager

and Bailey, 1953; Wells, 1954; Buist, 1959; Chapman, 1962; Wager et al., 1965; King, 1964; 1965a, 1965b; Windley, 1965; Skelhorn et al., 1966; Walker and Skelhorn, 1966; Philpotts, 1971, 1972, 1979; Wiebe, 1973, 1974, 1979, 1980; Yoder, 1973; Vogel and Walker, 1975; Vogel et al., 1976; Vogel and Wilband, 1978; Holgate, 1978; Eby, 1980; McSween et al., 1979; Gamble, 1979; Taylor et al., 1980; Vogel, 1982; Reid et al., 1983; Wiebe and Wilde, 1983.) Specifically, in the Icelandic oceanic island rifting environment, silicic and mafic associations have been reported by Bunsen (1851), Guppy and Hawkes (1925), Anderson (1949), Gibson and Walker (1963), Blake et al. (1965), Walker (1962, 1963, 1966), Blake (1966, 1969), Gunn and Watkins (1969), Roobol (1971, 1974), Jakobsson (1979); Sigurdsson (1971a), Sigvaldason (1979), Jorgensen (1980), Prestvik (1980), and Sigurdsson and Sparks (1981). Review papers on silicic and mafic associations have been presented by Walker and Skelhorn (1966), Roobol (1971), Yoder (1973), and King in a series of articles (1962, 1963a, 1963b, 1964, 1965a, 1965b). In many of these associations silicic and mafic rocks are interpreted as representing the coexistence of two distinct liquids.

The Austurhorn and Vesturhorn Tertiary complexes of Southeastern Iceland contain classic examples of coexisiting silicic and mafic magmas which crystallized in a hypabyssal environment (Blake, 1966; Roobol, 1974). These complexes consist predominantly of silicic intrusions, which have within them an intimate association of silicic and mafic rocks. The most conspicuous features of these complexes are mafic pillow-like xenoliths with cuspate boundaries surrounded by silicic rock. These types of complexes have been referred to by many workers as "composite intrusions", "acidic and basic complexes", "net-veined complexes" or "silicic and mafic complexes".

As has been pointed out (Vogel, 1982), the advantages of studying these high-level silicic and mafic complexes is that they represent, in comparison to

plutonic complexes, "quenched" systems and contain few cumulate phases. The small scale of the individual relationships between mafic "pillows" and the silicic rock aide in the field interpretation and sampling techniques.

FIELD DESCRIPTION OF THE SILICIC-MAFIC COMPLEXES

General

The silicic and mafic complexes occur within the Austurhorn and Vesturhorn Tertiary intrusions. K-Ar ages are 6.6 ± 0.4 (Austurhorn) and 6.6 ± 0.3 m.y. (Vesturhorn) (Moorbath et al., 1968). These intrusions occur along the coast of Southeastern Iceland with an exposed outcrop area of 11 km^2 and 19 km^2 respectively (Blake, 1966; Roobol, 1974) (Figure 1). They occur within 30 kms of each other and both have intruded basaltic lavas which gently dip to the west. These intrusions are composite stock-like bodies and were probably emplaced at depths less than 2 km, based upon the zeolite metamorphic facies of the intruded volcanics (Blake, 1966; Roobol, 1974). The intrusions consist of predominantly silicic rocks with subordinate basaltic and intermediate rocks. Tertiary silicic rocks in Iceland are almost exclusively associated with major volcanic centers (Walker, 1966).

The silicic and mafic complexes consist of differing amounts of silicic, mafic, and intermediate rocks. Although actual volumes of the contrasting rock types are difficult to estimate, silicic rocks at the level of exposure are the most abundant and the intermediate rocks are the least abundant. The general field relationships and distribution of rock types within the Austurhorn and Vesturhorn intrusions have been reported previously by Blake (1966) and Roobol (1974). The silicic and mafic complexes comprise only part of the total area of the intrusions, approximately 30-40% of the Austurhorn intrusion (Blake, 1966) and less than 10% of the Vesturhorn intrusion. The silicic and mafic complexes occur in three main

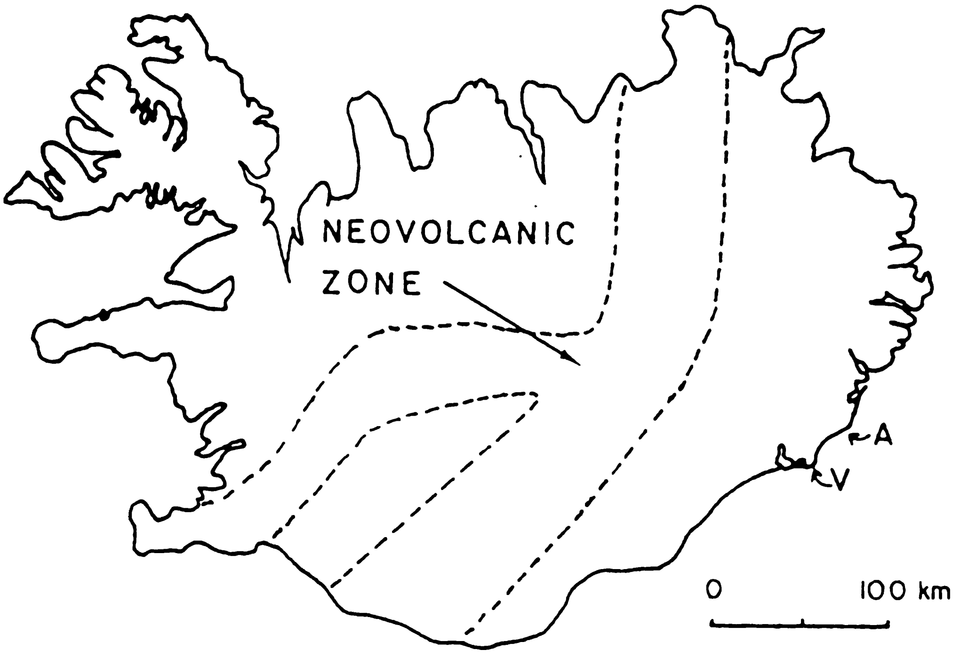


Figure 1. Location of the Austurhorn (A) and Vesturhorn (V) intrusions in Iceland in relation to the Neovolcanic zone.

areas in the Austurhorn intrusion and two main areas in the Vesturhorn intrusions (see maps of Blake, 1966, Figure 1; and Roobol, 1974, Figure 2). The Austurhorn silicic and mafic complexes have the best exposure. The exposed parts of the silicic and mafic complexes form at the margins of the silicic intrusions, however, the relationship of one silicic and mafic complex within the Austurhorn intrusion at Austurhorn is obscured by the sea. Silicic and mafic outcrops are dominated by pillow-like bodies of mafic rock with cuspate boundaries which are entirely surrounded by silicic rock (Figure 2a).

Description of Mafic Pillows

A description of these mafic pillow-like bodies, their petrography, and relationships with the silicic rocks will be presented in order to establish that these rocks represent the coexistence of two magmas. This detail is presented because many silicic and mafic complexes have often been misinterpreted as intrusion breccias. In addition, the described relationships of the pillows with the silicic rocks are interpreted to indicate a very complex sequence of cooling and intrusion events in the silicic magma chamber.

In general, three types of mafic "pillows" occur. These pillow types are defined for discussion purposes only and are not defined to carry genetic inferences because there is a continuous variety of pillow endmembers between those generally discussed. Chilled pillows have distinctive fine-grained margins (Figure 2b). They are typically aphantic and porphyritic with occasional phaneritic centers. Chilled and gradational pillows distinctively display a gradational boundary on an edge of the pillow with the silicic rock (Figure 2c). They also are often porphyritic. The gradational boundary is typically coarser-grained than the rest of the pillow and may have a cuspate or diffuse boundary with the silicic rock. Chilled and chilled-gradational pillows contain pyroxene and

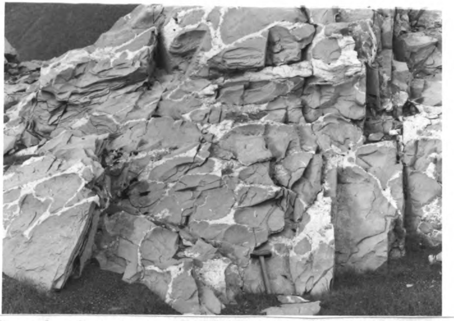


Figure 2a. Austurhorn. One of the two kinds of typical outcrops found in the silicic and mafic complexes (see text). Chilled pillows of mafic rock are entirely surrounded by silicic rock. Hammer in photograph is provided for scale.

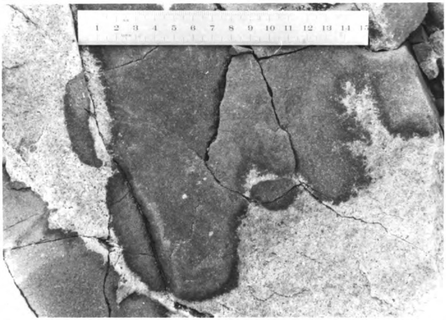


Figure 2b. Austurhorn. Close-up of a chilled pillow. The chilled margin of the pillow often appears as a darker colored rind. Cuspate boundaries of several different orders are visible on the pillow (see text).

Figure 2c. Vesturhorn. Chilled-gradational pillows with a distinct chilled margin and gradational zones outside the chilled pillow margins. Gradational zones may entirely surround a chilled pillow or only partially surround the pillow.

plagioclase as phenocrysts (Figure 3a). They are medium-grained pillows with a typical grain size of 0.25 cm. The third type of pillows are unchilled pillows and they, distinctly, have no fine-grained textures and display boundaries which can be sharp to gradational with the silicic rock. These pillows may have phenocrysts of plagioclase.

All pillows are generally rounded, although a few have high aspect ratios, and range in size from several millimeters to 3-4 meters across with many being approximately one meter in diameter. Many pillows have cuspate boundaries with smaller cusps developed on the larger cusps. Third and fourth order cuspate boundaries are common on chilled and chilled-gradational pillows (Figure 2b), but are less common on unchilled pillows. Pillow density within a given outcrop can be highly variable, but typically occurs as depicted in Figure 2a. Two outcrop patterns are observed: those which contain only chilled pillows (Figure 2a) and others which contain all three generalized types of pillows (Figure 3b).

Chilled pillows are aphanitic at their margins with a visibly chilled boundary up to several centimeters in thickness. Chilled margins are easily distinguishable because they are darker than the pillow interiors (Figure 2b). The visible chilled rinds vary in thickness from one or two centimeters to several tens of centimeters. These pillows gradually increase in grain size toward their centers. Some pillows have a well developed, chilled margin, several centimeters in thickness, on one side of the pillow and a homogeneous, fine-grained margin on the other. No systematic orientation of chilled margins was noted. The distribution of phenocrysts within chilled pillows is erratic and variable, and usually no more than a few percent are present. Phenocrysts consist of pyroxene and plagioclase at the Austurhorn, whereas only plagioclase was noted at the Vesturhorn. In the silicic rock adjacent to many of the pillows there is an increase in the abundance of mafic minerals or clots of mafic minerals present as

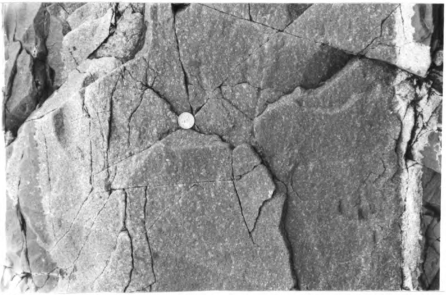


Figure 3a. Austurhorn. Unchilled pillow (samples Ic-4 to Ic-9) with a gradational boundary at its top margin and a sharp and cuspate boundary at its bottom. Note the chilled boundary on the uppermost and lowermost (Ic-3) pillows.

Figure 3b. Austurhorn. Photograph exhibiting the intimate nature of all pillow types (i.e., chilled, chilled-gradational, and unchilled pillows) in a single outcrop. The unchilled pillow with both cuspate and angular boundaries (i.e., pillow with the hammer and those pillows to the right of it) looks as if it could be fit back together in a "jig-saw puzzle" manner. Observe the chilled pillows in between these unchilled pillows. Multiple intrusions events in the silicic chamber are based upon these relationships (see text).

one approaches the pillow (see Figure 2). This feature results in a mottled texture in the silicic rock.

The chilled-gradational pillows have a lighter grey "gradational zone" of variable width which, in some cases only partially surrounds them. These pillows are coarser grained and usually have cuspate boundaries although sharp angular boundaries do occasionally occur. The darker pillow interior may have cuspate boundaries in contact with the graduational zone or the silicic rock, and increases in grain size from its margin to its interior. The darker pillow interior may or may not have an obvious chilled margin. This relationship of a more mafic pillow interior surrounded by a gradational or hybridized zone, all of which is surrounded by the silicic rock (Figure 2c) has been termed a skialith (Chapman, 1962) or a "pillow within a pillow" structure (Taylor et al., 1980). Chilled-gradational pillows are often porphyritic with plagioclase and any individual pillow may contain a highly variable phenocryst content (usually less than 5%). Figure 2c also shows the highly mottled texture of the silicic rock as well as many smaller pillows which can have cuspate, angular, and diffuse margins. These smaller pillows probably represent fragments of larger pillows.

Unchilled pillows are coarser grained than the chilled or chilled-gradational pillows. These pillows distinctly lack a chilled zone. Unchilled pillows have cuspate and angular boundaries often on the same pillow. This feature can be seen on other pillow types, but is more commonly seen with the unchilled pillows. Gradational boundaries or diffuse zones also occur around the unchilled pillows (Figure 3a). These pillows can be porphyritic (i.e., plagioclase), but most are hypidiomorphic-granular and non-porphyritic. Higher concentrations of phenocrysts were observed in some pillows, compared with other pillow types (Figure 3a), especially in proximity to the silicic rock.

Figures 3a and 3b are examples of the intimate nature and occurrence of all pillow types in close proximity which is a common feature of many of the outcrops. The bottom boundary of the unchilled pillow has a sharp cuspate margin. The upper boundary of the unchilled pillow grades into a more porphyritic leucocratic rock which in turn grades to the left and right (out of the photograph) into the typical silicic rock. At the top of the photograph is another chilled pillow.

It is emphasized that the pillow display a continuous variety of pillow endmembers and pillow types have only been described only to facilitate their description. Thus it is not suggested that these pillow names be carried on to other localities.

Complex Pillow Relationships

It is not uncommon to find all of the pillow types in a single exposure (Figure 3b). In general, two types of outcrops occur most often within the silicic and mafic complexes; those which contain only chilled pillows and those which contain all three pillow types. These observed pillow relationships reveal a complex sequence of events in the magma chamber. These relationships are best interpreted as the result of several coexisting liquids with varying viscosities, temperatures. This implies different comingling histories for different pillows.

For example, in one case, chilled pillows surrounded by silicic rock were observed with internal zones characteristic of unchilled pillows. In another exposure (Figure 3b) there are many unchilled pillows which are non-porphyritic and have cuspate boundaries on one side of the pillow and angular boundaries on another. This feature occurs in other pillow types but is less common in chilled and chilled-gradational pillows. Chilled and chilled-gradational pillows also occur within the photograph. The large cluster of unchilled pillows (Figure 3b) appear to have broken up into smaller pieces by "brittle" fracture and the silicic rock

intruded along these fractures. The angular boundaries of these pillows have a "jig-saw puzzle" fit whose unified parts would form a single large pillow which had cuspate boundaries on all sides. At the far right of the photograph is a chilled pillow with chilled boundaries "sandwiched" between the angular boundaries of the unchilled pillow described above. Again this is indicative of a complex sequence of events in the silicic magma chamber.

Chilled pillows with sharp boundaries and chilled margins and textures most certainly represent liquid-liquid relationships between the silicic and mafic magmas. The origin of the unchilled pillows is less clear; however, because of their relationships to other pillows and the presence of cuspate boundaries on these pillows, they are interpreted as also being in a liquid state with the silicic magma albeit with different cooling and crystallization histories than many of the chilled pillows. Similar types of cuspate boundaries have been experimentally produced (Yoder, 1973; Kouchi and Sunagwa, 1982).

For the field description of Figure 3b, the sequence of events is interpreted as follows: The unchilled pillow would have intruded the silicic magma in a liquid state, formed pillows, brittlely failed, broken apart, and then was intruded by the still liquid silicic magma and another pulse of molten mafic magma which pillowed and had a more rapid cooling history.

Other relationships are observed which indicate a complex intrusion history of mafic pillows. For example, in Figure 4a, a chilled pillow with a chilled boundary (center of photograph) is partially surrounded by a material indistinguishable from a unchilled pillow. The chilled pillow has chilled and cuspate boundaries in contact with the unchilled pillow material on two sides and the silicic rock on the third side. In another exposure, observed only at one locality in the Austurhorn intrusion (Figure 4b), silicic pillows are surrounded by the silicic rock. Both the pillows and the silicic rock are highly silicious with

Figure 4a. Austurhorn. All three pillow types in intimate association exhibiting that all forms of pillows occur between the endmember types described. Pillow described in the text is to the right of the ruler.

Figure 4b. Austurhorn. Rare unchilled silicic pillows surrounded by silicic rock. These pillows were observed only at one locality. A change in texture between the pillow and the surrounding silicic rock probably accounts for their distinguishing features in the field.

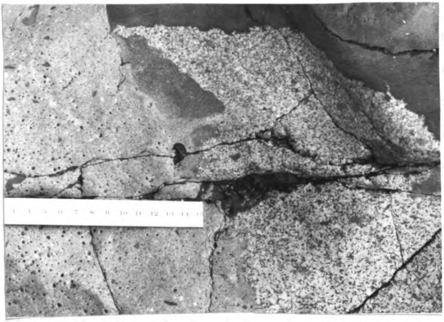


Figure 4c. Austurhorn. Chilled pillows often have coarser grained silicic rock unlying them. The silicic rock displays a mottled texture due to the many smaller mafic pillows and clots of ferromagnesium minerals.

68.9% SiO_2 (Ic-38b) and 73.0% SiO_2 (Ic-38a) respectively (see Table 1). No apparent chilled margin is present on these rocks. The rocks have similar mineralogy, but differ texturally. The darker pillows lack the abundant granophyric texture of the silicic rock. The presence of silicic pillows with cuspate boundaries surrounded by silicic rock most likely result from a viscosity difference between these two compositions. The three dimensional nature of these pillows cannot be observed.

Silicic Rocks

The macroscopic texture of the silicic rock is variable, but usually displays plagioclase phenocrysts which are often surrounded by graphic textures or, less commonly, hypidiomorphic textures. Within the silicic and mafic complexes the silicic rock often displays a mottled texture due to the variable mafic mineral content (see Figures 2b, 2c, 4a, 4c). The silicic rocks locally contain many vugs within the silicic and mafic complexes, and in the main body of the intrusion. The main body of the Austurhorn intrusion contains a variable plagioclase phenocryst content (from a few percent up to 43%, Blake, 1966) similar to the silicic and mafic complex. Textural differences may represent variable mafic components and/or changes in the physical parameters of crystallization.

Intrusion Breccia

There are angular mafic xenoliths (Austurhorn only) which are texturally different from those previously described. They are coarset grained (up to 1 cm) and have sharp or angular boundaries with the silicic rock. These xenoliths occur only in very close proximity to the margin of the silicic intrusion, and resemble the country rock. (e.g., sample Ic-40; see Table 1).

Table 1. Sample descriptions.

Sample Number		Field Description	Major Mineralogy or Texture
Ic-3	A	Chilled pillow margin from lower pillow in Figure 3a	Plagioclase and pyroxene phenocrysts
Ic-9 Ic-4 Ic-5 Ic-6 Ic-7	A	Unchilled pillow with diffuse zone surrounding it in Figure 3a from top (Ic-9) to bottom (Ic-7)	Mineralogy of plagioclase, biotite, graphic patches, quartz, ± amphibole, ± pyroxene plagioclase phenocrysts
Ic-8	A	Chilled pillow margin from top of Figure 3a	Similar to Ic-3
Ic-10a Ic-10b	A	Unchilled pillow (Ic-10b) and silicic rock surrounding it (Ic-10a)	Silicic rock has biotite, minor opaques, and phenocrysts of plagioclase
Ic-12 Ic-13	A	Chilled pillow margin (Ic-13) and interior (Ic-12)	Pyroxene and plagioclase phenocrysts
Ic-14	A	Angular xenolith (see text for probable origin) similar in texture and mineralogy to a unchilled pillow	
Ic-20 Ic-21	A	Taken from large outcroppings of silicic rock within the silicic and mafic complexes	Both contain biotite, minor opaques and plagioclase phenocrysts surrounded by graphic textures
Ic-22a Ic-22b Ic-22c	A	Chilled pillow margin (Ic-22a), interior (Ic-22b), and silicic rock surrounding it (Ic-22c)	Silicic rock is similar to Ic-20
Ic-29 Ic-30	A	Type 2 pillow chilled-gradational diffuse zone (Ic-29) and silicic rock surrounding (Ic30)	Silicic rock has hypidomorphic texture with patches of graphic texture

Table 1 (continued).

Sample Number		Field Description	Major Mineralogy or Texture
Ic-31	A	Chilled-gradational pillow	Similar to Ic-20 with more abundant biotite
Ic-28a Ic-28b	A	Chilled-gradational pillow at margin (Ic-28b) and 25cm into pillow (Ic-28a)	Variable
Ic-37a Ic-37b	A	Silicic rock from same pillowed outcrop with all pillow types present	Similar to Ic-20 except Ic-37b is more leucocratic than Ic-37a
Ic-38a Ic-38b Ic-39	A	Highly silicious pillow Ic-38b surrounded by silicic rock Ic-38a. Ic-39 is from pillow next to Ic-38b (see Figure 4b)	Ic-38a is similar to Ic-20 and Ic-38b, Ic-39 has hypidiomorphic texture with minor patches of graphic texture
Ic-41	A	Silicic rock collected from margin of silicic and mafic complex	Similar to Ic-20
Ic-40	A	Angular, coarse grained, gabbroic xenolith from near wall rock of the intrusion	Contains coarse plagioclase, pyroxene, opaques, and apatite
Ic-53a Ic-53b Ic-53c	V	Chilled pillow margin 3cm (Ic-53a) and 89cm (Ic-53c) from contact with the silicic rock which surrounds the pillow	Ic-53a and Ic-53c have large plagioclase phenocrysts and silicic rock Ic-53b is similar to Ic-20
Ic-59	V	Silicic rock from a $5m^2$ area which is free of pillows within the silicic and mafic complex	Similar to Ic-20

Table 1 (continued).

Sample Number		Field Description	Major Mineralogy or Texture
Ic-61	V	Chilled pillow interior	Pyroxene, plagioclase, and opaques. Plagioclase phenocrysts
Ic-66 Ic-67	V V	Chilled-gradational pillow from 10cm (Ic-66) and 30cm (Ic-67)of contact with silicic rock	Subophitic texture Plagioclase phenocrysts
Ic-68b Ic-68c	V	Silicic rock near chilled-gradational pillow interior (Ic-68c)	Ic-68b is similar to Ic-20 and Ic-68c is similar to Ic-61
Ic-74a Ic-74b Ic-74c Ic-75	 V 	Chilled-gradational pillow, Ic-75 is from the interior of the pillow and Ic-74a is from the contact with the silicic rock. Ic-74b is 3-6cm and Ic-74c is 8cm from the margin	Variable
Ic-77	V	Chilled pillow interior	Similar to Ic-61

Summary of Field Description

In summary, both the Austurhorn and Vesturhorn intrusions are predominantly composed of silicic rocks. Within these intrusions there are silicic and mafic complexes which consist of an intimate association of silicic and mafic rocks. Mafic rocks which are, generally, pillow-shaped bodies with cuspate boundaries of mafic composition are entirely surrounded by silicic rocks. The pillows are variable with respect to size, composition, and shape. Many pillows have chilled margins. These field relationships indicate a complex history of intrusion of the mafic pillows. The silicic rock is relatively homogeneous outside the silicic and mafic complexes and heterogeneous with respect to their mafic mineral content within the silicic and mafic complexes. The field data are interpreted to indicate the presence of several liquids of differing compositions and crystallization temperatures which are contemporaneous in the same environment.

PETROGRAPHY

A petrographic description of all exposed rocks at the Austurhorn and Vesturhorn intrusions has been reported previously, by Blake (1966) and by Roobol (1974) respectively. To avoid redundancy, only the silicic and mafic complexes will be described.

Similar pillow types have similar mineralogy and textures. In both of these intrusions the silicic rocks are texturally similar but vary most importantly in their mafic mineral content and the amount of plagioclase phenocrysts. As discussed previously, because pillows display a continuous variation between chilled pillows, unchilled pillows with gradational boundaries, and unchilled pillows, the types are defined only for ease of description.

In Pillows with Chilled Margins

Chilled pillows at their margins (e.g., Figure 5a) are very fine grained and contain sparse and larger grains of plagioclase, opaques, ± poikilitic biotite, ± poikilitic amphibole, ± augitic pyroxene. In many chilled margins an occasional swallow-tailed plagioclase with a high aspect ratio is present. In addition, many of these pillows at their margins have what is interpreted to be another quench texture (Figure 5b), that of radiating acicular opaques presumably of a continuous crystallographic nature. This texture occurs frequently along with the swallow-tailed plagioclase at pillow margins.

Chilled pillows interiors consist of plagioclase, pyroxene and opaque grains and often have a subophitic texture. Some of the larger pillows have equigranular textures with grains up to 2 mm in diameter. Plagioclase, from the Austurhorn, as determined from microprobe analysis, have cores which range up to An_{85} and rims down to An_{32}. Both complexes have chilled pillows which are porphyritic with respect to plagioclase and range up to 3 mm across (Austurhorn) and 7 mm across (Vesturhorn). The large plagioclases found at the Vesturhorn intrusion are often corroded and rounded by resorption (Figure 6c). Pyroxene phenocrysts in the Austurhorn are up to 1.5 mm across in the chilled pillows. Pyroxenes are augitic and of those analyzed have an average composition of $En_{49}\,Fs_{13}\,Wo_{38}$, and ranged from $En_{46}\,Fs_{28}\,Wo_{27}$ to $En_{50}\,Fs_{11}\,Wo_{39}$. Phenocrysts are not abundant in chilled pillows of either suite (less than 2% by volume at the Austurhorn and less than 5% at the Vesturhorn intrusion).

Grain size gradually increases from the margins to the centers of the chilled pillows (Compare Figures 5a, 5c). Some pillow margins contain hydrated phases. The effects of hydration are less visible in the interior of the pillow compared to the margins, with amphiboles and biotites occurring at pillow margins and

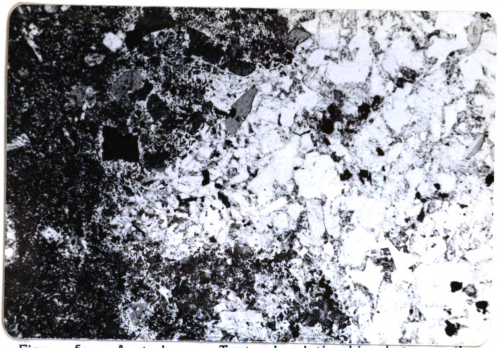


Figure 5a. Austurhorn. Textural relationships between the margin of a chilled pillow with highly cuspate coundaries and the silicic rock (scale 7mm).

Figure 5b. Austurhorn. Chilled pillow margin and texture of radiating opaque phases believed to be of a continuous crystallographic nature (scale ≃ 2.5mm).

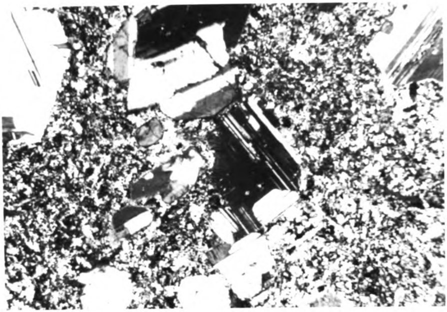


Figure 5c. Vesturhorn. Plagioclase phenocrysts within a chilled pillow. Most plagioclases have high An cores up to An_{85} to An_{32} cores (Austurhorn). Plagioclase phenocrysts are often rounded and corroded (scale 7mm).

pyroxene occurring in the pillow interiors. Cuspate contacts with the silicic rock are typically sharp (Figure 6a).

Chilled Pillows with Gradational Boundaries

The chilled-gradational pillows are similar to the chilled pillows in their textures and mineralogy. In general, grain size increases from the margin to the interior of the pillow. The hybridized zone surrounding these pillows are typically coarser grained, equigranular (approximately 0.5 mm), and consist of varying amounts of plagioclase, pyroxene, amphibole, biotite, opaque phases, and graphic intergrowths of quartz and feldspar. Chilled margins on the gradational zones may be present or absent. The contacts of these diffuse zones with the silicic rock range from being sharp to gradational over 10 to 15 cm. Plagioclase compositions from the Austurhorn are variable and range from An_{80} down to andesine rims (An_{37}).

Pillows without Chilled Margins

The unchilled pillows exhibit a range of mineral constituents and contain plagioclase, opaques, widely varying amounts of graphic intergrowths of feldspar and quartz, amphibole, biotite, and pyroxene. Pyroxenes often have rims of amphibole or biotite. Contacts of these pillows may be angular (Figure 6a) or gradational. Figure 6a shows a contact of a unchilled pillow where mafic phases appear to have crystallized and grown larger at the pillow boundary more readily than other phases. These pillows are predominantly hypidiomorphic-granular, with a few plagioclase or amphibole crystals being up to 7 mm in size at the contact, with a typical grain size of 2-3 mm throughout the pillows.

Petrography of Silicic Rocks

The silicic rock exhibits a range in textures and mineralogy. The most typical rock type consists of plagioclase, graphic intergrowths of feldspar and

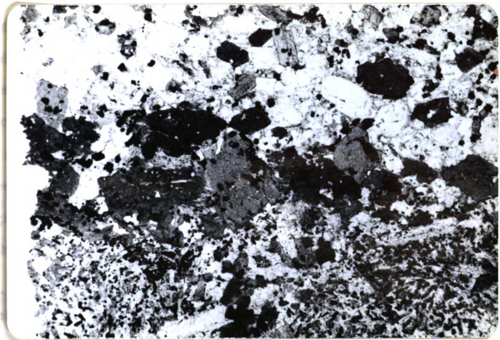


Figure 6a. Vesturhorn. Chilled-gradational pillow margin in contact with silicic rock (scale 7mm). Coarser grained texture of ferromagnesium minerals often develops at the gradational pillow margin.

Figure 6b. Austurhorn. Typical texture observed in the silicic rock (scale 7mm). The silicic rock is commonly porphyritic with plagioclase which are surrounded by graphic intergrowths of feldspar and quartz.

quartz, minor opaque phases, biotite, and quartz. The mottled texture of the silicic rock in the net-veined complexes is due to a variable mafic mineral content of amphibole, biotite, opaque phases, and variable amounts of plagioclase phenocrysts, graphic intergrowths, and quartz. Blake (1966) reported that the silicic rock near the pillows often has hypidiomorphic granular texture. However, although this texture is present locally, no systematic distribution of this texture was observed. Figures 5a and 6b show the typical textures of the silicic rock. The plagioclase phenocrysts are zoned, often rounded (Figures 5a, 6b) and/or rimmed by turbid feldspar and quartz. Plagioclase cores ranged up to $An_{47}Ab_{45}Or_{7.5}$ at the Austurhorn intrusion. The turbid feldspar phenocrysts and the turbid feldspars in the graphic intergrowths are cryptoperthic. Most of the plagioclase phenocrysts are less than 0.5 cm, but a few are up to 1.0 cm. in length. Opaque grains are exsolved.

The coarser-grained phenocryst zones of silicic rock located on the undersides of many of the pillows (Figure 4c) contain plagioclase phenocrysts up to 1.2 cm in length and euhedral amphiboles, opaques, zircon, and sphene. Some of the zircons are up to 0.2 mm in size.

Alteration

Alteration in the silicic and mafic complexes can be locally abundant and is most common along joints and fractures, but is usually of minor extent. The silicic rock alteration locally has abundant epidote group minerals, chlorite and rarely calcite. Alteration in the mafic rocks is minor, with alteration phases of chlorite and/or epidote group minerals. Areas which displayed abundant alteration were avoided during sampling.

The plagioclase and matrix feldspars in the silicic rocks often exhibit a turbid appearence which is probably due to minor hydrothermal alteration. Sampling of these feldspars was unavoidable since this alteration is common to

the silicic and mafic complexes. It is believed that this alteration, which would effect Na_2O and K_2O, is minor because the silicic rocks have low Na/K ratios as would be characteristic of unaltered silicic-oceanic rocks (Sinton and Byerly, 1980).

SAMPLING AND ANALYTICAL METHODS

Table 1 gives a brief description of each sample which was collected and analyzed, as well as the locality and any characteristic mineralogy or textural features.

Samples were collected to reflect the maximum variation present and thus do not reflect true volumes (Table 1). Detailed sampling of individual pillows or pillow sequences (eg. pillow interiors, pillow margins, and the silicic rock in close proximity) has only been characterized by samples Ic-3 through Ic-9 (Austurhorn, See Table 1). Sample numbers less than forty are from the Auturhorn intrusion and those greater than forty are from the Vesturhorn Intrusion. Samples were collected from the Vesturhorn Intrusion at both the eastern (Ic-53a,b,c) and western (Ic-59 through Ic-77) occurrences of silicic and mafic rocks indicated on the geologic map of Roobol (1974, Figure 1). The Austurhorn Intrusion was sampled at all of the occurrences of silicic and mafic complexes except a small 0.3 km^2 complex located at the far northwestern end of the intrusion (see Blake, 1966, Figure 2). All samples are from the silicic and mafic complexes of the two intrusions.

Only fresh samples with a low amount of alteration and free of miariolitic cavities were selected for chemical analysis. Exceptions were samples Ic-38a,b which are alterated along fracture planes spaced approximately 2.5 cm apart. Due to the numerous mafic "inclusions" in the silicic rock, each piece was sliced to a thickness of 2 cm. and any mafic inclusions were ground or cut from the

sample. Samples were then crushed and ground to a fine rock flour between porcelain plates.

Forty-three samples were analysed for major elements; twenty-nine samples were from the Austurhorn Intrusion and fourteen samples from the Vesturhorn Intrusion. The analyses were performed by Barringer Magenta using inductively coupled plasma emission spectrometry (I.C.P.E.S.). Eight trace elements were also determined by the same methods and they include Ni, Cu, Zn, Cr, Co, Sr, V, and Ba. Methodologies and error analysis using the I.C.P.E.S. methods has been evaluated in geological samples by Dahlquist and Knoll (1978) and by Burman and Bostrom (1979). The precision of these chemical analyses can be found in Vogel (1982). Ferrous iron was determined by a wet chemical technique described and tested by Weis (1974).

Thirty-four samples were analysed for Na, La, Ce, Sm, Eu, Tb, and Lu (see Vogel, 1982 for precision) by instrumental neutron activation analysis (INAA) methods and the techniques of Gordon et al. (1968). Th was analysed by INAA using the correction technique of Korotev (1976). Twenty-five samples were run from the Austurhorn Intrusion and nine samples from the Vesturhorn Intrusion. Where Na was determined by both INAA and I.C.P.E.S., the values from INAA were used. Major elements, trace elements, and C.I.P.W. norms are reported in Table 2. Table 3 lists the reported major element analyses for silicic rocks and mafic pillows from the Austurhorn Intrusion as reported by Blake (1966) and the average Icelandic pitchstone as reported by Walker (1962). Pyroxene compositions (Table 4) and plagioclase compositions were determined using an ARL EMX microprobe. Operating conditions of 15Kv and a sample current of 20 mA were used for most elements except Ti, Mg, Fe, and Mn for which 20Kv was used. A defocused beam was used for most analyses.

Table 2. Major elements, trace elements, and CIPW norms.

GRANITIC ROCKS

	Ic-38a	Ic-37b	Ic-59*	Ic-41	Ic-20	Ic-21	Ic-22c	Ic-37a	Ic-10a	Ic-38b	Ic-68b*	Ic-31	Ic-39	Ic-53b*	Ic-30
SiO_2	73.00	72.50	72.90	72.50	73.90	72.50	72.50	71.60	69.80	68.90	71.60	67.50	65.2	66.2	66.2
TiO_2	0.23	0.28	0.41	0.33	0.35	0.36	0.41	0.62	0.53	0.40	0.62	0.83	0.49	0.58	0.62
Al_2O_3	12.70	13.30	13.50	12.90	13.80	14.20	14.40	14.00	14.40	14.40	14.90	13.70	14.90	15.30	15.90
Fe_2O_3	2.29	1.67	1.59	2.36	0.86	1.57	1.73	0.75	1.69	1.05	2.59	1.59	1.80	3.97	2.90
FeO	1.10	1.14	1.45	2.03	2.03	1.29	1.53	2.48	1.78	2.20	1.88	3.52	2.68	2.34	2.65
MnO	0.08	0.05	0.03	0.14	0.04	0.05	0.06	0.10	0.03	0.09	0.05	0.10	0.16	0.05	0.06
MgO	0.05	0.18	0.39	0.08	0.35	0.25	0.32	0.66	0.50	0.33	0.60	0.96	0.46	0.53	0.49
CaO	0.37	0.57	1.40	1.16	1.10	0.82	1.21	1.78	1.49	1.09	2.37	2.14	1.62	2.60	2.10
Na_2O	5.07	4.11	4.05	4.46	4.57	4.46	4.12	4.74	4.39	5.88	4.73	4.47	5.54	4.86	4.72
K_2O	3.70	4.12	2.50	3.05	3.56	3.99	3.97	3.48	3.98	3.61	3.04	3.02	3.34	2.37	3.07
P_2O_5	0.01	0.02	0.04	0.02	0.03	0.02	0.02	0.07	0.02	0.07	0.07	0.10	0.08	0.08	0.07
L.O.I.	1.01	0.63	0.76	0.43	1.13	0.64	0.47	0.78	0.50	0.74	0.51	0.69	0.80	0.46	0.79
TOTAL	99.61	98.57	99.02	99.46	101.72	100.15	100.74	101.06	99.11	98.76	102.93	98.62	97.18	99.34	99.64

C.I.P.W. NORMS

	Ic-38a	Ic-37b	Ic-59*	Ic-41	Ic-20	Ic-21	Ic-22c	Ic-37a	Ic-10a	Ic-38b	Ic-68b*	Ic-31	Ic-39	Ic-53b*	Ic-30
Q	28.51	31.89	36.61	31.38	29.58	29.10	29.88	25.00	25.02	17.98	25.57	23.22	15.47	20.80	20.57
C	0.00	1.11	1.71	0.20	0.50	1.11	1.17	0.00	0.21	0.00	0.00	0.00	0.00	0.21	1.18
OR	22.19	24.86	15.04	18.21	20.91	23.69	23.40	20.51	23.85	21.76	17.55	18.22	21.09	14.19	18.37
AB	43.54	35.51	34.88	38.13	38.44	37.93	34.77	40.00	37.67	50.76	39.10	38.62	48.73	41.67	40.44
AN	0.98	2.75	6.80	5.68	5.23	3.96	5.86	6.63	7.36	2.28	10.20	8.58	5.79	12.54	10.09
NE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WO	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.72	0.00	1.16	0.35	0.67	0.84	0.00	0.00
EN	0.13	0.46	0.99	0.20	0.87	0.63	0.80	1.64	1.26	0.84	1.46	2.44	1.19	1.34	1.24
FS	1.30	0.35	0.74	2.84	2.50	0.57	0.81	3.09	1.07	2.73	1.46	4.05	3.03	4.90	3.67
MT	2.55	2.47	2.35	2.68	1.24	2.29	2.50	1.09	2.49	1.55	3.00	2.35	2.71	3.06	3.11
IL	0.44	0.54	0.79	0.63	0.66	0.69	0.78	1.17	1.02	0.78	1.15	1.61	0.97	1.12	1.19
AP	0.02	0.05	0.10	0.05	0.07	0.05	0.05	0.17	0.05	0.17	0.16	0.24	0.20	0.19	0.17
OL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(DI)	0.72	0.00	0.00	0.00	0.00	0.00	0.00	1.46	0.00	2.38	0.69	1.35	1.71	0.00	0.00
(HY)	1.05	0.81	1.73	3.04	3.37	1.20	1.61	3.99	2.33	2.35	2.58	5.81	3.35	6.24	4.90
PLAG	2.21	7.20	16.32	12.97	11.98	9.45	14.42	14.22	16.35	4.30	20.70	18.17	10.63	23.13	19.96
MG•	5.23	21.96	32.40	5.38	23.15	25.67	27.15	32.17	33.36	21.10	31.97	32.71	23.43	18.95	20.67

TRACE ELEMENTS

	Ic-38a	Ic-37b	Ic-59*	Ic-41	Ic-20	Ic-21	Ic-22c	Ic-37a	Ic-10a	Ic-38b	Ic-68b*	Ic-31	Ic-39	Ic-53b*	Ic-30
La	124	91	-	-	66	50	67	70	61	62	51	-	61	57	66
Ce	225	144	-	-	121	121	121	132	112	126	110	-	131	117	127
Sm	29	17	-	-	14.0	12.7	14	17	12.0	14	15	-	17	17	17
Eu	3.8	2.6	-	-	2.4	2.2	1.8	2.8	2.3	3.5	3.8	-	4.6	5.9	4.7
Tb	4.0	2.1	-	-	2.0	2.0	2.6	2.0	1.7	1.9	2.1	-	2.5	2.6	2.3
Lu	2.2	1.4	-	-	1.2	1.3	1.2	1.4	1.1	1.5	1.1	-	2.5	1.2	1.7
Th	11.3	9.0	-	-	10.5	9.2	9.8	9.1	9.6	8.3	7.2	-	9.3	7.1	7.1
Ni	4	5	6	4	5	4	7	12	6	6	11	13	6	12	10
Cu	4.1	5.6	7.4	4.3	4.7	4.7	5.2	7.3	19.3	4.5	8.7	16.6	6.0	6.7	5.4
Zn	143	69	40	171	43	57	60	111	40	137	55	111	239	53	90
Cr	8.1	7.4	9.7	5.0	9.3	9.4	9.3	13.8	12.4	8.9	11.5	11.1	5.6	9.3	8.2
Co	26	28	13	16	3	3	40	33	6	17	21	40	26	23	28
Sr	30.7	58.7	129	118	67.4	83.2	96	109	132	31.9	254	110	113	277	206
V	3.4	9.5	17.3	5.0	17.1	14.1	15.6	48.7	35.6	9.2	35.2	30.5	10.8	32.1	29.5
Ba	490	510	320	610	510	520	640	470	750	310	520	370	720	690	730

Table 2 (continued).

INTERMEDIATE ROCKS

Ic-9	Ic-29a	Ic-4c	Ic-28b	Ic-66*	Ic-74a*	Ic-75*	Ic-28a	Ic-67*	Ic-74c*	Ic-5	Ic-74b*
63.0	60.3	60.7	60.3	57.1	58.9	58.0	58.0	55.7	47.1	56.2	59.4
1.46	1.11	1.60	1.65	2.02	2.34	2.90	2.07	2.51	2.79	2.44	2.57
15.00	16.50	14.80	14.90	14.10	14.60	14.60	14.90	13.60	14.50	14.40	14.90
3.60	6.08	3.83	3.39	2.85	2.48	3.20	2.62	3.28	3.19	3.58	3.20
4.97	4.07	5.35	5.53	6.24	6.46	6.12	6.55	7.22	6.67	6.77	6.57
0.12	0.13	0.14	0.23	0.16	0.17	0.17	0.20	0.18	0.18	0.18	0.18
1.99	0.72	2.25	2.29	2.79	2.70	2.40	3.05	3.40	3.18	3.56	3.05
4.24	2.77	4.82	4.64	5.04	5.46	5.80	5.58	5.48	6.06	6.37	5.95
4.54	5.10	4.35	4.80	3.63	4.06	3.84	4.53	3.44	3.94	3.77	3.67
1.89	1.89	1.75	2.08	1.80	2.00	1.81	1.74	1.49	1.67	2.10	1.53
0.21	0.11	0.21	0.39	0.74	0.68	0.71	0.46	0.63	0.66	0.23	0.76
0.95	0.65	0.89	1.01	0.99	0.9	0.78	0.93	1.00	1.44	1.35	0.93
101.97	99.43	100.69	101.22	97.46	100.77	100.33	100.63	97.93	101.38	100.95	102.71

C.I.P.W. NORMS

16.23	12.59	14.36	11.19	14.70	12.49	14.41	8.76	13.56	11.41	8.34	15.32
0.00	1.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11.06	11.35	10.37	12.27	11.03	11.84	10.74	10.31	9.08	9.87	12.46	8.88
38.05	43.84	36.91	40.55	31.84	34.41	32.64	38.45	30.03	33.36	32.03	30.51
14.83	13.23	15.73	12.94	17.48	15.73	17.33	15.23	17.81	16.96	16.23	19.32
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.94	0.00	2.87	3.13	1.43	2.90	2.89	3.98	2.50	3.68	5.84	2.01
4.91	1.82	5.62	5.69	7.20	6.73	6.00	7.62	8.74	7.93	8.90	7.46
5.50	9.61	6.10	5.64	6.29	6.28	4.14	6.84	6.95	5.34	5.80	5.42
4.25	3.85	4.51	4.56	4.28	3.60	4.66	3.81	4.91	4.63	5.21	4.56
2.75	2.14	3.05	3.13	3.98	4.45	5.53	3.94	4.92	5.30	4.65	4.80
0.49	0.27	0.50	0.92	1.82	1.61	1.69	1.09	1.54	1.56	0.55	1.77
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.86	0.00	5.70	6.20	2.82	5.74	5.65	7.85	4.92	7.20	11.41	3.93
8.49	11.43	8.89	8.27	12.10	10.18	7.38	10.58	13.27	9.75	9.13	10.95
28.04	23.18	29.89	24.20	35.44	31.37	34.69	29.37	37.23	33.70	33.63	38.77
39.01	15.14	40.03	41.53	44.35	42.69	41.14	45.35	45.63	45.94	48.38	45.28

TRACE ELEMENTS

63	-	61	74	-	43	-	43	-	38	45	30
138	-	114	135	-	88	-	92	-	75	90	72
22.5	-	18.0	23	-	14.0	-	13	-	13	12.3	14
5.1	-	4.6	6.5	-	4.4	-	4.8	-	4.3	3.1	4.6
3.4	-	2.1	3.6	-	1.7	-	1.3	-	2.7	2.1	2.1
1.5	-	1.4	1.5	-	0.9	-	1.0	-	0.7	1.1	0.8
5.0	-	5.3	5.6	3.7	4.1	2.9	4.3	2.9	2.8	5.1	3.4
25	13	24	20	12	15	17	24	15	19	38	17
15.5	10.1	36.6	25.0	9.7	8.7	14.1	32.6	12.5	16.7	50.2	29.7
106	197	123	223	86	94	71	168	94	70	133	88
17.4	3.6	19.2	12.2	8.0	13.9	20.0	18.6	7.5	20.9	27.8	20.3
41	74	28	86	26	29	35	67	33	35	52	32
263	229	246	213	341	419	410	230	360	417	262	436
138	48.7	165	142	139	143	154	193	196	189	264	166
450	430	410	750	240	180	240	460	210	240	380	260

Table 2 (continued).

BASIC ROCKS

Ic-14a+	Ic-7b	Ic-22a	Ic-6	Ic-8	Ic-3	Ic-13	Ic-22b	Ic-40++	Ic-77*	Ic-10b	Ic-53c*	Ic-53a*	Ic-61*	Ic-12	Ic-68c*
53.90	53.50	53.5	52.6	51.2	51.2	51.7	51.2	51.2	51.2	51.2	51.2	51.7	50.7	50.7	49.8
2.67	2.78	2.88	2.82	2.26	2.89	2.10	2.82	2.98	3.97	2.82	2.48	2.43	3.43	2.13	3.52
14.30	14.70	13.70	14.60	15.20	14.30	15.30	13.60	13.10	13.60	14.30	15.90	15.10	12.80	14.80	13.00
3.32	3.08	2.91	3.94	3.45	3.83	2.95	3.62	6.94	3.92	3.33	3.81	3.49	3.60	2.90	4.68
7.45	8.66	7.01	8.24	8.32	8.34	0.05	8.35	9.59	7.90	8.79	6.29	6.40	8.91	8.01	7.85
0.18	0.22	0.18	0.19	0.19	0.20	0.19	0.23	0.25	0.19	0.22	0.16	0.17	0.18	0.18	0.20
3.73	4.11	2.33	4.59	5.22	4.63	5.44	3.66	4.19	4.97	4.19	4.11	4.16	4.79	5.27	4.79
6.88	7.22	5.58	7.86	9.04	8.01	8.92	6.19	7.18	8.07	7.27	7.79	7.66	7.30	8.70	7.32
3.88	3.64	4.58	3.41	3.41	3.57	3.26	4.69	3.42	3.96	3.70	3.78	3.43	3.47	3.24	3.29
1.29	1.26	2.05	1.35	0.92	1.21	1.13	1.53	1.14	1.21	1.21	0.89	0.92	1.09	1.23	1.25
0.38	0.36	0.47	0.36	0.21	0.31	0.21	0.46	1.15	0.36	0.36	0.23	0.24	0.41	0.21	0.32
1.38	1.06	3.58	1.46	1.52	1.13	1.49	2.53	1.36	1.08	1.48	1.00	0.91	1.59	1.29	1.47
99.31	100.59	98.77	101.42	100.95	99.62	100.75	99.88	102.51	100.43	98.96	97.64	96.61	98.76	98.66	97.49

C.I.P.W. NORMS

7.18	5.67	5.41	4.96	1.50	3.08	1.72	0.46	4.75	2.29	2.98	4.58	7.12	5.35	1.35	5.57
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7.78	7.48	12.73	7.98	5.47	7.26	6.73	9.38	6.68	7.20	7.34	5.44	5.68	6.63	7.47	7.69
35.51	30.95	46.71	28.87	29.02	30.67	27.79	41.19	28.68	33.73	32.82	33.10	30.33	30.22	28.16	28.99
18.16	20.15	11.31	20.55	23.59	19.72	23.96	11.98	16.88	15.86	18.96	24.62	24.13	16.60	22.81	17.72
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.91	5.63	6.07	6.72	8.41	7.76	8.04	7.01	4.59	9.21	6.53	5.77	5.82	7.48	8.40	7.49
9.48	10.28	6.10	11.44	13.08	11.71	13.65	9.46	10.34	12.46	10.71	10.59	10.83	12.25	13.48	12.42
7.01	9.22	6.35	7.58	9.10	7.87	9.30	8.42	13.40	5.10	9.38	4.77	5.41	7.44	9.38	5.32
4.91	4.49	4.43	5.72	5.03	5.64	4.31	5.45	6.44	5.72	4.95	5.72	5.29	5.37	4.32	7.07
5.18	5.31	5.75	5.36	4.32	5.57	4.02	5.56	5.61	7.59	5.50	4.87	4.82	7.68	4.16	6.96
0.92	0.86	1.17	0.85	0.50	0.75	0.50	1.13	2.70	0.86	0.88	0.56	0.59	1.00	0.51	0.79
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11.59	11.11	12.05	13.15	16.47	15.17	15.73	13.83	9.17	17.77	12.88	11.16	11.29	14.59	16.44	14.45
10.81	14.02	6.47	12.59	14.12	12.16	15.26	11.06	19.16	9.00	13.74	9.97	10.76	12.69	14.81	10.78
35.15	39.43	21.75	4.59	44.83	39.13	46.29	22.53	37.04	31.99	36.62	42.65	44.31	35.46	44.75	37.93
47.16	45.83	37.20	49.82	52.79	49.74	54.64	43.86	38.75	52.86	45.93	53.80	53.67	48.89	53.97	52.10

TRACE ELEMENTS

36	42	37	26	12	17	15	34	-	-	37	14	29	19	14	18
73	74	74	55	36	50	40	65	-	-	65	43	58	45	39	46
11.0	11.5	11.2	9.1	6.3	8.2	6.5	10	-	-	10.1	7	12	9	8.0	8.5
3.4	3.2	3.5	2.9	2.2	2.8	2.2	3.8	-	-	3.4	2.9	3.2	3.1	2.2	2.9
1.2	1.5	1.1	1.2	1.1	1.6	1.5	1.1	-	-	1.5	1.4	3.4	1.4	1.1	1.8
0.8	0.8	0.8	0.6	0.5	0.5	0.5	0.7	-	-	0.7	0.4	0.9	0.5	0.5	0.5
3.5	4.5	3.7	2.9	3.4	1.7	4.8	4.1	-	-	3.0	2.5	5.1	4.1	2.6	2.1
33	41	20	44	60	44	65	24	13	42	38	40	38	30	51	44
55.3	39.6	26.1	68.8	100	91.8	124	12.8	4.5	27.9	40.1	92	112	45.1	117	132
138	151	134	141	126	147	143	162	127	66	166	96	104	65	143	113
10.9	30.5	10.5	35.9	49.7	35.8	44.3	8.0	0.8	38.5	27.0	19.4	21.3	7.4	39.3	32.9
40	47	57	49	49	88	54	40	41	57	48	42	45	53	49	68
289	270	233	288	270	309	271	254	344	295	267	354	318	311	258	338
261	320	201	342	321	341	302	281	198	358	331	263	253	343	292	377
210	210	460	190	80	210	90	210	150	160	210	180	180	90	150	310

Table 3. Major elements from Blake, 1966.

		Acidic			Mafic "Pillows"		Avg. Pitchstone
	1	2	3	4	5	6	Walker (1962)
SiO_2	72.1	70.9	66.5	66.66	54.3	54.1	70.5
TiO_2	0.35	0.34	0.59	0.25	2.10	2.19	0.3
Al_2O_3	12.7	14.3	15.2	14.89	14.7	14.8	12.4
Fe_2O_3	2.4	2.1	2.1	2.74	2.6	2.7	1.1
FeO	1.6	1.5	3.1	3.22	7.8	7.9	1.9
MnO	0.16	0.04	0.13	Tr	0.21	0.15	0.1
MgO	0.15	0.29	0.78	1.04	3.8	3.8	0.3
CaO	1.26	1.21	2.63	3.22	7.2	7.2	1.4
Na_2O	5.1	5.7	5.7	4.44	5.2	4.1	4.6
K_2O	3.6	3.2	2.7	2.72	1.0	1.4	2.8
P_2O_5	0.12	0.06	0.38	0.18	0.53	0.48	0.05
H_2O	.85	.4	.45	.53	1.3	1.3	4.6
Total	100.4	100.0	100.3	99.89	100.7	100.1	100.05

Table 4. Microprobe analysis of pyroxenes from Type 1 "pillows" (Austurhorn only).

	Ic-3-1	Ic-3-2	Ic-8-1	Ic-8-2	Ic-8-3	Ic-13-2	Ic-13-3	Avg.
SiO_2	61.95	59.28	57.04	58.76	55.76	51.36	52.50	56.66
Al_2O_3	3.91	3.32	2.56	3.95	2.07	0.77	0.90	2.49
TiO_2	1.91	1.36	1.32	1.13	1.03	1.53	0.98	1.32
CaO	12.22	14.62	14.30	15.11	15.88	18.86	19.68	15.81
MgO	14.81	12.42	14.93	12.40	12.53	17.47	17.39	14.56
FeO	8.17	7.05	7.50	6.60	7.05	6.59	5.92	6.98
MnO	0.01	0.00	0.09	0.08	0.09	0.08	0.08	0.06
Na_2O	0.33	0.33	0.38	0.52	0.43	0.61	0.70	0.47
Total	103.31	98.39	98.12	98.54	94.83	97.28	98.15	98.35

PETROCHEMISTRY

Major Elements

Due to the complex chemical variation in these rocks, for ease of discussion, they have been separated into three main groups (Table 2): silicic rocks (greater than 65% SiO_2), intermediate rocks (55% to 65% SiO_2), and mafic rocks (less than 55% SiO_2). A wide range of compositions are found within the silicic and mafic complexes. These rocks range in composition from a basaltic to a rhyolitic nature. Intermediate rocks are found as entire pillows with cuspate boundaries and also in the gradational zones of pillows. C.I.P.W. norms (Table 2) show two important features. Within the mafic rocks none of the rocks are olivine normative and many of the silicic rocks are corundum normative.

The variation of MgO, TiO_2, and P_2O_5 in the silicic and mafic complexes exhibit many similarities and differences when compared with the lava variation observed in Iceland. Plots of the major oxides versus MgO indicate that the variation of the major elements is linear except for Al_2O_3, P_2O_5, and TiO_2. The variation of major elements is similar in both of the rock suites except in TiO_2 and P_2O_5 (Figure 7). TiO_2 is generally higher in the mafic rocks found at the Vesturhorn silicic and mafic complexes (up to 4%) than at the Austurhorn silicic and mafic complexes (up to 2.89%). P_2O_5 is also generally higher at the Vesturhorn silicic and mafic complexes (up to 0.8% as compared to 0.47%). In both suites, however, TiO_2 and P_2O_5 are enriched in many, but not all, of the intermediate rocks. This is most pronounced with respect to P_2O_5. The angular xenolith (Ic-40), which differs mineralogically and texturally from the pillows described, is enriched with respect to total FeO and P_2O_5 compared to all other rocks found at either intrusion and is not included on the variation diagrams presented.

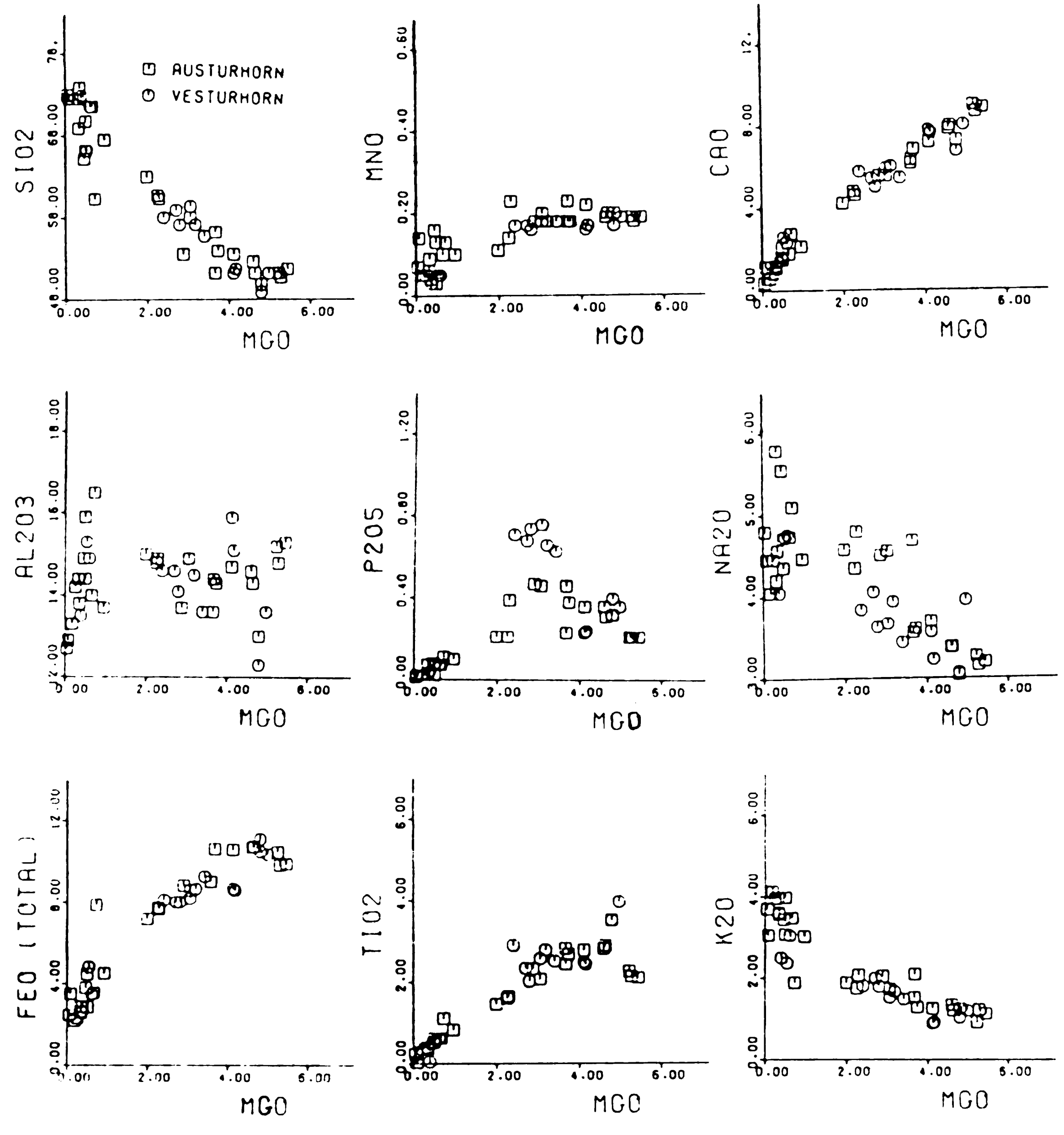


Figure 7. Major element variation against MgO for the Austurhorn (squares) and Vesturhorn (circles) silicic and mafic complexes.

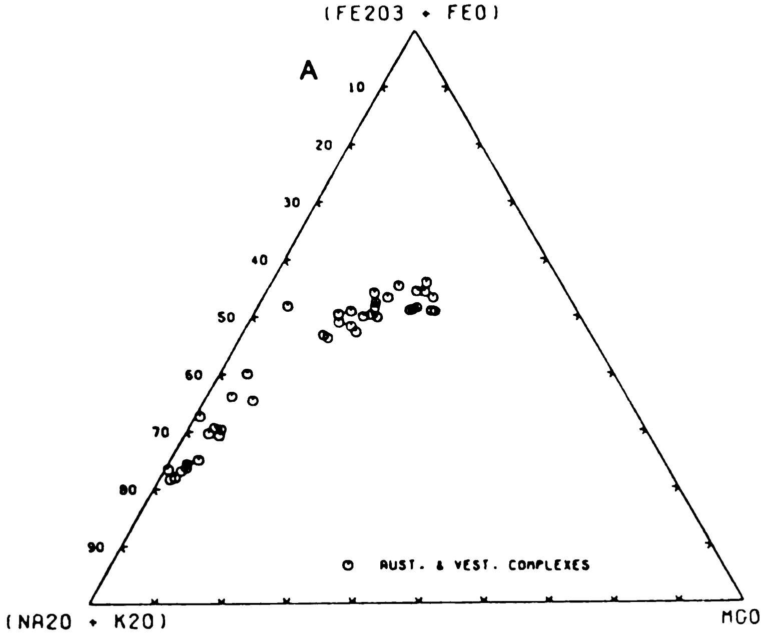


Figure 8a. AFM plot for the rocks from the silicic and mafic complexes.

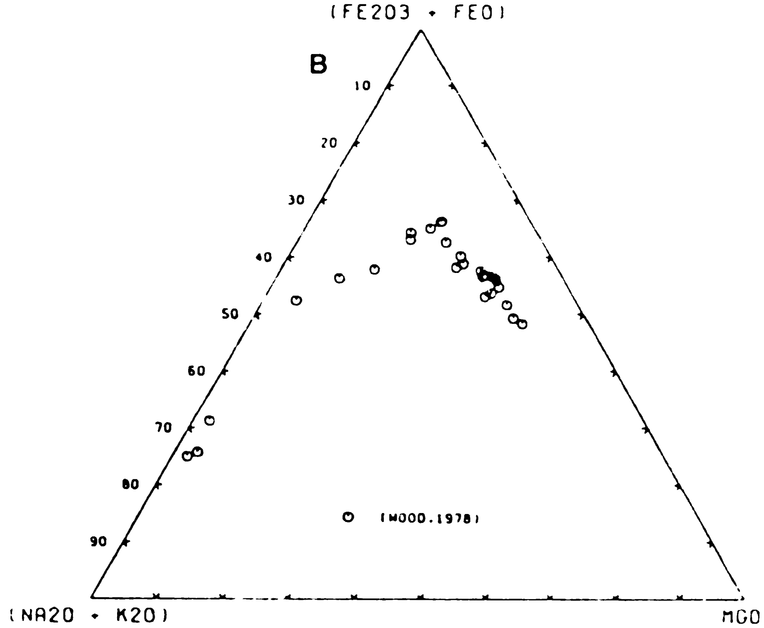


Figure 8b. AFM plot for the lavas sampled to exhibit the entire range of compositions observed in the Tertiary of Iceland. Data from Wood (1978).

Both suites of rocks exhibit a "gap" in MgO. Figure 8a is an AFM plot for all of the rocks from the silicic and mafic complexes found at the two intrusions which illustrates the presence of this "gap". If these rocks are compared with typical variation of the lavas in the Tertiary of Eastern Iceland which also exhibit a gap (Wood, 1978), the size of the "gap" is greatly reduced (see Figure 8b for comparison). However, analyses of rocks from the 1875 Askja eruption indicate that no "gap" is present in MgO (Sigurdsson and Sparks, 1981). Thus, from consideration of the AFM plots presented, the end members of the rocks found at the Austurhorn and Vesturhorn silicic and mafic complexes are similar to the volcanic variations found throughout Iceland. However, the volcanic analogs of the intermediate rocks found in the silicic and mafic complexes are apparently less common, but have been reported (Walker, 1966; Sigurdsson, 1977; Sigurdsson and Sparks, 1981). The AFM plot (Figure 8a) also indicates that primitive high MgO rich rocks found in many volcanic sequences in Iceland are not found in these silicic and mafic complexes. The "gap" observed on ARM plots for both the silicic and mafic complexes and Icelandic lavas needs explanation. A model which could explain this gap will be presented in Part II of this paper.

Trace Elements

Whole rock trace element abundances are presented in Table 2. Trace element abundances have not often be measured in silicic and mafic complexes and this is especially true of the Icelandic environment. Modeling of the trace element abundances will be extensively used in this paper. The general characteristics of the trace elements will be presented briefly. The chondrite normalized REE distribution patterns are LREE enriched (Figure 9) for all rock types. Silicic rocks are the strongest LREE enriched and have a negative europium anomaly. The REE patterns for intermediate rocks plot between silicic and mafic compositions with some overlap and have slight positive to negative

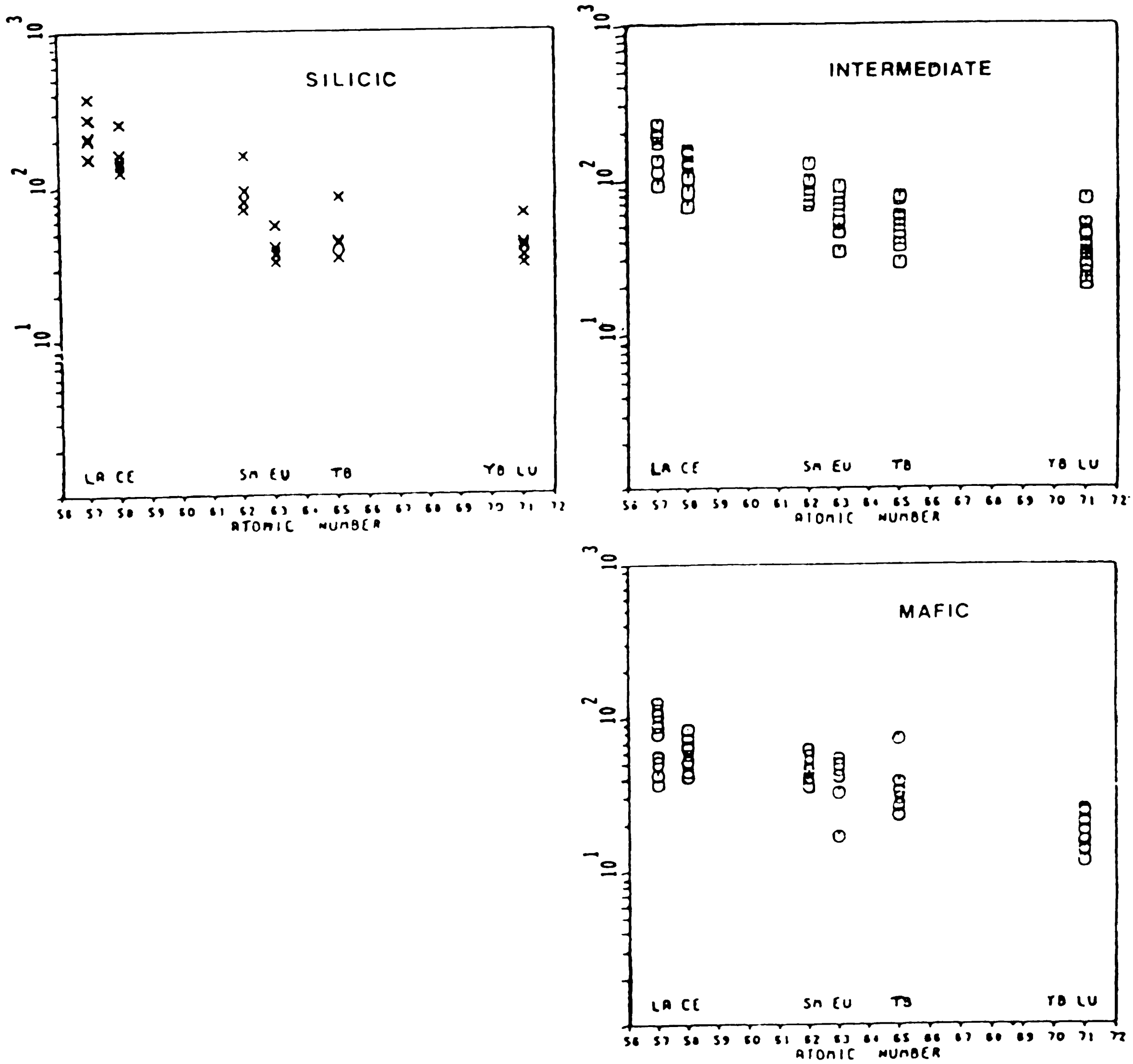


Figure 9. Chondrite normalized REE plots for silicic, intermediate, and mafic rock types as defined in text.

europium anomalies. In general, mafic rocks have no europium anomalies. All of the rocks have high $(La/Lu)_N$ ratios (Figure 11, which are comparable ratios to the $(Ce/Yb)_N$ ratios used by most workers) than are usually exhibited in most Icelandic volcanics (for example, see Wood, 1978; Mattson, in prep.). These ratios are high except for those rocks which are associated with volcanic centers which exhibit variation from rhyolite to basalt (O'Nions and Gronvold, 1973). The distribution of other trace elements will be discussed in other sections of this paper.

EVALUATION OF MODELS OF ORIGIN

Immiscibility

Much interest has been renewed in liquid immiscibility as a potential explanation of the variation of rock types in many environments. Experimental work, theoretical considerations, and petrographic observations have provided evidence that immiscibility can potentially occur in natural silicate systems (Roedder, 1951, 1978, 1983; Ferguson and Currie, 1971, 1972; Massion and Koster Van Groos, 1973; Rutherford et al., 1974; McBirney and Nakamura, 1974; Irvine, 1975, 1976; Visser and Koster Van Groos, 1976, 1977, 1979; Watson, 1975, 1976; Naslund, 1976, 1983; Watson and Naslund, 1977; Freestone, 1978; Ryerson and Hess, 1978, 1980; Visser, 1979; Dixon and Rutherford, 1979; Biggar, 1983; Freestone and Powell, 1983). This information can be used to test an immiscibility model for the rocks under discussion.

Experimental investigations in immiscible systems indicate that the REE's, phosphorous, and titanium are partitioned toward the mafic liquid (Watson, 1976; Ryerson and Hess, 1978, 1980; Visser and Koster van Groos, 1979). Watson reported a five fold increase of the REEs in the mafic liquid and Ryerson and Hess reported a ten fold increase. The differences may be accounted for by the

differing Si/O ratios (Eby, 1980), which could affect melt structure and thus partitioning, used in the experimental charges. Trace elements can thus be used to evaluate an immiscibility model.

The REE's in the Austurhorn and Vesturhorn silicic and mafic complexes are enriched in the silicic rock in comparison to the mafic rock types. In a given sequence of rocks (e.g. a mafic pillow interior, a diffuse zone surrounding the pillow and the silicic rock) all in close association, the silicic rock is more enriched in the REEs than the intermediate rock and the mafic rock. Thus, the REE abundances observed are not consistent with immiscibility, because the REEs are partitioned into the silicic rocks. Differences in Si/O ratios, observed in some alkaline rocks interpreted as immiscible systems (Eby, 1980), cannot explain the observed REE distributions in the silicic and mafic complexes with regard to immiscibility.

Major element trends in immiscible pairs have been generalized (e.g., Naslund, 1983). The mafic rocks under discussion in Iceland have higher aluminum and dissimilar FeO/MgO and MnO/FeO ratios in comparison to the silicic rocks. These values should be similar in an immiscible system (Naslund, 1983). Thus, the major element values found in the silicic and mafic complexes are not consistent with an immiscibility model. Phosphorous and titanium are depleted in the silicic rocks relative to the intermediate and mafic compositions as might be expected in an immiscible system, but this same relationship could be generated by almost any fractionation process and is not a critical test of immiscibility.

The fact that mafic pillows are chilled indicates a temperature difference between the magmas. This is inconsistent with immiscibility in situ because, by definition, immiscibility occurring in a single homogeneous liquid is a thermal equilibrium process (i.e., both liquids would be at the same temperature). Other

observations are not supportive of an immiscibility model in place. This includes the presence of diffuse zones which surround many of the pillows and that common phases (e.g. plagioclase) in immiscible systems should be of the same composition, which is not found at these silicic and mafic complexes. In addition, more complex models involving immiscibility, such as the separation of the liquid phases at depth and then later coming into contact at a higher structural level (i.e., lower pressure) is inconsistent with the observed REE distributions as well as requiring an extremely complex "plumbing system" and thermal history.

Magma Mixing

The field relationships at the Austurhorn and Vesturhorn silicic and mafic complexes strongly support a model of commingling and limited mixing between mafic and silicic magmas. The field observations which are interpreted to support this model includes the presence of diffuse zones which surround many of the mafic pillows and the highly mottled textures of the silicic rock which reflects an increase in mafic mineral content as the pillows are approached.

Multiple Linear Regression Analysis. Evaluation of mixing models or crystal fractionation models by multiple linear regression analysis (Wright and Doherty, 1970) has become commonplace in igneous petrology. In most cases, simple multiple linear regression analysis of the major element data using a mixing of silicic and mafic end members to produce intermediate rocks from these intrusions yields unsatisfactory residuals. The major influences in those regression analyses are SiO_2, Al_2O_3, total FeO, P_2O_5, K_2O, and TiO_2. More complex models of magma mixing were thus considered.

Two complex models of magma mixing are; 1) that mixing proceeds in a stepwise fashion with diffusion playing an important role and 2) that magma mixing and crystal fractionation occur simultaneously. In this model magma A and B mix to form magma C. This product in turn mixes with either magma A or

B again. Although this situation should still produce a linear major element variation the process can become more complex or non-linear if one of both of the mixing magmas have crystals present which are fractionating (e.g. crystal settling or filter pressing) or if kinetic properties such as rates of diffusion become the rate limiting step (i.e., disequilibrium). If magma mixing is the dominant process which has occurred at the Austurhorn and Vesturhorn silicic and mafic complexes then, by definition, on the scale of the individual complexes, the rocks represent a case of disequilibrium because a single homogeneous product of mixing is not present. Locally the rocks may represent a quasi-stable equilibrium. Multiple linear regression analysis of rocks from the most thoroughly sampled pillow outcrop, an unchilled and gradational pillow (Ic-3 through Ic-9, see Table 1 and Figure 3a) indicate that a stepwise magma mixing model along with minor fractionation of pyroxene can produce the observed sequence of rocks (Table 5).

In model I (Table 5) silicic rock (Ic-20) can be mixed with an unchilled pillow margin (Ic-6) to produce an intermediate (Ic-5) a hybrid of the same pillow. In model II a hybrid from the same pillow (Ic-4c) can be mixed with pillow margin (Ic-6) to produce another hybrid (Ic-7). In model III hybrid (Ic-4c) and silicic-granophyric rock (Ic-20) can be mixed to produce the unchilled and gradational pillow margin (Ic-9). In model IVa (not shown) silcic rock (Ic20) is mixed with a chilled pillow margin (Ic-3) to produce the unchilled and cuspate pillow margin (Ic-6). A slight variation on model IVa is to add pyroxene into the model as a fractionating phase from chilled pillow margin (Ic-3) which contains pyroxene phenocrysts (Model IVb). Pyroxene may or may not be actually involved. Note its negative coefficient as would be expected (Model IVb) if it was removed by fractional crystallization. Thus in a stepwise mxing model these rocks can be accounted for whereas unsatisfactory results are obtained in endmember mixing between silicic rock (Ic-20) and a chilled pillow margin (Ic-3) to produce

Table 5. Multiple linear regression analysis.

MODEL I

	Ic-20	+	Ic-3	+	Avg. Pyx.	=	Ic-6	Pred.	Residual
SiO_2	73.90		51.20		56.66		52.60	52.60	0.00
TiO_2	0.35		2.89		1.32		2.82	2.87	-0.05
Al_2O_3	13.80		14.30		2.49		14.60	14.56	0.04
FeO	2.80		11.79		6.98		11.79	11.75	0.04
MnO	0.04		0.20		0.06		0.19	0.20	-0.01
MgO	0.35		4.63		14.56		4.59	4.55	0.04
CaO	1.10		8.01		15.81		7.86	7.92	-0.06
Na_2O	4.57		3.57		0.47		3.41	3.66	-0.25
K_2O	3.56		1.21		0.0		1.35	1.30	0.05
P_2O_5	0.03		0.31		0.0		0.36	0.31	0.05
Mix	2.63%		99.4%		-0.36%		r^2=0.9999; ΣR^2=0.079		

MODEL II

	Ic-4c	+	Ic-6	=	Ic-7	Pred.	Residual
SiO_2	60.7		52.60		53.50	53.54	-0.04
TiO_2	1.6		2.82		2.78	2.64	0.14
Al_2O_3	14.80		14.80		14.70	14.57	0.13
FeO	8.80		11.79		11.43	11.30	0.13
MnO	0.14		0.19		0.22	0.18	0.04
MgO	2.25		4.59		4.11	4.26	0.15
CaO	4.82		7.86		7.22	7.39	-0.17
Na_2O	4.35		3.41		3.64	3.53	0.11
K_2O	1.75		1.35		1.26	1.41	-0.15
P_2O_5	0.21		0.36		0.36	0.34	0.02
Mix	14.4%		85.2%		r^2=0.9999; ΣR^2=0.048		

Table 5. Continued.

MODEL III

	Ic-4C	+	Ic-20	=	Ic-9C	Pred.	Residual
SiO_2	60.70		73.9		63.0	63.03	-0.03
TiO_2	1.60		0.35		1.46	1.47	-0.01
Al_2O_3	14.80		13.80		5.00	14.86	0.14
FeO	8.80		2.80		8.21	8.18	-0.03
MnO	0.14		0.4		0.12	0.13	-0.01
MgO	2.25		0.35		1.99	4.43	0.11
CaO	4.82		1.10		4.24	4.43	0.11
Na_2O	4.35		4.57		4.54	1.99	-0.10
K_2O	1.75		3.56		1.89	0.19	0.02
P_2O_5	.21		.03		.021	0.19	0.02
Mix	89.1%		12.1%		r^2=0.9999; ΣR^2=0.048		

MODEL IVb

	Ic-20	+	Ic-3	+	Avg. Pyx.	=	Ic-7	Pred.	Residual
SiO_2	73.90		51.20		56.66		52.60	52.60	0.00
TiO_2	0.35		2.89		1.32		2.82	2.87	-0.05
Al_2O_3	13.80		14.30		2.49		14.60	14.56	0.04
FeO	2.80		11.79		6.98		11.79	11.75	0.04
MnO	0.04		0.20		0.06		0.19	0.20	-0.01
MgO	0.35		4.63		14.56		4.59	4.55	0.04
CaO	1.10		8.01		15.81		7.86	7.92	-0.06
Na_2O	4.57		3.57		0.47		3.41	3.66	-0.25
K_2O	3.56		1.21		0.0		1.35	1.30	0.05
P_2O_5	0.03		0.31		0.0		0.36	0.31	0.05
Mix	2.63%		94.4%		-0.36%		r^2=0.9999; ΣR^2=0.079		

Table 5. Continued.

MODEL V

	Ic-20	+ Ic-5	+ Ic-4C	+ Ic-6	+ Avg. Pyx.	= Ic-3	Pred.	Residual
SiO_2	73.90	56.20	60.70	52.60	56.66	51.20	51.21	-0.01
TiO_2	0.35	2.44	1.60	2.82	1.32	2.89	2.79	0.10
Al_2O_3	13.80	14.40	14.80	14.60	2.49	14.30	14.25	0.05
FeO	2.80	9.99	8.80	11.79	6.98	11.79	11.89	-0.10
MnO	0.04	0.18	0.14	0.19	0.06	0.20	0.20	0.00
MgO	0.35	3.56	2.25	4.59	14.56	4.63	4.62	0.01
CaO	1.10	6.37	4.82	7.86	15.81	8.01	7.96	0.05
Na_2O	4.57	3.77	4.35	3.41	0.47	3.57	3.47	0.10
K_2O	3.56	2.10	1.75	1.35	0.0	1.21	1.27	-0.06
P_2O_5	0.03	0.23	0.21	0.36	0.0	0.31	0.31	0.00
Mix	-19.7%	42.9%	23.6%	31.3%	2.2%	$r^2=0.9999$; $\Sigma R^2=0.039$		

intermediate (Ic-6). Model V collectively models the stepwise model by mixing silicic rock (Ic-20) with hybrids (Ic-5, Ic-4c) and unchilled pillow margin (Ic-6) with minor pyroxene fractionation to produce chilled pillow margin (Ic-3). Models which involve crystal fraction from the mafic rock types to yield the intermediate rocks or the silicic rocks do not produce satisfactory residuals using the phenocrysts phases present in these rocks; nor phenocryst phases common to Icelandic lavas. The phenocryst phase compositions used are from Icelandic lavas as reported by Carmichael (1967).

Many of the intermediate pillows contain anomalously higher P_2O_5 and TiO_2 values than would be expected from a simple mixing model. The Austurhorn silicic and mafic complexes contains intermediate pillows which are high in both P_2O_5 and TiO_2 (for example, Ic-28a,b) relative to the most mafic pillows with chilled margins (Ic-12, Ic-3). The Vesturhorn silicic and mafic complexes also contains intermediate pillows which have anomalously high P_2O_5 (Ic-74a,b,c for example, Ic-74b is a chilled margin). TiO_2 in the Vesturhorn silicic and mafic complexes is not as enriched in comparison to all of the chilled mafic pillows. For instance, many of the intermediates are higher in TiO_2 than chilled mafic pillows Ic-53a,c or Ic-75, but lower than chilled mafic pillows Ic-61 or Ic-68c. A complex situation is presented in which all of these compositions (i.e., silicic, low P_2O_5-TiO_2 intermediates, high P_2O_5 intermediates and mafic rocks) are present in a liquid state at the same time. The variation in P_2O_3 and TiO_2 cannot be explained by simple mixing, mixing and crystal fractionation, or silicate liquid immiscibility. A more complex, at present unknown, model (diffusion?) must be evoked to account for this variation.

Mixing and Trace Elements. Trace element modeling based upon the major element models reported in Table 5 exhibit departures from the expected trends for some elements. In part, the distribution of the trace elements may be due to

disequilibrium effects. For example, for model V in Table 5 the following are the calculated REE abundances from the model and the actual measured REE contents in chilled pillow margin Ic-3 respectively: La (18, 29), Ce (51, 59), Sm (8.7, 9.6), Eu (2.82, 2.80), Tb (1.41, 1.58), and Lu (0.78, 0.48). However, viewed collectively the trace element trends for all rock types are most consistent with mixing.

Plots of La vs. Sm or Ce vs. Sm (Figure 10) in general yield linear plots as would be expected from end member mixing. A stronger test of mixing is a plot of a LREE/HREE vs another incompatible ratio (Langmuir et al., 1978). Theoretically, rocks which have mixed between two end member produce a linear trend on a ratio-ratio plot of incompatible elements when both ratios have a common denominator (Langmuir et al., 1978). A plot of $(Ce/Lu)_N$ vs. $(La/Lu)_N$ (Figure 11) has a linear trend although a small degree of scatter is present. The observed scatter of the plotted points is more apparent from the Vesturhorn than from the Austurhorn mixed rocks. These types of plots are particularly suited in differentiating between crystal fractionation and magma mixing because crystal fractionation produces little variation on such a plot. The observed variation of the mixed rocks is greater by a factor of two when compared to a maximum theoretical variation produced by crystal fraction. However, a plot of $(Ce/Yb)_N$ versus Ce (see Mattson, in prep.) does not descriminate between the slopes of the crystal fractionation trend and the mixed trend observed in these rocks.

Some of the chilled margins exhibit a significant departure from the linear trend which may indicate localized conditions of disequilibrium. This conclusion is supported by the fact that samples Ic-53a and Ic-53c, from the same chilled pillow, show departures on opposite sides from a linear trend. Other pillows exhibit a linear trend; for example, chilled pillow Ic-12 (interior) and chilled pillow Ic-13 (margin). Thus, localized disequilibrium affects may be apparent in

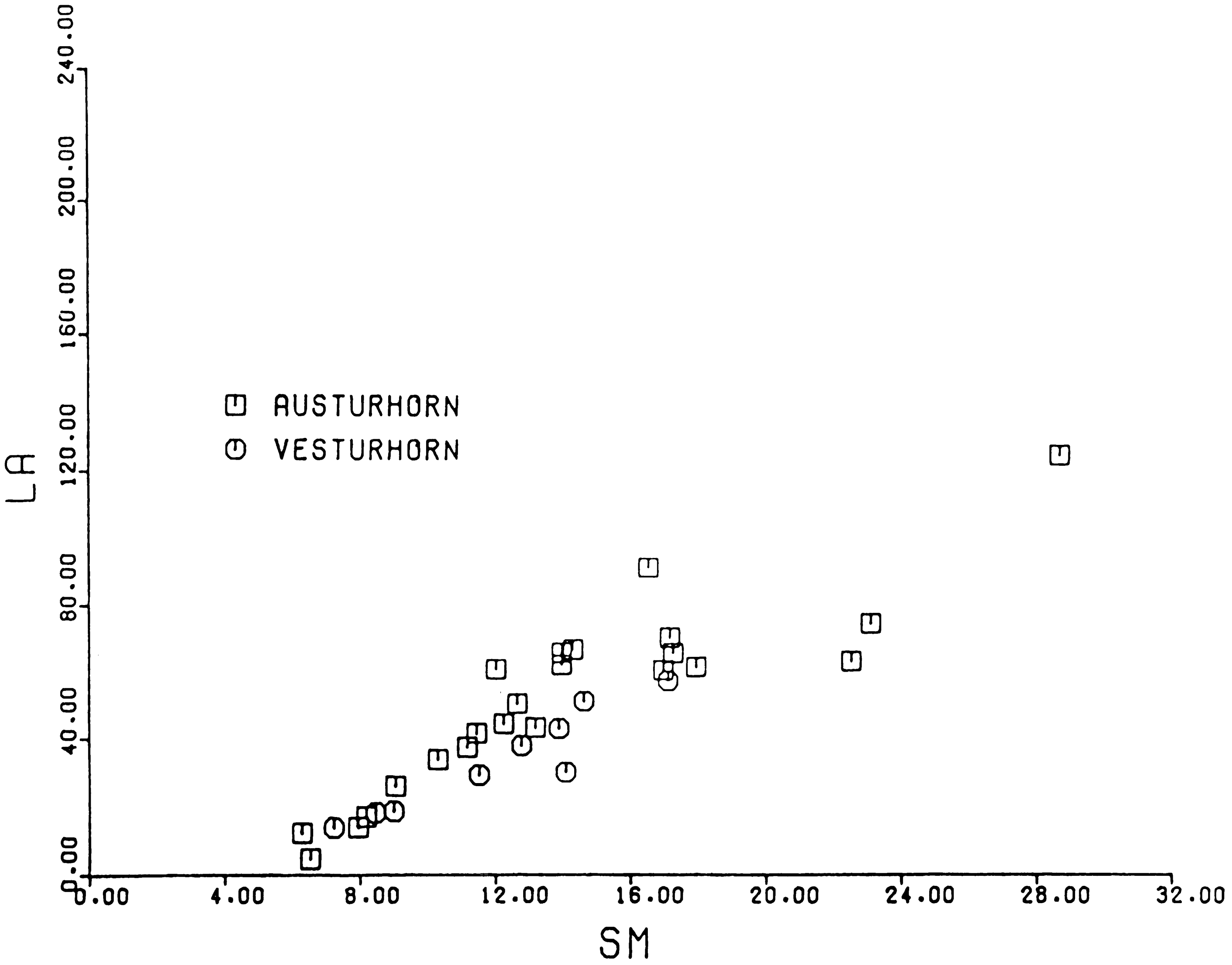


Figure 10. La vs. Sm for the Austurhorn and Vesturhorn silicic and mafic complexes (symbols as in Figure 7).

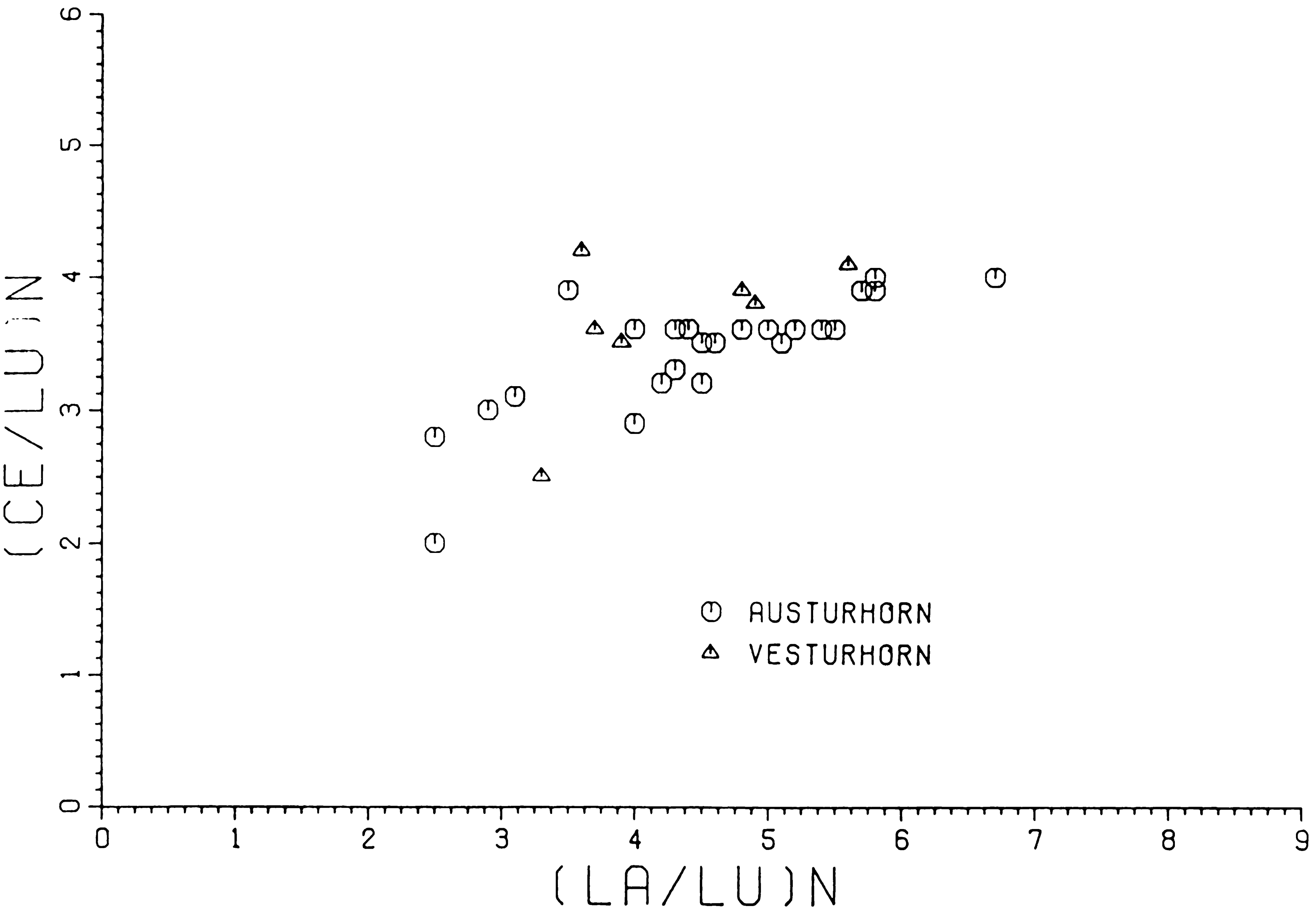
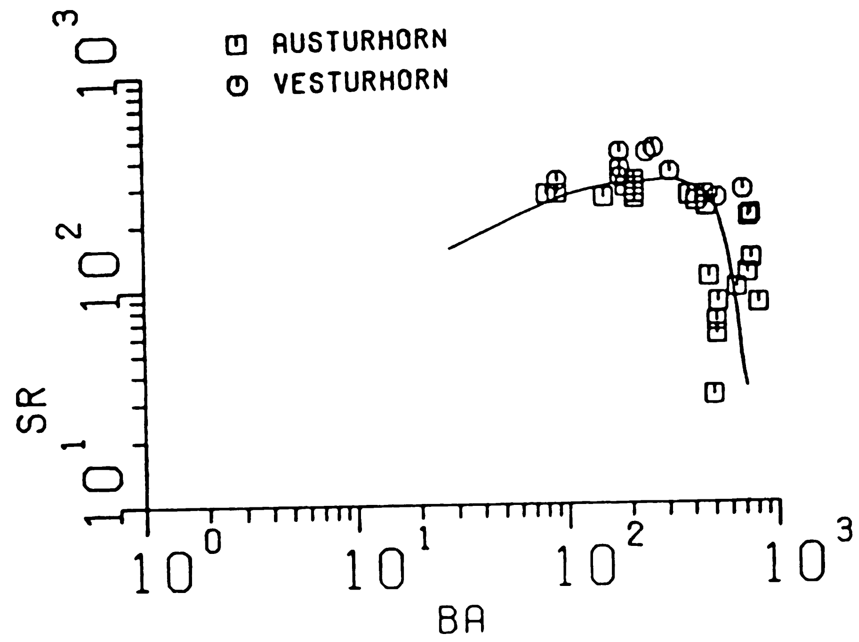


Figure 11. Plot of (Ce/Lu)N vs. (La/Lu)N for the Austurhorn (circles) and Vesturhorn (triangles) silicic and mafic complexes. Large variations are observed in (La/Lu)N while smaller variations are observed in the (Ce/Lu)N ratio.

some of the samples, but the trend produced on this plot is most consistent with magma mixing.

Complex Models. Other trace element distributions are not consistent with a crystal fractionation or an immiscibility model. Log-Log plots of Sr vs. Ba, Sr vs. La, Sr vs. Ce, or V vs. Ba have similar trends. These plots have an initial positive slope for mafic rocks and then a sharp negative slope for silicic rocks. Rocks which are intermediate compositionally plot at the change in slope. Plots are presented for the silicic and mafic complexes and for lavas found in the Tertiary of Iceland (Wood, 1978) for compositions ranging from basalt to rhyolite (see Figure 12). The observed trends in Sr vs. Ba plots (Figures 12) cannot be duplicated by simple Rayleigh fractional crystallization of olivine, orthopyroxene, augite, clinopyroxene, or a plagioclase; or by using any combination of these minerals; or by varying the distribution coefficients through the reported range in the literature. The observed trends indeed cannot be produced by any combination of these minerals fractionating.

Crystal fractionation of minor mineral phases, such as apatite or an opaque phase, are known to strongly effect the trace element trends. The observed Sr-Ba variation and a Rayleigh fractional crystallization model were used to test if minor phases could provide the variation observed. However, using reasonable estimates of fractionating mineral proportions of five percent apatite and ten percent of an opaque phase, and an initial concentration in a mafic or intermediate parent of 300 pm Sr to produce an silicic rock with 80 pppm Sr, the calculated distribution coefficients using a Rayleigh law model are approximately K_D-60 (apatite) and $K_D = 60$ (opaque phase). The distribution coefficients needed to produce the Sr values observed are unreasonably high. Estimates of Sr distribution coefficients can be made by comparisons of the distribution coefficients for Eu, which should behave similarly. A maximum value, K_D of 50



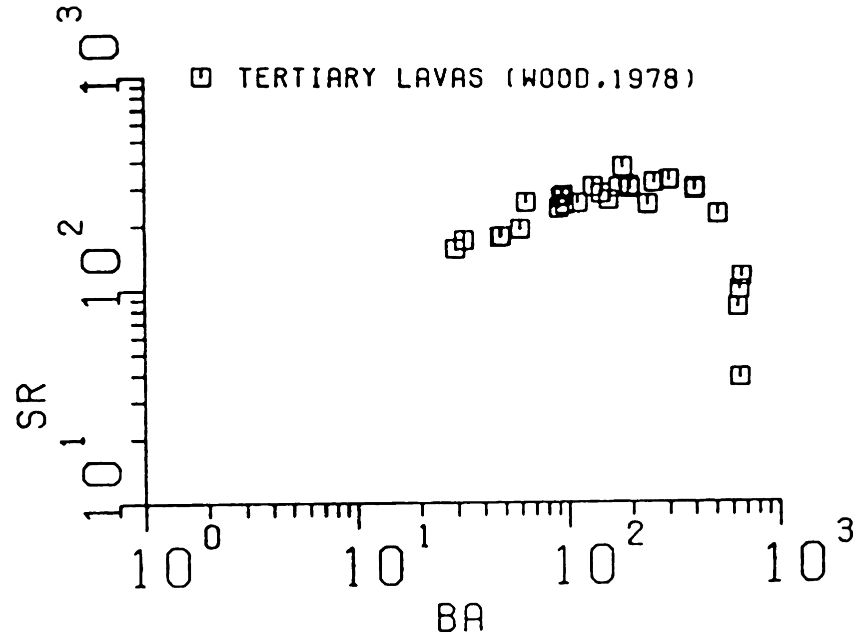


Figure 12. Log plots of Sr. vs. Ba for the silicic and mafic complexes (symbols as in Figure 7) and for the lavas found in the Tertiary of Iceland (Wood, 1978). Solid dark line is the trend of lavas observed in the Tertiary of Iceland.

(apatite) for Eu (Nagasawa, 1970), for a rhyolitic composition would estimate the maximum value expected for Sr since lower SiO_2 magmas would likely have lower K_D values. Experimental determinationa of Sr partition coefficients in apatite (Watson and Green, 1981) from granite and thoeliitic andesite compositions range from 1.3 to 2.4 which are much too low to produce the variation observed. Also the partition coefficient for Sr are apparently insensitive to changes in pressure, temperature and melt composition (Watson and Green, 1981). Reported K_Ds for Sr in magnetites from andesite compositions range from 0.23 to 0.42 (Luhr and Carmichael, 1980). Additional consideration of plagioclase as a fractionating phase would only have a minor effect on the estimated bulk distribution coefficients and have only a minor effect upon the modeled distribution of these elements in comparison to the trends observed. In addition, apatite and opaque phases are not observed as phenocryst phases in the silicic and mafic complexes. Thus crystal fractionation alone cannot produce the observed variation in Sr in these rocks.

Simple magma mixing between silicic and mafic compositions would not explain the observed trends of Sr vs. Ba because a linear trend would be expected between end members. A model involving magma mixing and crystal fractionation is also difficult to reconcile with observed trends because of the continous but non-linear variation between Sr vs. Ba. Fractionation of apatite or plagioclase produces a similar trend as mixing between silicic and intermediate pillows would, but it cannot explain the horizontal trend between mafic and intermediate compositions. It should be remembered that both mafic and intermediate pillows have apparently mixed with the silicic rock, yet the differences occur between these compositions (i.e., there is not a linear trend from mafic to silicic compositions). The observed trends involving Sr and Ba remain problemmatical.

DISCUSSION

A Final Note on Immiscibility

Walker (1983) has stated that all the occurrences of silicic and mafic complexes are controversial as to whether they represent silicate liquid-immiscibility or commingling of magmas. As discussed previously, field relationships and the trace element partitioning observed in these complexes provide an excellent means to separate these two processes. The presence of chilled boundaries on the mafic pillows described in this paper and in others (e.g., Wager and Bailey, 1953; Taylor et al., 1980; Vogel, 1982) preclude immiscibility in place due to the fact they represent thermal disequilibrium between the two liquids. Thermal equilibrium is a necessary condition during silicate-liquid immiscibility. Arguments which maintain that the common phases of immiscible liquids, which should be compositionally the same, could reequilibrate at lower temperatures without any evidence of having done so would seem to be extremely fortuitous. In addition, silicate liquid immiscibility which has occured at depth, efficiently separated into its liquid components, and then been intruded at a higher structural level (now out of the immiscibility field due to changing physical parameters) to form a silicic and mafic complex, would seem to be an unnecessarily complex model and still does not explain the trace element data nor the lack of thermal equilibirum.

P_2O_5 and TiO_2 and the Extent of Mixing and Diffusion

The field evidence at both of these silicic and mafic complexes indicates that magma mixing, in situ, was common, but spatially limited to the localized areas surrounding many of the pillows. The lack of extensive mixing probably reflects the lower temperature and greater viscosity of the silicic magma in comparison to the mafic magma. Similar textures and mixed compositions as

observed in the silicic and mafic complexes have been produced experimentally by the simultaneous melting of mafic and silicic compositions in a bomb (Yoder, 1973) and by mechanical mixing (Kouchi and Sunagawa, 1982). It is likely that small amounts of silicic magma may be mixed with a large amount of mafic magma, especially if the silicic magma is superheated and convection occurs simultaneously.

Field observations strongly support magma mixing as the dominant process which has occurred in these silicic and mafic complexes. Hypotheses which could account for the variation of rock types, especially the high P_2O_5 and TiO_2 intermediate compositions and the behavior of Sr and Ba observed, concurrent with mixing, include; 1) that more than two unsampled (?) end members are involved in the mixing process, 2) a zoned mafic magma chamber mixed with the silicic magma, similar to the chemical gradients in magma chambers envisioned by Rice (1981), Huppert and Sparks (1980), Huppert and Turner (1981), Turner and Gustafson (1981), Walker and DeLong (1982), Vogel (1982), Marshall and Sparks (1984), and 3) that the compositions present represent disequilibrium products, such that, some elements such as phosphorous and titanium have diffused preferentially under a Soret effect.

If more than two unrelated magmas are involved as end members then it is surprising that simple mixing or complex mixing between three end members cannot produce the variation observed. Multiple linear regression models testing this hypothesis yield unsatisfactory residuals. Various intermediate samples were chosen to be used in multiple linear regression models involving a third magma type. Involvement of a third magma type from a separate and unrelated magma chamber would not seem to be justified, although the results do not clearly discriminate between the possibilities suggested.

Recent experimental data on Soret diffusion (Walker and Delong, 1982) in mafic rocks allows a qualitative evaluation of this type of diffusion. The direction of diffusion for the major oxides, except P, in a temperature gradient has been experimently produced on MORB compositions. The trends produced by diffusion are quite unlike trends expected from fractional crystallization. For example, Si, Na, Al and K are partitioned toward the hot end of the cylindrical axial cavity and Ca, Ti, Fe, Mg and Mn are partitioned toward the cold end of the cylindrical axial cavity (Walker and Delong, 1982).

A comparison of an individual unchilled pillow having a gradational boundary (i.e., samples Ic-9, Ic-4c, Ic-5, Ic-7b, Ic-6, see Table 1) with these experimental results are qualitatively inconsistent with a Soret diffusion model until one examines the field relationships. The expected direction of diffusion for these nine elements for samples Ic-9 (silicic) through Ic-6 (mafic) is qualitatively the same as produced in the experimental runs on MORB compositions. However, Ic-6 is from the lower unchilled and cuspate boundary of the pillow and Ic-9 and Ic-4c from the upper diffuse boundary of the pillow. The experimental data obtained from runs with a temperature difference of $< 200^{\circ}$C would predict that Ic-9 was significantly hotter than Ic-6. The presence of chilled pillows with chilled boundaries both above and below this pillow (i.e., a small temperature gradient) would not appear to support a Soret diffusion model.

Ti and P can have important effects on the structure of silicate melts (Ryerson and Hess, 1980; Mysen et al., 1980a, 1980b) and thus their viscosity, the diffusion of elements and other derivitive properties. A variation in P or Ti in either magma can affect how two magmas mix and the diffusion of elements between the two. A limiting factor is the low diffusivity of phosphorus in silicate liquids (Doremus, 1973; Watson, 1976). Strict quantitative evaluation of a Soret model is not possible because the temperature gradient and initial composition cannot be assumed. Also the effect of the addition of phosphorus and varying starting compositions on the Soret diffusion coefficients has not yet been evaluated. Trace elements are also effected by melt structure (Mysen and Virgo, 1980) and this may have produced some of the trace element scatter such as that observed on the $(Ce/Lu)_N$ vs. $(La/Lu)_N$ plot. Thus an evaluation of whether magma mixing or Soret diffusion or both are operating mechanisms in the magma chamber cannot be clearly delineated. Gradients produced by mixing and diffusion have been noticed elsewhere (Taylor et al., 1980; Vogel, 1982).

Diffusion rates would probably be the rate limiting step in a Soret diffusion model with a commingling of magmas. The diffusion coefficients for Sr, Ba, K, Na, Ca, and P are approximately 10^{-6} to 10^{-7} $cm^2 sec^{-1}$ (Hofman and Magaritz, 1977; Doremus, 1973; Watson, 1976, 1982, 1983; Watson and Jurewicz, 1984). Thus for the pillow sequence Ic-9 through Ic-6, which is over 100 cm wide, approximately 300 to 3,000 years would be required to produce the variation observed. Simple diffusion would be limited in time. It is concluded that Soret diffusion plays a minor role between the edge of a pillow and the interior of a pillow, but may be responsible for some of the trace element scatter observed. Magma mixing aided by mechanical or a localized convective transfer is accepted as the dominant process which has occured.

It is of interest that the Austurhorn and Vesturhorn silicic and mafic complexes exhibit such a similar range of compositions, especially with respect to the high P_2O_5 and TiO_2 intermediate compositions. such similar compositional ranges occur elsewhere in Iceland. For example, at the 1875 Askja eruption which has also been described as an intimate association of silicic, intermediate, and mafic magmas (Sigurdsson and Sparks, 1981). High P_2O_5 and TiO_2 intermediate lavas are also present. These occurrences over widely separated areas suggest more than a casual relationship. This variation may be due to the development of

a zoned mafic magma chamber which has underplated a silicic magma or the involvement of more than one mafic magma.

At the Ardnamurchan net-veined intrusion, also a part of the North Atlantic Volcanic Province, located on the western coast of Scotland both high and low TiO_2-P_2O_5 mafic pillows are found (Vogel, 1982; Marshall and Sparks, 1984). The large range in mafic rock types present are interpreted as resulting from the processes of magma mixing and crystal fractionation (Vogel, 1982; Marshall and Sparks, 1984). In contrast to the Icelandic examples described, the occurrence in Scotland exhibits little evidence of mixing in situ, but the evidence for commingling of silicic and mafic magmas is widespread. Thus mixing and fractionation processes must have occurred at depth and not at the level of exposure. Mixing of a silicic magma with a zoned mafic magma at depth has been postulated to account for these observations (Vogel, 1982; Marshall and Sparks, 1984). In part, the significance of the chemical variation observed in the silicic and mafic occurrences over a widely separated areas of the North Atlantic Volcanic Province are that 1) magma mixing between silicic and mafic magmas is a common occurrence, and 2) that a wide range of mafic compositions are present which cannot be solely accounted for by simple mixing processes. Complex models such as, multiple events of mafic magma injection into a silicic magma chamber or the underplating and development of a zoned mafic magma beneath the silicic magma are necessary in order to account for the field relationships and chemical variation observed.

Superheating of the Silicic Rocks

The silicic rocks found in the silicic and mafic complexes were likely superheated. Evidence for this includes; 1) the lack of chilled boundaries on many of the intermediate rocks (unchilled pillows); and 2) the lack of chilled boundaries on some edges of the more mafic pillows (chilled-gradational pillows).

Superheating of silicic compositions, if common in Iceland, may have important ramifications in producing the variation of rock types observed as well as playing a role in the eruption of silicic compositions. Magma mixing as a triggering mechanism for eruption of silicic magmas (Sparks et al. 1977) may be heavily dependent upon the volumes present and degree of superheating of the silicic magma. Evidence from the 1875 Askja eruption indicates that the silicic magma was superheated. Temperatures of 990°C to 1010°C were reported (Sigurdsson and Sparks, 1981) on the basis of plagioclase geothermometry. Walker (1963) reports the existence of welded tuffs, in the Tertiary of Iceland, where the tuff is only five feet in thickness. The Skessa Tuff is also a composite tuff (Walker, 1963) reflecting an intimate association of silicic and basic magma. Similar composite tuffs (Blake, 1969) and composite flows and dikes which are followed by basaltic volcanism (Gibson and Walker, 1963) were also likely superheated.

Another intrepretation of the plagioclase compositions is that they do not represent equilibrium conditions in the magma chamber. Anomalously high calculated temperatures may not represent rocks with quenched-in equilibria (Drake, 1976). Plagioclase core compositions, for silicic rocks, in the Austurhorn intrusion range up to An_{47}, for the 1875 Askja products $An_{52.7}$ (Sigurdsson and Sparks, 1981), and from the Iceland Research Drilling Project up to An_{80} (Schmincke et al., 1982). The latter are clearly in disequilibrium with its magmatic host. However, the field evidence, described above, is strong evidence that silicic magmas can become superheated.

Origin of the Mafic Rock Types

The most primitive MgO rich mafic pillows with chilled margins resemble the lava compositions of low-magnesia basalt, ferrobasalts, and basaltic andesite found in the Tertiary lavas of Eastern Iceland (Wood, 1978). All of these compositions are not generally thought to represent primary mantle melts, but

more evolved melts which have undergone fractionation. Thus, the mafic rocks found in the silicic and mafic complexes probably represent evolved compositions and not primary mantle melts. The range in compositions of pillows with chilled boundaries is extraordinary and simple mixing calculations does not account for their presence in the same environment.

In the pillows with gradational boundaries many intermediate compositions occur which do not have analogous volcanic compositions (i.e., between icelandite and rhyolite compositions) in the Tertiary of Iceland (see Figure 9). However, many of these compositions do have analogous volcanic compositions in the neovolcanic zone (Sigurdsson and Sparks, 1981) suggesting that not enough detailed sampling of the Tertiary lavas has been conducted or that these intermediate lava compositions may be extremely rare occurrences. In summary, many of the mixed rocks found at these two intrusions have analogous volcanic counterparts.

In the type 1 pillows which are quenched, the plagioclase phenocrysts often have resorbtion textures and have cores up to An_{85}. Plagioclase which is not in equilibrium with its host lava has been discussed in other Icelandic settings (Jakobsson, 1979; Flower et al., 1982). These crystals are not in equilibrium based upon their textures and high An cores. They may be 1) relict from a primitive magma where plagioclase floated to the top of the chamber, 2) be the result of the mixing of a primitive porphyritic magma with a more evolved mafic magma, or 3) the result of mixing of a small amount of silicic magma with a porphyritic mafic magma. All of these processes would have occurred at depth and not at the present level of exposure in these two intrusions.

SUMMARY

The rocks at both the Austurhorn and Vesturhorn silicic and mafic complexes contain unequivocal examples of liquid-liquid relationships between magmas. Field and chemical data are most consistent with commingling and magma mixing between silicic and mafic magmas and preclude liquid immiscibility. Complex models of mixing are necessary to explain the observed features at these silicic and mafic complexes. Because such composite intrusions can often be misinterpreted as intrusion breccias detailed field work is required before making such distinctions.

A complex history of intrusion and interaction between coexisting silicic, intermediate, and mafic magmas is indicated by the field data as well as the chemical variations. Of particular interest is the existence of high P_2O_5 and TiO_2 intermediate rocks which cannot be related by fractional crystallization or simple mixing. The observed trace element variation of Ba and Sr are difficult to explain by existing models. Models which could account for these chemical variations are: 1) the involvement of more than two compositionally different mafic magmas which have invaded the same silicic magmatic chamber, or 2) the involvement of a zoned evolved mafic magma which mixes with a silicic magma.

Mixing of silicic and mafic magmas which form a homogeneous magma is not likely unless the volume of the mafic magma is much larger than the silicic magma and unless the silicic magma is superheated. The silicic magmas at the Austurhorn and Vesturhorn silicic and mafic complexes are interpreted as having been superheated. Because extensive mixing between silicic and mafic compositions did not occur it is suggested that mixing between small volumes of mafic magma and larger volumes of silicic magma did not occur due to temperature and viscosity differences. Mixing between large volumes of mafic magma and small volumes of silicic magma may be possible. Many of the mafic compositions found at these two intrusions exhibit similar variation to that observed in the lavas of Iceland. However, many of the intermediate compositions found are rarely observed as volcanics. A comparison of the

chemical variation observed in the Tertiary lavas of Iceland with the chemical variation observed in these silicic and mafic complexes, reported here, and several other occurrences of mixed rocks reported in the literature will be presented in Part II of this paper.

The major element compositions and trace element trends in the mafic pillows are most consistent with their origin resulting from a combination of magma mixing, minor crystal fractionation and minor diffusion gradients between the mafic magma pillows and the silicic magma. The mafic pillow types probably do not represent a primitive mantle melt and exhibit disequilibrium plagioclase which was probably inherited from a more primitive magma.

The significance of the mixed rocks studied can be related to Smith's (1979) and subsequent workers models (e.g., Thompson, 1980; Hildreth, 1981; Vogel, 1982; Bell, 1983; Marshall and Sparks, 1984) on the evolution of small volume high-level silicic magma chambers which typically occur in the North Atlantic Igneous Provinces. Germane to all of these models is the interaction of mafic and silicic magmas. Mafic magma underplating silicic magma transfers thermal energy to the silicic magma increasing the silicic magmas likelihood of eruption, stratifies the magma chamber, and influences the chemical evolution of the magma chamber and thus, the erupted products. Small volume systems have the greatest potential for erupting silicic and mafic portions of the magma chambers (Smith, 1979). This study has documented this interaction from the study of two silicic and mafic complexes which may represent the only preserved stage of such processes before destruction by turbulent mixing, eruption, and surfacial processes.

Mechanical mixing is the dominant process which has occurred in these high-level complexes. An important implication of this study is that the volume of mafic magma involved may have a strong influence on the extent of mechanical

mixing which occurs. In small volume magma systems, such as occur in the North Atlantic Igneous Province, only part or occasionally the entire chamber may be sampled and erupted. Only in few well documented cases has a large range of volcanic products been observed (e.g., Askja eruption, Sigualdason, 1979; Sigurdsson and Sparks, 1981). Other volcanic occurences are known in Iceland but have not been extensively studied (e.g., Walker, 1963). In general, the field, petrographic, and geochemical studies on the Austurhorn and Vesturhorn silicic and mafic complexes are consistent with a Smith model of a stratified magma chamber. Part II of this paper will present a comparison of the chemical variation observed from documented cases of magma mixing with the variation observed in the lavas found in the Tertiary of Iceland.

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GENERAL INTRODUCTION: PART II

Many examples of magma mixing between mafic and silicic magmas are known to occur in Iceland. The examples include rhyolitic flows with presumably still liquid basaltic inclusions, composite dikes, silicic and mafic complexes, and rhyolitic pyroclastics with mixed ejecta. A wide variety of intermediate compositions are known to occur in these examples of magma mixing. A comparison of the known mixed rock compositions with intermediate lavas (basaltic andesite and icelandite) suggest that most intermediate lavas are derived from magma mixing processes. Trace element ratios (Ce/Yb)N, (La/Lu)N, and (Ce/Lu)N found in intermediate lavas are also inconsistent with simple crystal fractionation processes. The known examples of magma mixing are most consistent with the development of a zoned magma chamber (mafic magma capped by silicic magma) which controls the dynamics of eruption and the formation of intermediate lavas.

Mafic magmas in Iceland are generally richer in TiO_2, P_2O_5, K_2O, and FeO than normal Morb. Due to the excess thickness of the oceanic crust, a cooler geothermal gradient through which magmas intrude, and hydrothermal circulation systems found in Iceland, magmas are delayed in the crust and evolve toward more iron-enriched compositions. The variation observed in trace element ratios such as (Ce/Lu)N, (La/Lu)N, and (Ce/Yb)N are inconsistent with simple crystal fractionation models for mafic rock types ranging from high magnesia basalt, low magnesia basalt to ferrobasalt. These trace element ratios and the major element variations can be explained in terms of a modified open system fractionation model.

Mafic magmas (high magnesia basalts, low magnesia basalt and ferrobasalts) effected by modified open system processes may mix at any point in their evolution with silicic magmas and form intermediate compositions. Silicic magmas are most likely generated by the partial melting of a hydrated basaltic crust.

PART II: LAVA VARIATION AND A COMPARISON WITH KNOWN EXAMPLES OF MIXING

INTRODUCTION

Research into the processes and products produced by magma mixing have recently undergone a revived interest. Although too numerous to mention here, these works have been conducted on nearly every type of common tectonic and evolutionary lava-trend association known to occur (e.g., Sparks, 1983).

This investigation was begun in order to access the role of magma mixing in the Icelandic crust. Several examples are available from the Icelandic literature which have documented magma mixing in situ (e.g., Mattson et al., in prep.) between silicic and mafic magmas. The examples of magma mixing contain a wide variety of intermediate compositions. A comparison of these known mixed compositions with the variation observed in lavas will be presented.

Dynamic models for mafic magma evolution have also been the subject of theory which has produced the concept of open-system fractionation in magma chambers (O'Hara, 1977; Pankhurst, 1977; O'Hara and Mathews, 1981). Open-system fractionation requires a magma chamber which has a steady or periodic influx of fresh hot magma, a flux out of the magma chamber, and is undergoing crystallization at the same time. The major element trends, trace element variations, and consideration of the field distribution of the lavas (tholeiitic to rhyolitic) found in the Icelandic crust will be compared to the chemical trends observed in the occurrences of silicic-mafic magma mixing coupled with the chemical trends which would be predicted by open-system models.

Much recent investigation has been conducted on the evolution of continental silicic volcanism and a major thrust of this research has been the

proposal that concomitant with the silicic volcanism is the involvement of hot mafic magma underplating these systems (e.g., Smith, 1979; Hildreth, 1979, 1981). The mafic magma supplies the necessary heat to the silicic system for eruption and other physical and chemical processes which occur in the silicic magma chambers. In large volume systems, the interaction of silicic and mafic magmas is often obscured. In order to investigate this interaction of contrasting magma types it has been suggested that the small volume silicic systems such as those which occur in Iceland (Smith, 1979) and the North Atlantic Tertiary Volcanic Province as a whole (Thompson, 1981) should be the most likely place for this interaction to be preserved in the volcanic products.

Smith (1979) has pointed out the relationship between volume of erupted products and caldera area. In large silicic systems the drawdown never taps the mafic end member. Thus it has been suggested that the study of small eruptive volumes of silicic pyroclastics should be best suited to evaluate the interaction of silicic and mafic magmas because drawdown may tap both the silicic and mafic magmas (Smith, 1979). In Iceland these systems are sufficiently small enough that the zoned magma chambers should be tapped and erupt a large range of compositions as pyroclastic deposits and as lavas. There is also evidence found for this interaction at hypabyssal levels in the crust (e.g., Vogel, 1982; Mattson et al., in prep.), in the form of silicic and mafic complexes, which have subsequently been exposed by erosion.

The aim of this study is to compare the examples of mixed rocks with the lava variation observed in Iceland. If the intermediate lavas observed in Iceland are due to the mixing of mafic and silicic magmas then this may have many important ramifications on the development of silicic magma chambers in many environments and the origins of oceanic islands with intermediate lavas of tholeiitic affinities. This comparison uses only Tertiary age rocks since most of

the occurrences of mixed rocks which have been studied are Tertiary in age and because the processes investigated are thought to span a wide time frame. Recent volcanic activity from the active volcanic zones or the neovolcanic zone in Iceland have not been included in this study although it is of a similar nature. The comparison presented considers the major elements, trace elements, and field setting of the mixed rocks in comparison to the lava variation observed in the Tertiary of Iceland. Another aim of this study is to evaluate whether mafic magma mixing (i.e., open-system) processes can account for some of the lava variation observed in the Icelandic crust. This comparison leads to an interpretation of the general dynamics of the magmatic systems found in the Icelandic crust.

In Iceland numerous examples occur which document that mafic and silicic magmas interact. These examples in Iceland include rhyolitic pyroclastics with mixed ejecta (Walker, 1962; Blake, 1969; Sigvaldason, 1979; Jorgensen, 1980; Sigurdsson and Sparks, 1981; Sparks et al., 1981), rhyolitic flows with presumably liquid basaltic inclusions (Walker, 1962; Gibson and Walker, 1963; Sigurdsson, 1971; Jakobsson, 1979), composite dikes (Walker and Skelhorn, 1966; Blake et al., 1965; Gibson and Walker, 1963; Gunn and Watkins, 1969; Guppy and Hawkes, 1925; Cargill et al., 1928) and composite intrusions or silicic and mafic complexes (Blake et al., 1965; Blake, 1964, 1966; Roobol, 1971, 1974; Prestvik, 1980; Mattson et al., in prep.). The coexistence of silicic and mafic magmas in the same environment is a characteristic of the North Atlantic Tertiary Province (Thompson, 1981; Blake et al., 1965) of which Iceland is a part.

In general, the reports on the Icelandic mixed rocks have been treated as rare occurrences, whereas it will be shown that they may represent the more common case. However, investigations of the Askja eruption of 1875 have emphasized that the "mixed" ejecta compositions have resulted from the

interaction of silicic and mafic magmas in a subvolcanic chamber (Sigvaldasson, 1979; Sigurdsson and Sparks, 1981; Sparks et al., 1981). Mafic magma injection into the silicic magma chamber provided the heat necessary for eruption and produced intermediate mixed magma.

In the hypabyssal environment many studies have been conducted on silicic and mafic complexes or net-veined complexes which record the interaction of silicic and mafic magmas. These complexes probably represent the vestiges of mafic and silicic magma interaction in the subvolcanic chamber. The complexes usually consist of mafic pillow shaped bodies with cuspate and chilled boundaries entirely surrounded by the silicic rock (e.g., Mattson et al., in prep.; Vogel, 1982; Blake et al., 1965). Many instances of mixed boundaries occur around these chilled pillows. It is not known in all instances whether the silicic magmas erupted, but it is clear that intermediate compositions were produced as a result of this interaction.

The silicic and mafic complexes and other documented cases of mixing, in Iceland, provide an opportunity to compare the compositions of mixed rocks produced from the interaction of silicic and mafic magmas with the overall evolutionary trend of lavas with tholeiitic affinities. The known mixed magma compositions are represented in the silicic and mafic complexes, the composite dikes, and the mixed ejecta from pyroclastic deposits.

PRESENTATION OF THE MODEL

Numerous laboratory studies have been made in recent years on the dynamics of magma interaction in high level magma chambers (Huppert and Sparks, 1980a, 1980b; Huppert and Turner, 1981; Turner and Gustafson, 1981; Huppert et al., 1982a, 1982b, 1983; Turner et al., 1983; Sparks and Huppert, 1984). These studies suggest that the introduction of hot primitive mafic magma in a

magma chamber can initiate mixing processes which are often followed by or preceeded by crystallization processes. Also, hot primitive magma introduction into a subvolcanic magma chamber can produce compositional and thermal stratification, mixing, and, possibly with vesiculation of the magma, eruption of the chamber. In Iceland, it is proposed that mafic magma evolution is dominated by an open magmatic system in which new magma influx, periodic eruption, and crystallization simultaneously play important roles. The above processes are invoked by many studies in order to account for the lava variation observed in an oceanic environment (e.g., O'Hara, 1977; Donaldson and Brown, 1977; Dugan and Rhodes, 1978; Rhodes et al., 1979; Rhodes and Dugan, 1979; Shibata et al., 1979; Walker et al., 1979; Stopler and Walker, 1980; Stopler, 1980; Sparks et al., 1980; Biggar, 1983; Fujii and Bougault, 1983).

Also proposed is the mixing of silicic and mafic magmas at higher levels in the Icelandic crust which produces intermediate lavas of icelandite and basaltic andesite compositions. This interaction of contrasting magmas may trigger eruption of the silicic magmas (Holmes, 1931; Blake, 1969; Sigvaldasson, 1974, 1979; Sparks et al., 1977, 1981; Eichelberger, 1980; Sigurdsson and Sparks, 1981; Blake, 1981; Oskarsson et al., 1982). Silicic magmas are generated by the melting of a hydrated mafic crust (O'Nions and Gronvold, 1973; Oskarsson et al., 1979, 1982) and/or the remelting and mobilization of silicic rocks from depth in the Icelandic crust (Sigurdsson, 1977; Sigurdsson and Sparks, 1981).

In the model proposed the evolution of primitive mafic lava compositions is by open-system fractionation processes. The open-system accounts for lavas ranging in composition from high-magnesia basalt through low magnesia basalt to ferrobasalt. Little of the major element variation observed need be accounted for by mantle heterogeneity or differing degrees of partial melting. These open-systems occur where intense magmatic activity is concentrated in the crust

(i.e., under the central volcanic complexes). This is a modified model of open-system crystallization (i.e., non-steady state). The modified model of open-system fractionation is different from the trace element model of O'Hara (1977) because it is proposed that major element changes also occur in the magma chamber and non-steady state conditions exist. Steady state conditions imply that a fixed rate of magma influx, outflux, and crystallization is occurring in the magma chamber. Steady state conditions are probably rarely obtained, hence a "modified model of open-system crystallization". This system leads to an enrichment in Ti, P, K, trace elements, and light/heavy trace element ratios due to the fact that olivine, pyroxene and plagioclase are common fractionating phases. The modified open-system operates on a periodic time frame for a given fissure swarm and central volcano. These magma reservoirs have a longer residence time and are occasionally "starved" magmatic systems in comparison to MORB systems because of the thicker crust found in the Icelandic environment. These conditions give rise to the evolved nature of the Icelandic lavas in comparison to the volcanism normally seen along the Mid-Atlantic Ridge. In contrast, the evolution of mafic lava compositions found on the fringes of the eruptive lenses, do not form open mafic magma chambers. These magmas take a more direct route to the surface. Thus mafic lavas found on the fringes of the central volcanic complexes would represent more primitive compositions which are directly erupted to the surface from a mantle reservoir.

Initially, in the evolution of an eruptive lens, magma moves up through the thick Icelandic crust establishing small eruptions from small magma reservoirs. With increasing intensity of plutonism the likelihood of establishing an open magmatic systems increases. With time large volumes of magma raise the geothermal gradient and establish hydrothermal systems. Fissure eruptions dominate this volcanism in the early states of development. Central volcanic

complexes are developed in the areas where the geothermal gradient is highest and the development of "magma traps" occurs which ponds and delays the arrival of magma to the surface. The "magma traps" (i.e., a modified open magmatic system) may be the result of 1) highly fractured volcanic rocks with a ground water aquifer, and 2) the development of a silicic melt zone above a mafic magma chamber which impedes its rise to surface. Many other magma traps are possible (Elder, 1978). The occurrence of magma traps in the Icelandic crust has been suggested previously (Walker, 1974b, 1975a; Fridleifsson, 1977).

Once magma traps are established, situations are created where magmatic systems are "opened" by periodic influxes of new magma. The influx of new magma may wax and wane creating steady state and non-steady state open magmatic systems periodically beneath the eruptive lenses in Iceland. The open-system and modified open-systems are maintained by the large scale geothermal zones associated with the central volcanoes and/or the development of a silicic melt zone above the magma chamber which impedes the flow of magma to the surface. Varying degrees of crystallization occur in the chamber dependent upon the residency time, the rate of new magma influx, the rate of magma out flux, and the heat lost to the walls of the chamber. The open magmatic system may be a single large chamber or a series of smaller and interconnected chambers.

The modified open-system which receives periodic magma influxes intrudes the fissure swarms and erupts the lavas associated with the central volcanic complexes. The mafic lavas effected by the modified open-system exhibit various enrichments in TiO_2, K_2O, and P_2O_5. Open-system effected magmas at high levels in the crust become capped or ponded by hydrothermal circulation leading to the iron enrichment trend typical of the Icelandic environment. A similar FeO enrichment is postulated for the rocks which are believed to be derived from mafic magma capped by silicic magma found in the British Tertiary Volcanic

Province (Bell, 1983). Under the central volcanoes intense hydrothermal circulation or silicic magma may cap the mafic magma leading to the more evolved compositions found in Iceland. These chambers may still occassionally receive influxes of steady state open-system effected magma from below. If the influx of new magma wanes, iron enrichment ensues due to the fractional crystallization of predominantly plagioclase, but also olivine and pyroxene, which also increases the magmas content of TiO_2, K_2O, and P_2O_5. Open system processes, mixing and crystallization, can lead to larger enrichments in TiO_2, K_2O, and P_2O_5 than would be expected from simple fractional crystallization. These enrichments are aided by an inverse density gradient in the magma chambers because initially denser iron-enriched magma is intruded by less dense, hotter and primitive magma. This creates conditions where little fractional crystallization occurs before rapid convective overturn of the magma chamber.

These modified open system mafic magmas may mix at any point in their evolution with silicic magmas and produce intermediate magmas. Mafic magmas which underplate silicic magma are rapidly cooled, stratified, and eventually may lead to conditions which initiate mixing and/or eruption (Sparks et al., 1977; Eichelberger, 1980; Turner et al., 1983; Huppert et al., 1982, 1983) of the silicic magma or a homogeneous intermediate mixed magma.

SOURCES OF DATA

For the comparison of silicic and mafic mixed rocks with the lava variation observed in the Tertiary of Iceland a wide variety of sources from the literature were drawn upon. Major element data are available. However, trace element data are often lacking, particularly for the mixed rock examples. Trace elements are only available for the silicic and mafic complexes of the Austurhorn and Vesturhorn Intrusions (Mattson et al., in prep.). The comparison is limited in many instances by this lack of data, but should be improved upon as more data are made available.

Major elements for the Tertiary lava variation of tholeiitic affinities were obtained from Wood (1976, 1978), on 36 lavas which are aphyric or sparsely phyric from scattered localities in Eastern Iceland; from Carmichael (1964), on 24 lavas from the Thingmuli Volcano of Eastern Iceland; from the Iceland Research Drilling Project (IRDP), on 236 lavas from the drill hole located in Eastern Iceland (Flower et al., 1982); from Walker (1963), on 5 lavas from the Breiddalur Central Volcanic Complex in Eastern Iceland; from Bailey and Noe-Nygaard (1976), on 8 lavas from Northwest Iceland; and from Walker (1966), on the average silicic lava. It is not proposed that these analyses represent volumes of erupted material, but rather that they represent the entire common spectrum of lavas observed in the Icelandic volcanic piles with tholeiitic affinities. Trace elements (REE) are from Wood (1976, 1978) and the IRDP (Gibson et al., 1982). The specific field locations can be found by referring to the authors cited.

Major element data for the mixed rocks are from several different sources and diverse localities. The data is from Mattson et al. (in prep.) and Blake (1966), 47 analyses from the Austurhorn and Vesturhorn silicic and mafic complexes; Gunn and Watkins (1969), 6 analyses from the Stretishorn composite dike; Sigurdsson (1971) and Prestvik (1980), 9 analysis from mixed lava flows from Gjafakollur (GJA) mountain and the Oraefajokull central volcano, respectively; and Jorgensen (1980), 4 analyses from a mixed pyroclastic deposit from the Thorsmork ignimbrite. Trace element data is only available for the examples of silicic and mafic complexes (Mattson et al., in prep.). The field relationships, data, and descriptions of these individual cases of mixing can be found in the references cited.

A simple presentation of the major elements, trace elements, and field distribution of the lavas and known mixed rocks will be presented first. The significance of the chemical similarities and differences will be presented in the discussion section of this paper.

MAJOR ELEMENT VARIATION

Variations in TiO_2, P_2O_5, and K_2O in Icelandic Lavas and Mixed Rocks

Figures 13a, 14a, and 15a exhibit the variation observed in the Tertiary lavas for TiO_2, P_2O_5, and K_2O plotted against FM ratio. The FM ratio is calculated using the method of Wood (1978).

$$FM = \frac{FeO + MnO}{FeO + MnO + MgO} \times 100$$

Iron is calculated as FeO total. Higher FM ratios correspond to the more evolved lava types with rhyolites being defined as $FM < 92$, icelandite FM 82-91, basaltic andesite FM 78-81, ferrobasalt FM 74-77, low magnesia basalt FM 66-73, and high magnesia basalt $FM \leq 65$ (Wood, 1978) and is similar to the classification of Carmichael (1964)..

The P_2O_5 and TiO_2 versus FM ratio plots (Figures 13a, 14a) exhibit an increase in P_2O_5 and TiO_2 content of the lavas from approximately $FM = 47$ to $FM = 75$ and then a decrease in the P_2O_5 and TiO_2 at higher FM ratios. Many points, however, fall outside this generalized trend. Of particular interest are the lavas which fall at various positions below the typical enrichment trend observed for P_2O_5 and TiO_2 between $FM = 47\text{-}75$. Lavas at high FM ratios also exhibit considerable scatter in their P_2O_5 and TiO_2 contents, at FM greater than 75.

The IRDP data can be distinguished into three different stratigraphic groups as assigned by Flower et al. (1982); the upper, middle, and lower group lavas. Lavas within each group are believed to be genetically related. All of these

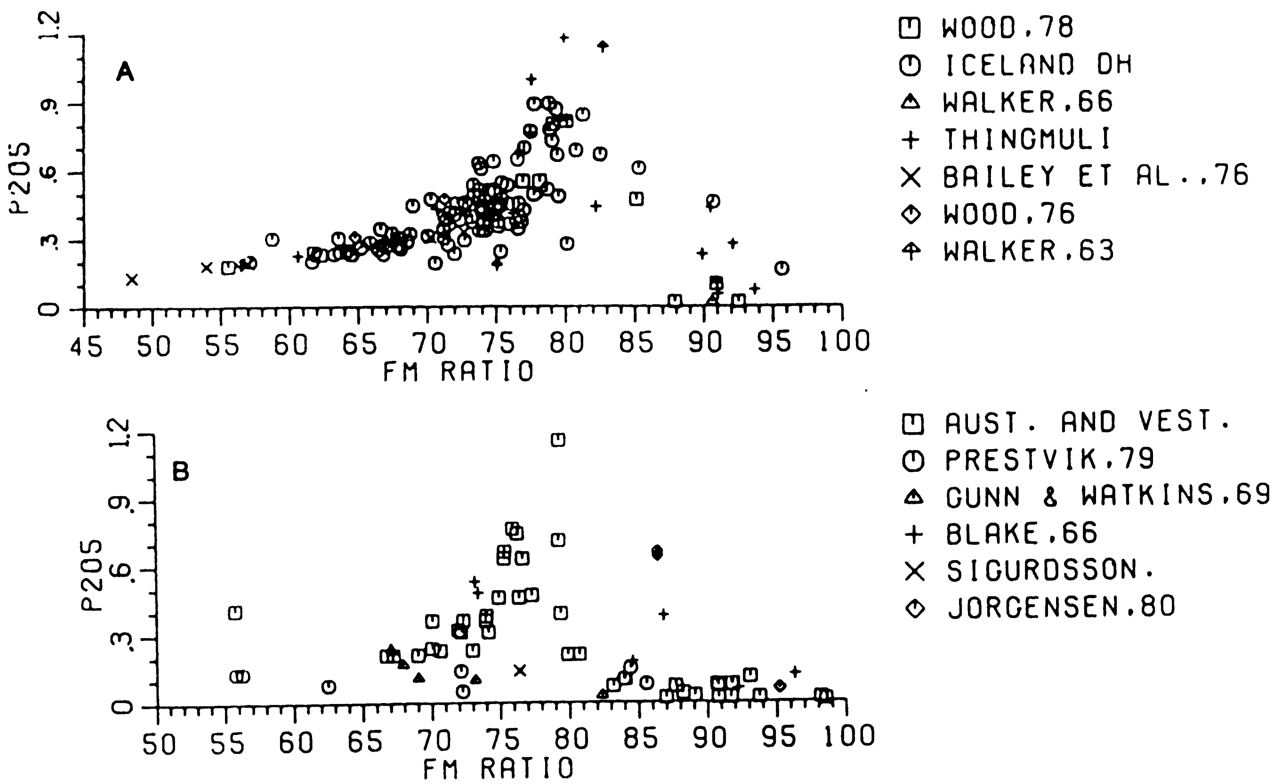

Figure 13. Variation in P_2O_5 vs. FM ratio. a) Variation in lavas ranging in composition from high magnesia-basalt through rhyolite. b) Variation in rocks of known mixed origin. See Text for localities.

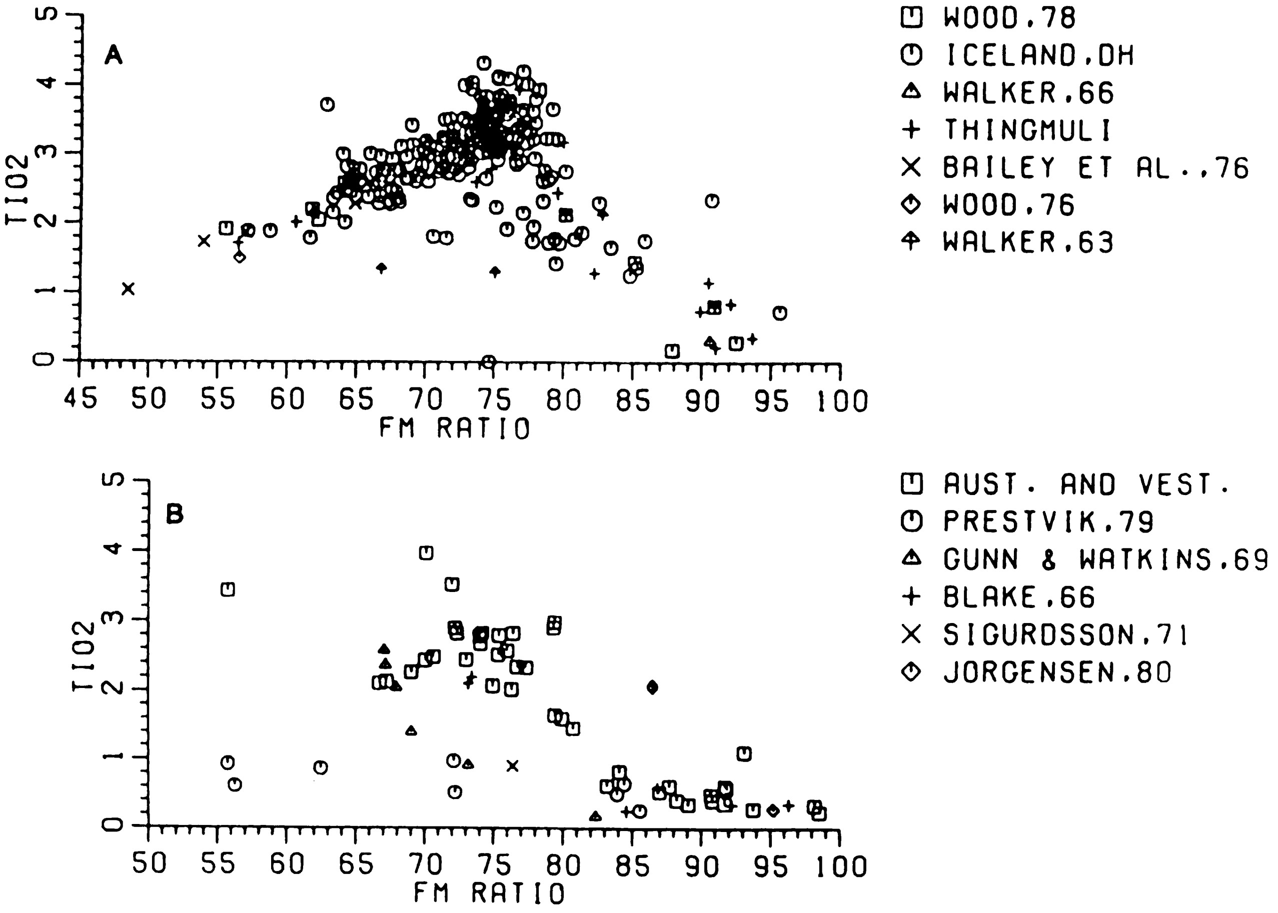

Figure 14. Variation in TiO_2 vs. FM ratio. a) Variation in lavas. b) Variation in known mixed rocks.

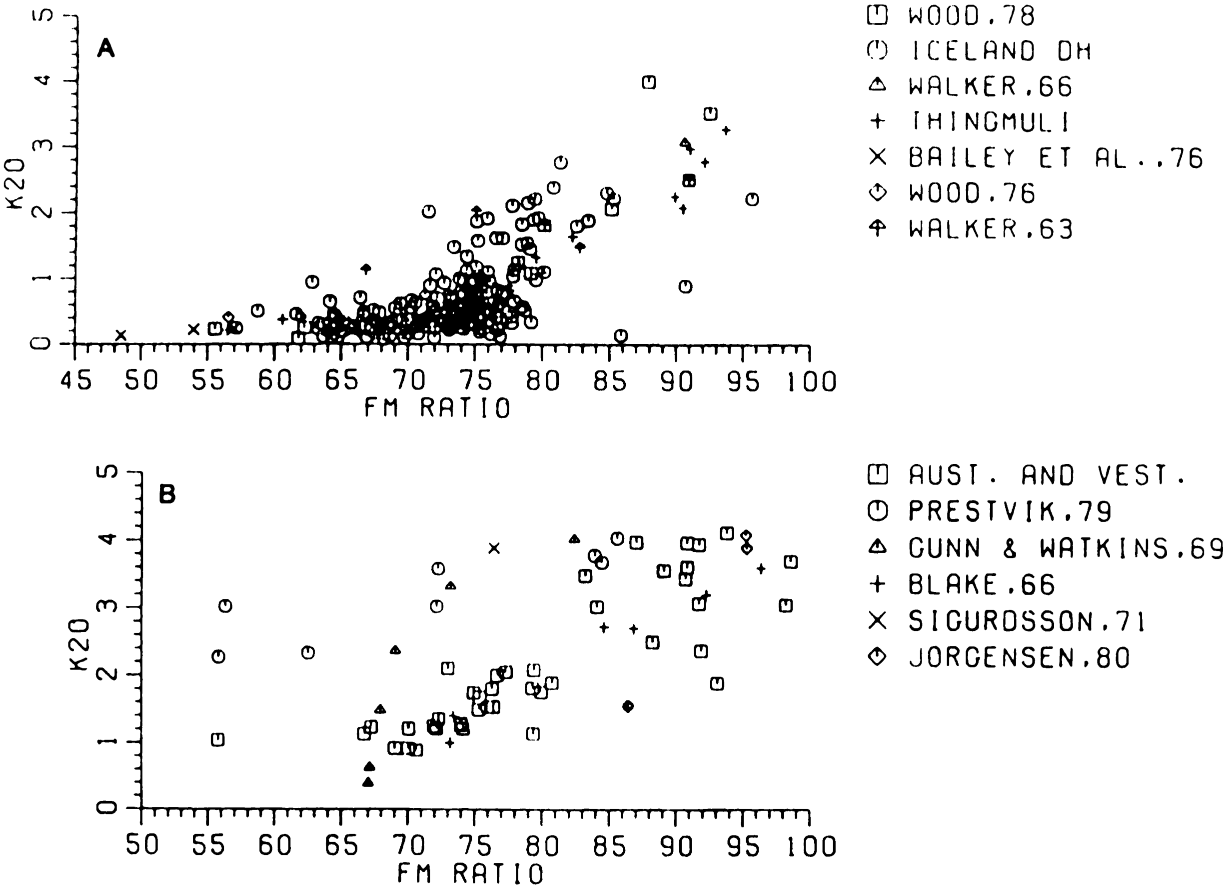

Figure 15. Variation in K_2O vs. FM ratio. a) Variation in lavas. b) Variation in known mixed rocks.

groups are plotted (Iceland DH) because it is the general trend of Icelandic lava evolution which is of interest. The specific differences between these compositional groups can be found in Flower et al. (1982). However, there is a large variation observed in a series of evolved and genetically related basalts from the middle group lavas of the IRDP (Flower et al., 1982). P_2O_5, for instance, varies from 0.25-0.88 in this group over a narrow range in silica content.

K_2O has a slight but continuous enrichment in K_2O with increasing FM ratio between FM ratios of 47 to 75-80 (Figure 15a). Many points fall above this generalized trend and exhibit considerable scatter in their positions. Lavas at high FM ratios exhibit considerable scatter and have, generally, higher K_2O contents than other lava types. The overall enrichments observed in K_2O, TiO_2, P_2O_5, the large variations observed in the middle group lavas of the IRDP data, and the wide scatter of lavas which fall off the main enrichment trends for these elements are difficult to reconcile with simple fractional crystallization models and partial melting models.

Figures 13b, 14b, and 15b exhibit the variation in TiO_2, P_2O_5, and K_2O versus FM ratio for the Tertiary rocks in Iceland which are due to silicic-mafic magma mixing processes. These plots show that considerable scatter is present in these oxides versus FM ratio. Individual consideration of a given example of mixing (e.g., the mixed examples from the Austurhorn or Vesturhorn intrusion), however, reduces the amount of variation observed. In general, the mixed rocks as a whole exhibit considerable scatter at low FM ratios in TiO_2 and P_2O_5 and considerable scatter in K_2O at high FM ratios. The variation observed in these diagrams is similar to the variation observed in the Icelandic lavas which do not fall on the generalized TiO_2, P_2O_5, and K_2O enrichment trends between FM ratios of 47 to 75-80. The mixed rocks plot with a similar scatter as the lavas with FM ratios greater than 75-80 which fall off the generalized enrichment

trends for TiO_2, P_2O_5, and K_2O. It is emphasized that these rocks represent compositions from instances of silicic-mafic magma mixing.

AFM PLOTS

Figures 16a and 16b are AFM plots for the lava variation observed in Iceland and the occurrences of mixed rocks in Iceland, respectively. The trends in both plots overlap, but a wider variation is observed in the lavas. Mg rich primitive compositions are not observed in the mixed rocks. The lavas exhibit the typical iron enrichment trend of tholeiitic lavas. From an iron enriched endmember the lavas then trend down toward the alkali corner of the diagram. Greater scatter in the data is apparent in this latter trend. A "gap" or area where no lavas occur is present approximately between 45 and 35 percent total iron. This gap is a well known feature of tholeiitic lavas. It has been suggested by Wood (1978) that this trend is caused by the rapid saturation of the magma in iron and titanium oxide phases which rapidly depletes the magma in these elements and discontinually produces a silicic magma. Multiple linear regression equations using the major elements of lavas have substantiated the possibility of this fractionation scheme (Wood, 1978).

However, the multiple linear regression analysis very narrowly constrains the proportion of liquids and the amounts of the fractionating phase assemblages. For example, Wood (1978) calculates that for the variation observed between icelandite and rhyolite, approximately 40% total crystallized phases must be fractionated from the icelandite lava in order to produce the rhyolite. This model does not explain why, on occasion, 10, 20, or even 30% total crystalline phases could not be fractionated and thus produce a continuous trend on the AFM plot. The author is not aware of any process which should so narrowly restrict the proportion (i.e., approximately 40% crystallized phases) of the phases fractionated

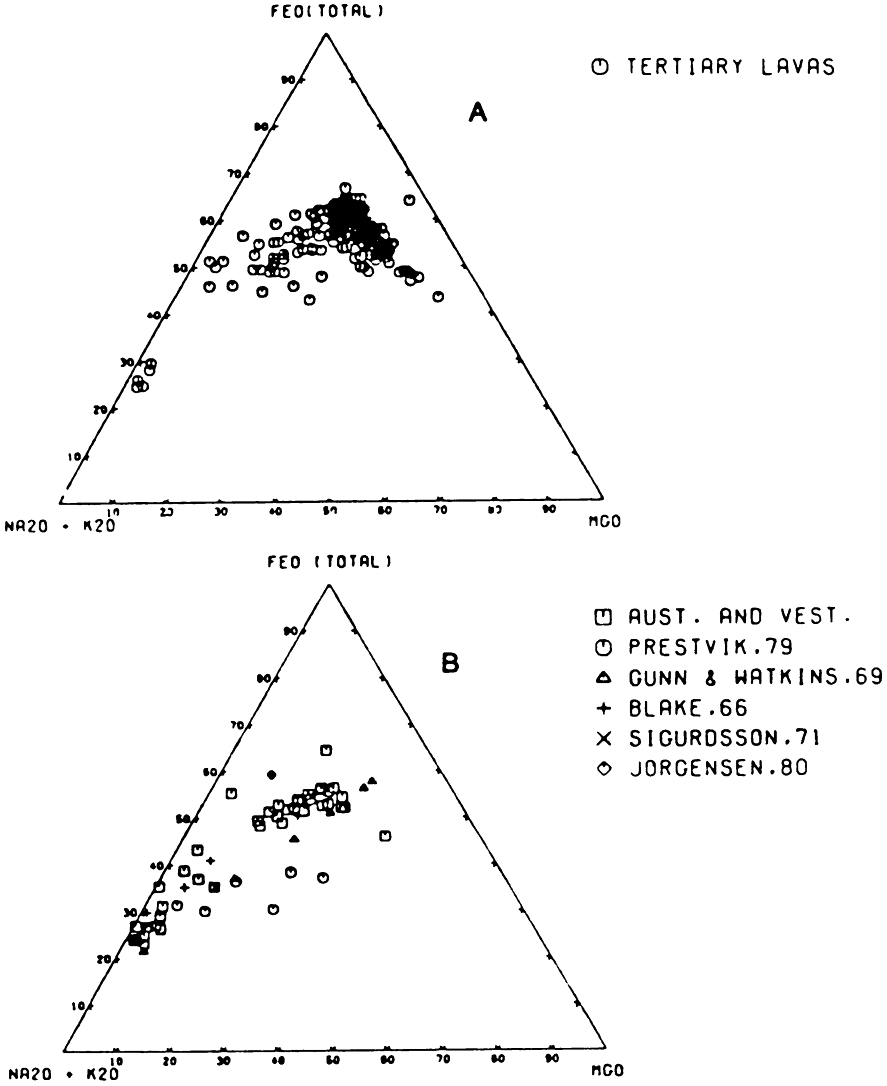

Figure 16. AFM plots. a) Variation observed in the Tertiary lavas (see Text for sources of data). b) Variation observed in known mixed rocks.

(i.e., each time in tholeiitic magmas crystallization history such that a gap should appear in the major elements). Ideally any proportion of total crystallized phases could be fractionated and thus no gap should appear on the AFM plot. The presence of a reaction point involving Fe-Ti oxides could produce such a "gap" but no such reaction is known. In addition, a simple fractionation model does not explain the wide variety of lava types at higher FM ratios. Tectonic and fluid dynamic processes are likely to be the controlling factors which produces this variation in the evolved lava compositions from evolve to rhyolite (i.e., mafic magmas rarely fractionate passed ferrobasaltic and occasionally basaltic andesite compositions). Thus, other processes should be considered which could produce this variation pattern (see Discussion section under; Magma Mixing for Lavas of Wide Compositional Contrast).

The mixed rocks exhibit no iron enrichment trend. Mixed rocks plot with a great deal of scatter from the silicic endmember toward the more evolved mafic endmembers. Each field occurrence of mixing is a separate event and thus should be considered in this context. A wide variation is observed in the intermediate mixed rocks; however, the bulk of the most primitive mafic rocks involved in the mixing process plot near an iron enriched endmember. This may be a general feature of mixing between mafic and silicic magmas due to the various dynamic properties (i.e., viscosity, density, and rheology) of the magmas involved. In the British Tertiary Volcanic Province, which is similar to the Icelandic Volcanic Province, mafic magmas are thought to be commonly mixed with silicic magmas due to the development of a stratified and crystallizing mafic magma chamber which underplates a silicic magma chamber (Vogel, 1982; Bell, 1983; Marshall and Sparks, 1984).

Although the mixed rocks and lava compositions extensively overlap a lack of mixed rocks occurs at, approximately, 50% total iron. This "gap" or lack of

abundance is thought to be real for the mixed rocks associations. This feature needs explanation (see Discussion). It also may be of importance that the gap in the lava compositions (35-45% iron) and the gap in the mixed rocks (50% iron) do not overlap, suggesting that there is more than a casual relationship present. Mixed rocks occur between 25% to 45% iron, but these compositions are precisely the compositions which do not occur as lavas. At the of the gap in lavas, the lavas range down to and slightly below 50% iron and this is exactly the composition which does not occur in the mixed rocks. This observation will be discussed in a later section of this paper.

Variation in SiO_2 and FeO (Total) Versus FeO(T)/MgO Ratio of Tertiary Icelandic Lavas and Mixed Rocks

Miyashiro (1974) used plots of SiO_2 and FeO (Total) versus FeO (Total)/MgO in order to illustrate the differences between tholeiitic and calc-alkaline differentiation trends. These diagrams are employed here to show the variation observed in the Tertiary lavas of Iceland (Figures 17a and 18a) in a similar manner as that used by Grove et al. (1982) to exhibit the variation observed in the Medicine Lake Highland (MLH) lavas. The solid dark line is the result of dynamic crystallization experiments at low pressure on the Oceanographer Fracture Zone basalts (Walker et al., 1979), MORB (Stopler, 1980), and MLH basalts (Grove et al., 1982). This trend of residual liquids outlines the ideal crystallization trend of a HAB and probably closely resembles the tholeiitic crystallization trend.

From the figures (Figures 17a and 18a) it can be observed that most basaltic compositions (i.e., the highly populated part of the diagram) form a trend with a positive slope paralleling the idealized trend of crystallization. This is the iron enrichment trend which can be related to the fractionation of common phenocrysts observed in Icelandic basalts of olivine, olivine and plagioclase, and plagioclase and clinopyroxene (Pearce and Flower, 1977). The iron enrichment

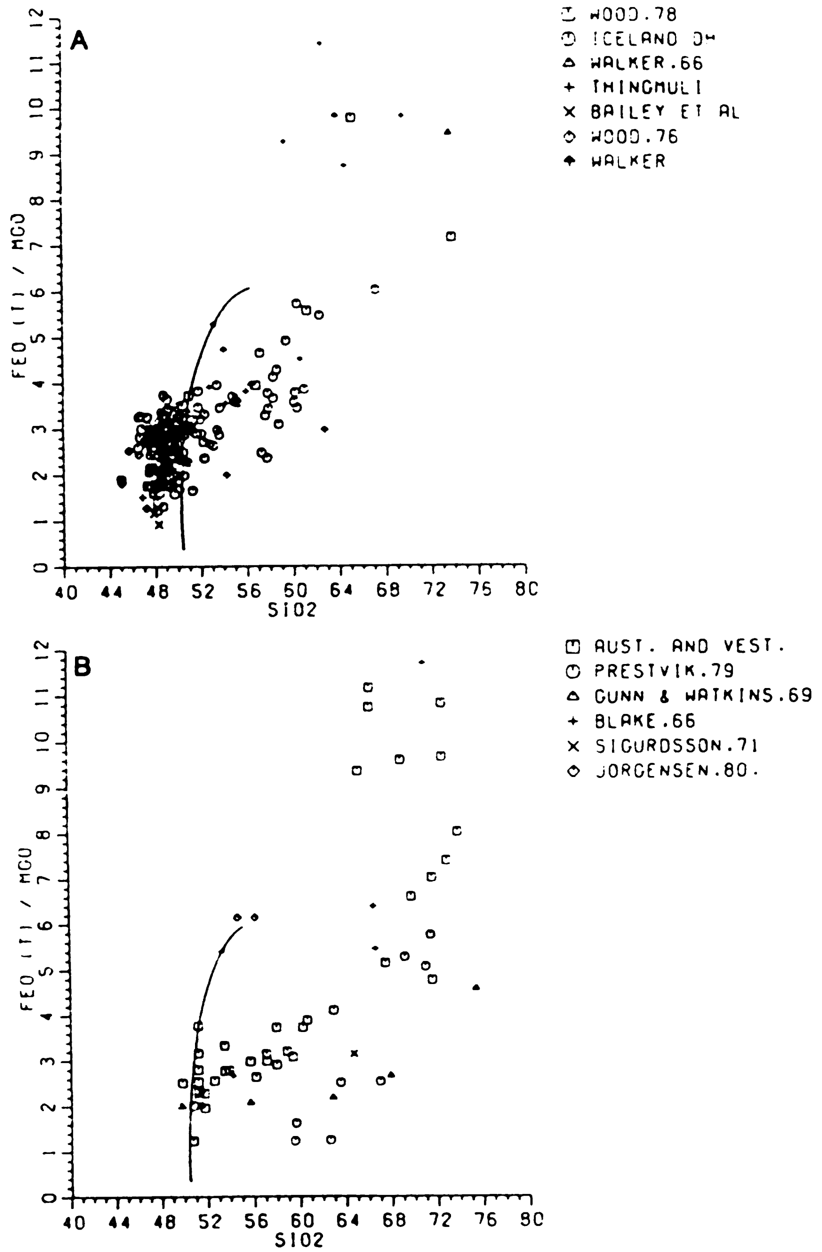

Figure 17. FeO(Total)/MgO vs. SiO_2: a) for Tertiary lavas. b) for known mixed rocks.

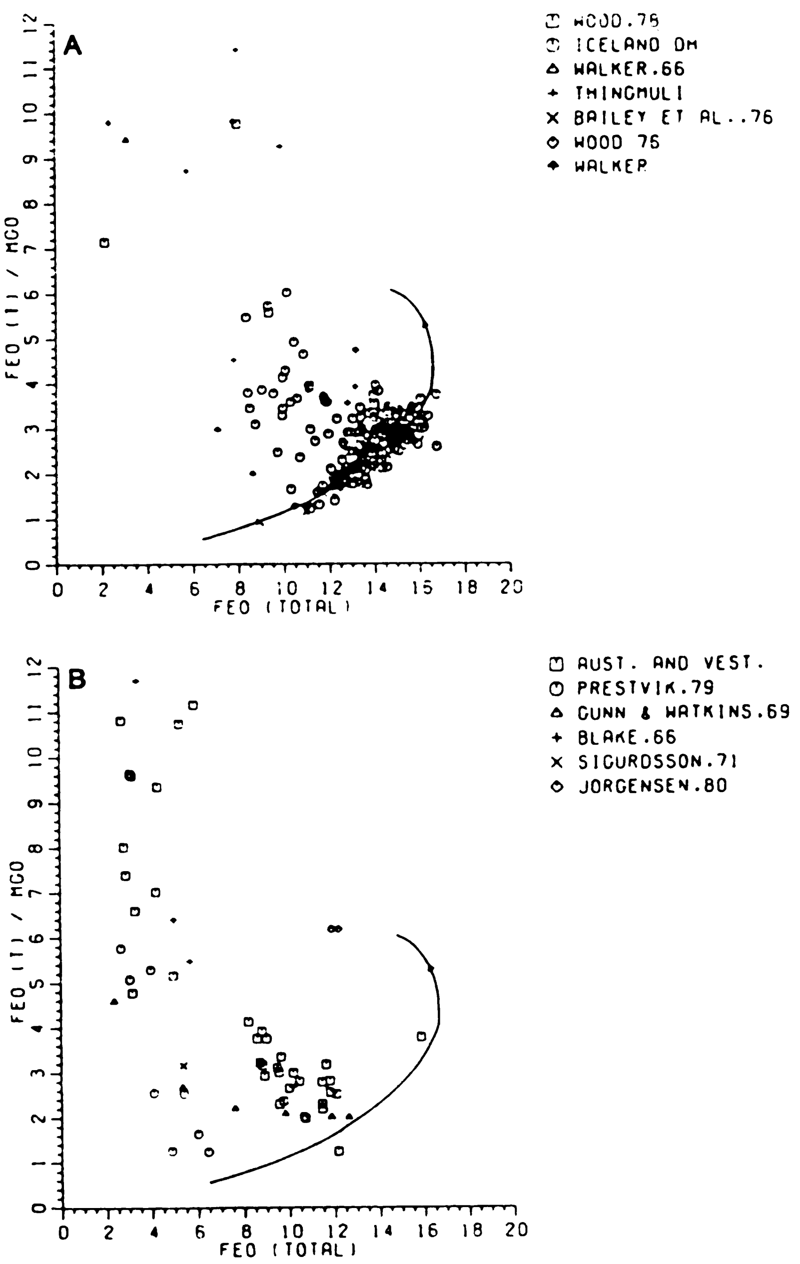

Figure 18. FeO(Total)/MgO vs. FeO total: a) for Tertiary lavas. b) for known mixed rocks.

trend is thought to be dominated by plagioclase fractionation based upon crystallization experiments on natural basalts (Grove and Baker, 1984). More evolved compositions have a different trend from the experimental trend. The evolved compositions have a trend which has a negative slope on the FeO plot and a positive slope on the SiO_2 plot toward more silicic compositions, albeit with a great deal of scatter in the distribution of plotted points.

Similar plots for the mixed rocks (Figures 17b and 18b) show that the data does not follow the dynamic crystallization trends. They exhibit trends with a high degree of scatter. If one takes an individual case of mixing, however, then the amount of scatter is greatly reduced. These mixed rock plots are very similar to the scatter observed on the plots for lavas for points which fall off of the experimental crystallization trends.

Ol-Cpx-Plag-Qtz Projections

The data from dynamic crystallization experiments on tholeiites from the Oceanographer Fracture Zone (Walker et al., 1980), on MORB (Stopler, 1980), and on the MLH volcanics (Grove et al., 1982) in comparison with the observed variation in lavas from these areas and other suites of rocks (Shibata et al., 1979; Gerlach and Grove, 1982) have allowed the successful interpretation of many compositions within the suites of lavas as having resulted from magma mixing processes. The experimental data were presented as a projection on ternary diagrams (Oliv.-Qtz.-Cpx; Oliv.-Qtz.-Plag.; Oliv.-Plag.-Cpx.). These plots, which indicate the trends of the cotectic topologies, are useful for calc-alkaline series rocks (Grove et al., 1982, 1983) and MORB (Walker et al., 1979; Stopler, 1980) comparisons, but may not be strictly applicable for low alkali-silica rich suites (Grove et al., 1982). Iron-magnesium ratios increase from mafic to silicic endmembers such that different iron enrichment trends may have slightly varying cotectic topologies (Longhi and Boudrea, 1979, 1980). However, on the gross scale that these plots will be considered here, the slight variations in the cotectic topologies is not expected to influence the conclusions drawn from their application. In addition, two methods have been used in calculating the projections (Walker et al., 1979; Grove et al., 1982). The Grove et al. (1982) method has arbitrarily been used.

Due to the various problems in interpretation of these projections and limited space the oliv.-qtz.-cpx-plag. plots are not presented here. They are available upon request from the author. A brief synopsis of the observed trends on these plots will be presented.

In general, mixed rock compositions distinctly fall off the projected liquidus boundaries on the low temperature side of the boundary. Most lavas of intermediate composition (basaltic andesite to Icelandite) also fall off the projected liquidus boundaries and plot in a similar manor as the mixed rocks. This suggests that intermediate lavas have a similar history as the mixed rocks. Most mafic magmas plot on the projected liquidus boundary (i.e., low magnesia basalts and ferrobasalts). High magnesia basalts and some low magnesia basalts fall off the projected liquidus surface on the high temperature side of the boundary. On the oliv.-qtz.-cpx. projection, however, the lavas (except high magnesia basalts), mixed rocks, and experimental liquidus compositions (lavas and mixed rocks with greater than approximately 20% of the qtz. component plot slightly to the right of the projected cotectic) all overlap and may reflect magma mixing trends or slightly different cotectic topologies (see Grove et al., 1982, Figure 15).

TRACE ELEMENT RATIOS OF THE MIXED ROCKS AND LAVAS

(Ce/Yb)N Versus Ce

(Ce/Yb)N Versus Ce plots have been used by a number of investigators to distinguish different magmatic processes (e.g., in Iceland, Wood, 1978; Gibson et

al., 1982). Usually these diagrams are used only for mafic lavas, but plots which encompass the whole range of lava compositions can yield much information.

Figure 19a is a plot of the variation found from the Austurhorn and Vesturhorn silicic and mafic complexes. In general, (Ce/Yb)N ranges between 2 and 3.6 and Ce varies from 36ppm in mafic rocks up to 225ppm in the silicic rocks. This trend is generally horizontal and linear within the limits plotted.

Also presented in Figure 19 is a similar plot of the variation found in lavas from the Tertiary of Eastern Iceland. This plot encompasses compositions which vary from high magnesia basalt through rhyolite and thus represents a much broader spectrum of rock types than are found in these two silicic and mafic complexes. This is particularly true for the mafic end of the spectrum as discussed previously.

The (Ce/Yb)N ratio for lavas varies from approximately 1.0 to 4.5 and varies in their Ce content from 16ppm to 188ppm. Two trends are observed on this plot. One trend with a steep positive slope, which includes lava compositions of high-magnesia basalt, low-magnesia basalt, ferrobasalt, and some basaltic andesites, and a second trend which is nearly horizontal (i.e., little variation in (Ce/Yb)N) which includes lava compositions of rhyolite (far right), Icelandite, basaltic andesite, ferrobasalt, low-magnesia basalt, and some high-magnesia basalt (with high (Ce/Yb)N ratios). Obviously, the two trends overlap. The trend observed for the mixed rocks on this plot also overlaps with the horizontal trend of the lavas discussed here.

(Ce/Lu)N Versus (La/Lu)N

The use of ratio plots has been suggested as a means by which to separate simple magma mixing processes between two endmembers (Langmuir et al., 1978) from other processes. Plots of ratios which have a common denominator should plot as a linear trend if simple magma mixing is assumed. In crystal fractionation

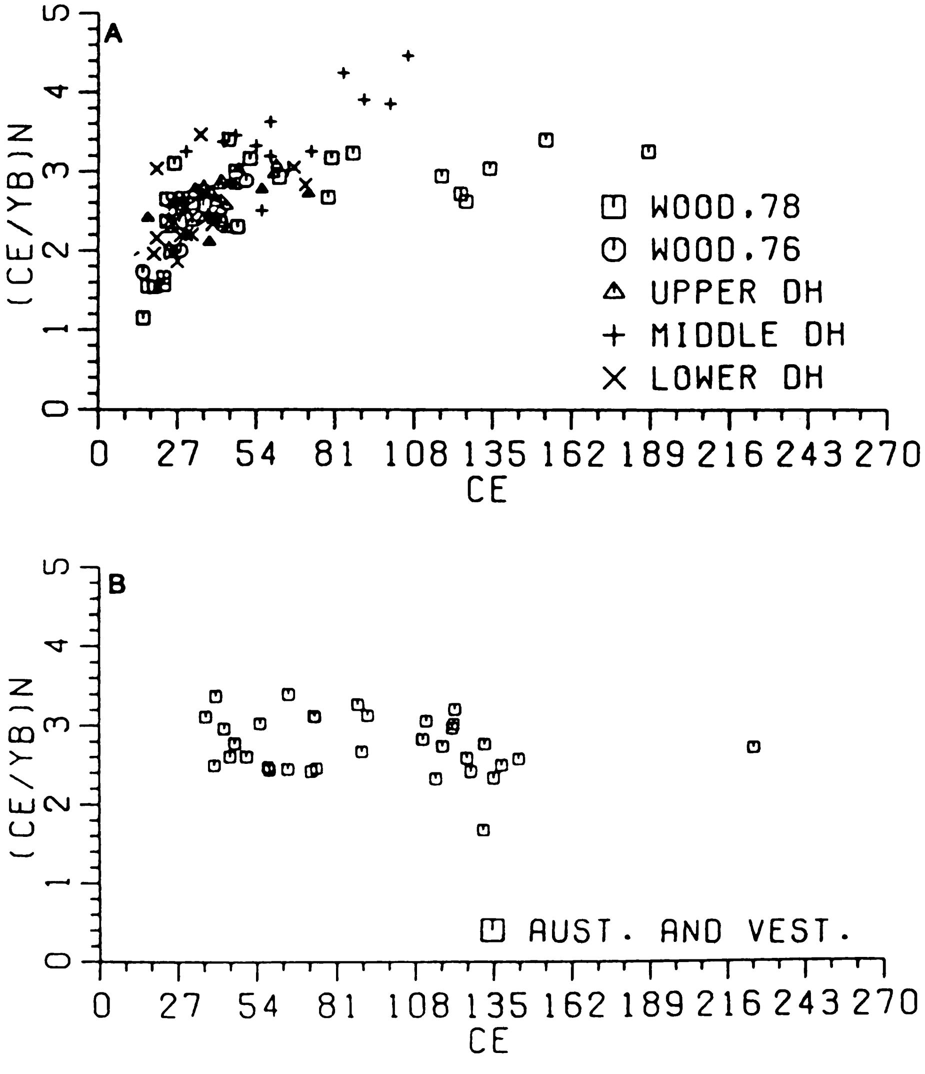

Figure 19. (Ce/Yb)N vs. Ce. a) Variation observed in Tertiary lavas. b) for known mixed rocks (Austurhorn and Vesturhorn).

models little variation can be produced on such a plot when a light REE and a heavy REE are ratioed. Ratio plots of (Ce/Lu)N versus (La/Lu)N are presented in this light for the variation observed in the Austurhorn and Vesturhorn mixed rocks and the variation observed in the Tertiary lavas in Iceland (Figure 20).

In the mixed rocks (Ce/Lu)N ranges from approximately 2 to 4.4 and (La/Lu)N ranges from approximately 2 to 7. In general, the silicic rocks have high ratios and the mafic rocks have low ratios. The points define a trend which is essentially horizontal although some scatter is observed. In part, some of the scatter observed is produced because the Austurhorn and Vesturhorn are two separate silicic and mafic complexes. However, this plot indicates a wide variation in these ratios for a group of contemporaneous rocks.

Also presented in Figure 20 is a similar plot for the variation observed in the lavas in the Tertiary of Iceland. This plot is remarkedly linear. (Ce/Lu)N and (La/Lu)N range from approximately 1 to 5 and 1 to 6.2, respectively. The variation observed for the IRDP extends over a wider range of values than lavas which were collected and analyzed to represent the widest range of rock types in the Tertiary of Eastern Iceland (Wood, 1978). Indeed, the variation observed for a single group of lavas, within the IRDP (i.e., middle group lavas) of presumably associated lavas and little major element compositional contrast (Flower et al., 1982), extends over half of the variation observed for all lava types. The dashed line on this plot represents the entire range of values found in the silicic and mafic complexes in which silicic rocks are abundant. Only three rhyolites are plotted and these fall within the dashed zone.

PUBLISHED ISOTOPIC RANGES FOR ICELANDIC ROCKS

Available published strontium, neodymium, oxygen and helium isotopic data from Iceland are summarized in Table 6. In general, strontium, neodymium and

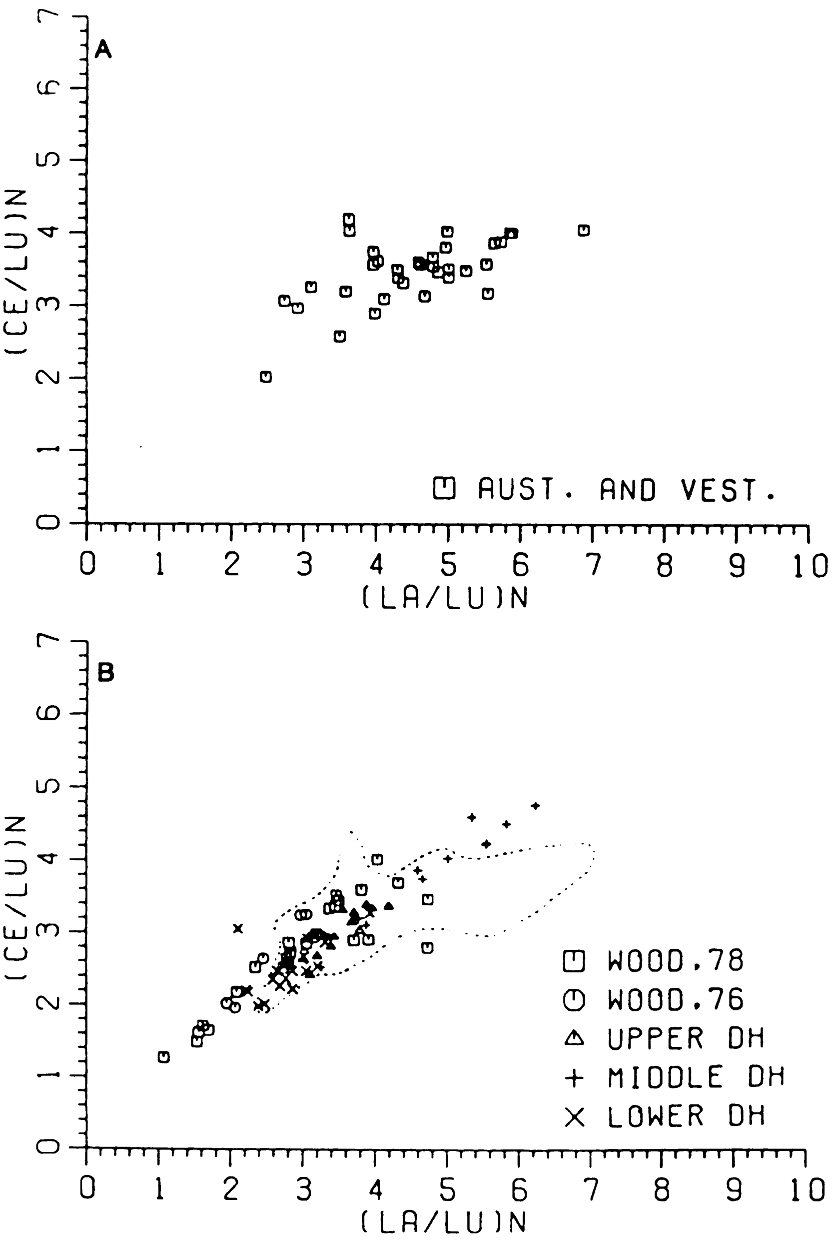

Figure 20. (Ce/Lu)N vs. (La/Lu)N: a) for known mixed rocks from the Austurhorn and Vesturhorn silicic and mafic complexes. b) for Tertiary lavas. Dashed field represents the field of variation observed in the mixed rocks.

Table 6. Ranges in Icelandic isotopes.

	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{3}He/^{4}He$	$\delta^{18}O$%
Basalts	0.7029-0.7036	0.512990-0.513168	3.59-23.9	+5.4-(-7.7)
(REF)	(1-5, 8, 12, 13)	(4, 7, 8)	(8)	
Icelandites	0.70315-0.70337	0.513027-0.513055	1.02-1.50	4.0-4.2 4.3
(REF)	(1, 8)	(8)	(8)	(10)
Silicic	0.70324-0.7072	0.512910-0.513068	0.072-0.93	+10.2-(-9.9)
(REF)	(1, 5, 8)	(7, 8)	(8)	(8-11)
Austurhorn and Vesturhorn				
Silicic	0.70350-0.70354 (A) 0.70349 (V)			
Gabbro	0.70350 (A)			
(REF)	(6)			

1. O'Nions and Gronvold, 1973
2. O'Nions and Pankhurst, 1973
3. O'Nions et al., 1974
4. Zindler et al., 1979
5. Wood et al., 1979
6. O'Nions and Pankhurst, 1973
7. O'Nions et al., 1977
8. Condomines et al., 1983
9. Muehlenbacks, 1972
10. Muehlenbacks et al., 1974
11. Hattori and Muehlenbacks, 1982
12. Schilling et al., 1983
13. Hart et al., 1973

oxygen isotope data exhibit variation for a given rock type which often overlaps. Silicic and intermediate rocks range to higher Sr-isotope values and do not range to as low of values in comparison to basaltic rock types. Opposite, but similar variation is observed in the Nd isotopic values.

Several models have been proposed in order to account for the radiogenic isotopic variations observed. These include various mantle heterogeneity models (Zindler et al., 1979; Wood et al., 1979; Wood, 1981), a "mantle plume" hypothesis, which involves vertical zonation in the mantle (Schilling, 1973, 1973a; Schilling and Noe-Nygaard, 1974; Schilling et al., 1981, 1982, 1983), the mixing of source regions within the mantle (Hart et al., 1973), and the mixing of magmas derived from mantle and crustal sources (Oskarsson et al., 1979, 1981).

Most of these models assume that the mantle from which the basalts are derived is isotopically heterogeneous or layered. Oskarsson et al. (1979, 1981) proposed that basalts derived from the mantle are isotopically homogeneous and are eventually effected by mixing with crustal derived melts (which includes alkaline type magmas). In the model presented here it is assumed that heterogeneity within the mantle, either laterally or vertically, produces the variable isotopic character of the tholeiitic basalts. However, the isotopic heterogeneity in the mantle does not necessarily coincide with major element heterogeneity in the mantle or in its derived melts. It is further assumed in this study that very little of the major element variation observed is due to mantle heterogeneity or different degrees of partial melting. This allows the question to be asked "How much of the tholeiitic type variation observed in major elements and trace elements can be accounted for by magma mixing and crystal fractionation processes?"

Stable isotopes are consistent with long residency times of magmas in the Icelandic crust. The oxygen isotopes are typically low and variable in comparison

to average values for MORB δ5.7%. The oxygen isotope values are interpreted to be the result of the variable interaction of Icelandic magmas with a hydrothermally altered and older Icelandic crust (Hattori and Muehlenbacks, 1982; Condomines et al., 1983). $^{3}He/^{4}He$ ratios for silicic and intermediate rocks are low and are interpreted as having been contaminated by atmospheric helium (Condomines et al., 1983). Finally, the favored interpretation of Condomines et al. (1981) of the measured ^{230}Th-^{238}U systematics of recent lavas indicate that magmas have a long residence time in the Icelandic crust.

DISCUSSION

Igneous Features of the Icelandic Crust Pertinent to Magma Mixing Processes

General. Models of Icelandic volcanism and plutonism must be reconciled with the observed features of the Icelandic crust and the distribution of the rock types. A brief overview of the igneous features of the Icelandic crust are presented in this light. The tholeiitic lava piles are erupted in a series of overlapping eruptive lenses (Gibson, 1966, 1969; Gibson and Piper, 1972; Walker, 1975; Jakobsson et al., 1978; Jakobsson, 1972, 1979). The eruptive lenses are located along dike swarms which are arranged in en echelon arrays in space and time (Walker, 1960, 1974a, 1975a; Saemundsson, 1978; Jakobsson et al., 1978). The central volcanic complexes are found at the center of the largest dike swarms and the thickest portion of the lava pile (Walker, 1960, 1974a, 1975a; Saemundsson, 1978; Jakobsson et al., 1978). Dike swarm intensity also increases with depth (Walker, 1960). The rifting is interpreted as being asymmetrical across the plate boundary, shifting laterally in time (Saemundsson, 1974; Helgason, 1984).

Recent basalts are picritic basalts and progress in time (i.e., younger) and composition to olivine tholeiites (Jakobsson et al., 1978). Fissure eruptions and the most evolved tholeiites occur in the central portions of the eruptive lenses in

both recent and Tertiary times (Walker, 1974a; Brooks et al., 1974; Sigvaldasson et al., 1974; Jakobsson et al., 1978; Jakobsson, 1979). Fissure eruptions are periodic and short lived events separated by long time intervals (Walker, 1975). Olivine tholeiites are the most abundant lava type in the Western Reykjanes Peninsula (Jakobsson et al., 1978), but in Central Iceland and in the Tertiary of Iceland the central volcanic complexes become larger and the amount of evolved lavas increases (Walker, 1963, 1966, 1974a; Gibson, 1969; Sigvaldasson et al., 1974; Palmason and Saemundsson, 1974; Brooks et al., 1974; Wood, 1978). The central portions of the eruptive lenses are the most likely sites where magma mixing processes should have occurred due to the volume of erupted material and being the localities of highest heat flow.

In the Western Reykjanes Peninsula, increasing eruptive volumes of mafic magma are associated with increasing K_2O, and decreasing TiO_2/P_2O_5 ratio (Jakobsson et al., 1978). This is inconsistent with simple fractional crystallization models and simple partial melting models (Jakobsson et al., 1978) and therefore other processes must account for their occurrence. A modified model of open-system fractionation will be presented which can produce the variation observed in K_2O, TiO_2 and P_2O_5 in these lavas. It has also been suggested (Johannesson, 1975; Jakobsson et al., 1978; Imland, 1983) that, in time, the evolved fissure swarms of the Reykjanes Peninsula might evolve and develop central volcanic complexes similar to those of Central Iceland and the Tertiary of Iceland.

It has been estimated that over fifty percent of the rift zone production of mafic magma (i.e., central volcanic complexes excluded) is of the primitive MORB type based upon major element variations (Imland, 1983). Previously it had been assumed that Icelandic basalts differed from ocean ridge basalts in having a higher iron and lower magnesium content. This has been shown not to be the case since many basalts similar to primitive MORB occur in Iceland (e.g., Sigvaldason,

1974; Sigvaldason and Steinthorsson, 1974; Oskarsson et al., 1979, 1982; Schilling et al., 1983). However, the relative amounts of evolved rock types is much higher in the Icelandic environment (ibid.). The amount of evolved rock types and total volcanic production increases inland along the rift zones (Imland, 1983).

This suggests that the volume of magma passing through the crust, the crustal thickness, and the degree and timing at which volcanism shifts laterally across the plate boundary may be important factors which govern the development of the central volcanic complexes and their eruptive volumes. Large volume systems have the most potential for open system fractionation processes and particularly mafic-silicic magma interactions.

The field distribution and chemical variation observed in Icelandic mafic magmas has been attributed to various partial melting models (e.g., Sigvaldason et al., 1974, 1976; Wood, 1978, 1979; Schilling, 1973; Schilling et al., 1983), crystal fractionation processes (e.g., Jakobsson et al., 1978; Wood, 1978; Schilling et al., 1983) and mantle heterogeneities on a variety of scales (e.g., O'Nions et al., 1976; Schilling et al., 1983). The mafic lava evolution has also been ascribed to "different production rates of mantle derived olivine tholeiite of invariant composition which is added to the crust from below and modified by mixing with anatectic melts in the crust and concomitant crystal fractionation" (Oskarsson et al., 1979, 1982). Partial melting, source heterogeneity, and crystal fractionation processes at the extreme primitive end of the mafic lava variation are difficult to separate clearly on the basis of major and trace elements. Isotopic analysis can point to differences in the mantle from one area to another, but these variations occur on a variety of scales in the oceanic environment and thus the distinction between "hot spots", smaller anomalies, and normal MORB becomes less clear. Especially when any attempt is made to correlate the major elements, isotopic variations, and fractionation processes involved. In this light, magma mixing

coupled with crystal fractionation processes were picked to be tested and, thus, allow loose limits to be placed on the amount of variation (a minimum) which could be caused by mantle heterogeneities and/or partial melting processes on the major and trace elements.

Central Volcanic Complexes. For magma mixing processes to be a common occurrence the intensity of volcanism, high heat flow, and long residence times of magma chamber would likely have to exist. The central volcanic complexes associated with the thickest part of the volcanic pile, the most evolved tholeiite, a high intensity of dike swarms, are associated with large mafic intrusions (Walker, 1975; Friedleifsson, 1977; Walker, 1974) and extensive hydrothermal activity (Bjornsson et al., 1972; Christensen, 1974; Walker, 1974; Palmason and Saemudsson, 1974; Palmason et al., 1979). Some of these gabbro intrusions exhibit features of multiple injection (Newman, 1967, as reported by Walker, 1975). Strong magnetic anomalies (Palmason and Saemundsson, 1974) and positive gravity anomalies of the central volcanic complexes indicates that dense rock exists below the surface (Walker, 1975). The central volcanic complexes are also associated with metamorphic aureoles and the shallowest depths to layer 3 in the Icelandic crust (Walker, 1975; Mackenzie et al., 1982; Palmason, 1971; Flouenz, 1980). From the above discussion it follows that the central volcanic complexes are indeed the sites of intensive plutonism and volcanism, high heat flow (i.e., a raised geothermal gradient), and thus also the most likely sites in which magma mixing processes could operate on a large scale.

The lava piles associated with the central volcanic complexes display many features which indicate that magmas were ponded by magma traps. The formation of magma traps would create conditions under which magmas would have longer residence times in the crust, be periodically tapped and fractionate to more evolved compositions. The central volcanic complexes exhibit the widest

variation in major element chemistry of the lavas. In the IRDP many lava flows are separated by thin clastic or pyroclastic deposits suggesting that the lava pile was built up by numerous small volume eruptions commonly separated by quiescent periods of variable duration (Robinson et al., 1982). At Hekla the volume of extruded material in each eruption is also a function of the length of the quiescent period. The longer the quiescent period the greater the total volume erupted (Sigvaldasson, 1974). Quiescent periods may increase the likelihood of magma mixing events. This idea is supported if the volume of material erupted is larger with longer quiescent periods.

The central volcanic complexes contain, almost exclusively, the silicic and intermediate lava compositions (Walker, 1966; Sigurdsson, 1967; O'Nions and Gronvold, 1973; Blake et al., 1965; Wood, 1976), silicic and mafic complexes, and the occurrences of mixed lavas, mixed pyroclastics (Blake, 1966, 1969; Blake et al., 1965; Walker, 1962, 1966; Sigurdsson, 1971; Sigvaldasson, 1979; Sigurdsson and Sparks, 1981; Sparks et al., 1981). The pyroclastic interbeds reflect the contemporaneous basaltic and silicic volcanism in the IRDP region (Robinson et al., 1982). Silicic magma may be one form of magma trap for mafic magma and this may help explain their contemporaneous occurrences. Silicic volcanism also tends to be related to repose time and the intensity of volcanism.

The field abundances of lava types in Iceland are characterized by a large abundance of silicic rocks (Walker, 1966, 1974), approximately 10%, a paucity of intermediate compositions (i.e., less than the silicic rock types) (Walker, 1964, 1966; Wood, 1976), and a majority of basaltic lava types. Frequency histograms of lava types (Martin and Piwinski, 1972; Sigurdsson, 1977; Jakobsson, 1979) and plutonic rock types (Petro et al., 1979) are in general agreement with the field estimates. Simple models of crystal fractionation from mafic rock types which produces silicic magmas would not be supported by the distribution of rock types

and thus alternative mechanisms are needed. In addition rhyolites and intermediate rock types are usually phenocryst poor (Walker, 1974b) which suggests that these magmas are at their liquidus temperatures or superheated. The added input of heat to create these conditions may be from the underplating of silicic magma chambers by mafic magma.

Silicic Rocks. Silicic rocks, as described previously, are associated with the same general features as the central volcanic complexes. They occur contemporaneously with basaltic volcanism and plutonism, and occur in an abnormally high abundance in the Icelandic crust. Other evidence which lends support to the above statement is discussed below. The silicic rocks occur in areas which have the highest geothermal gradient as interpreted from relict hydrothermal metamorphism and the shallowest depth to layer 3 in the crust. The layer 3 transition is interpreted as a metamorphic transition (e.g., Mackenzie et al., 1982). A high degree of variability is also found in their 87Sr/86Sr ratios (O'Nions and Gronvold, 1973), they exhibit evidence of often having been superheated (Gibson and Walker, 1963; Walker, 1963; Blake, 1969; Sigurdsson and Sparks, 1981; Mattson et al., in prep.), often contain phenocrysts which are not in equilibrium with the silicic magma (Sigurdsson and Sparks, 1981; Schmincke et al., 1982), and cannot be generated by simple fractional crystallization processes from a mafic parent based upon trace element abundances and the major element trend of Na_2O greater than K_2O in most of the silicic rocks (Gibson, 1969; Oskarsson et al., 1979, 1982; Mattson et al., in prep.).

Silicic magmas are commonly found in close association with mafic magmas. Rhyolitic tuffs from the IRDP exhibit evidence of being zoned with the more mafic fraction being found at the top of the sequence (Schimincke et al., 1982). The lower portion of the tuff representing the top of the magma chamber and the upper portion of the tuff representing a deeper part of the magma chambers.

Silicic volcanism often occurs preceding basaltic eruptions, following basaltic eruptions (O'Nions and Gronvold, 1973) or both (Sparks et al., 1981). Walker (1974b) suggested that a relationship existed between the volume of silicic magmatism and the intensity of basaltic volcanism.

These types of observations coupled with the numerous occurrences of silicic and mafic magma mixing has led many investigators to postulate the silicic magma is often underlain by large mafic magma reservoirs. The rapidly cooling mafic reservoir crystallizes while imparting heat to the silicic magma, superheating it and initiating eruption (Holmes, 1931; Blake, 1969; Sigvaldasson, 1974, 1979; Sparks et al., 1977, 1981; Eichelberger, 1980; Sigurdsson and Sparks, 1981; Oskarsson et al., 1979, 1982). These observations and models also lend support to the model that many homogeneous intermediate lavas may have formed as a result of silicic and mafic magma mixing.

The origin of the silicic rocks as direct a fractionate from a mafic parent is in conflict with the observations presented. Three models which have been proposed to account for the origin of the silicic rocks in Iceland. The first model is the remobilization of deep-seated silicic rocks toward the surface by a complex history of refusions, fractional crystallization, and hybridizations (Sigurdsson and Sparks, 1981) and similarly the melting of deep-seated plagiogranites (Sigurdsson, 1977). The second model is the partial melting of amphibolitized basalt or gabbro found in the Icelandic crust (Gibson, 1969; Oskarsson et al., 1979, 1982; Sigvaldason, 1974a, 1974). The partial melting is due to the sinking of a hydrated basaltic crust which is subjected to an increase in the geothermal gradient as the crust moves away from the Icelandic ridge system (Oskarsson et al., 1979, 1982). Experimental investigations on the fusion of the Picture Gorge tholeiite at 5 kb H_2O (Helz, 1976) and a Kilauea tholeiite at 1 kb and 2.5 kb H_2O (Spulber and Rutherford, 1983) suggest that silicic compositions (similar to many of those in

Iceland) can be produced by the partial melting of a water present system in oceanic basalts (see Table 7). Thermal modeling of basaltic magma passing through the crust indicates the minimum temperature of melting can be reached in a few years (Patchett, 1980; Hardee, 1982; Lowell, 1982). The third model is the partial melting of oceanic layer 3 to produce silicic rocks (small degrees of melting) and intermediate (more extensive melting) compositions (O'Nions and Gronvold, 1973). All of these models directly or indirectly derive silicic magma from the Icelandic oceanic crust.

Trace Elements

When the variation in (Ce/Yb)N, (La/Lu)N, and (Ce/Lu)N in the Tertiary mafic rocks from the Tertiary of Iceland are considered they are most easily interpreted as the result of an open-system crystal fractionation model. Also, simple fractional crystallization models, regardless of the initial (Ce/Yb)N, (La/Lu)N, and (Ce/Lu)N of the mafic lavas, cannot produce the variation observed in the intermediate and silicic lavas. Finally, in trace element modeling the field distribution of rock types is also an important consideration. Field relationships will, therefore, be discussed in conjection with the trace element models.

Modeling of (Ce/Yb)N Versus Ce. In order to distinguish between magmatic processes which have occurred in the Icelandic lavas a plot of (Ce/Yb)N versus Ce is presented in Figure 21 for various different models. The curves drawn (1-4) are from Pankhurst (1977) and Wood (1978). Model 1 is for batch melting of peridotite with garnet in the source. Model 2 is for batch melting of peridotite in equilibrium with clinopyroxene, orthopyroxene, and olivine. Model 3 is for closed system fractionation of olivine, pyroxene, and plagioclase. And Model 4 is for open-system fractionation at low pressure. Closed system fractionation and the observed mixing trend between mafic and silicic magmas nearly parallel each other on this plot.

Table 7. Experimental Melt Compositions and Average Icelandic Silicic Rocks.

	1	2	3	4	5	6	7	8
SiO_2	70.9	73.1	74.5	70.1	73.7	74.0	75.1	71.5
TiO_2	0.79	0.22	0.07	0.1	0.83	0.19	0.26	0.48
Al_2O_3	14.9	12.9	15.6	18.4	12.9	13.6	12.6	14.4
Fe_2O_3	-	-	-	-	-	0.47	1.08	1.42
FeO	4.65*	3.77*	1.21*	1.56*	3.12*	1.85	1.26	2.04
MnO	0.06	0.05	-	-	0.07	0.10	0.06	0.07
MgO	0.88	0.56	0.00	0.02	0.57	0.13	0.11	0.42
CaO	3.37	2.32	1.2	4.27	2.14	1.50	1.14	1.47
Na_2O	3.58	4.32	3.7	4.2	3.59	5.11	4.86	4.72
K_2O	0.43	2.39	3.7	1.3	2.53	3.01	3.39	3.44
P_2O_5	0.45	0.35	-	0.03	0.12	0.03	0.04	0.05

1. Experimental melt from DO8 Tholeiite 1 Kb fluid (Spulber and Rutherford, 1983).
2. Experimental melt from Kilauea Basalt 1 Kb fluid (Spulber and Rutherford, 1983).
3. Experimental melt from Picture Gorge Tholeiite 5 Kb fluid 700°C (Helz, 1976).
4. Experimental melt from Picture Gorge Tholeiite 5 Kb fluid 825°C (Helz, 1976).
5. Average of rhyolite glass from 1875 Askja (Sparks et al., 1977).
6. Average of four rhyolites from Hekla, Iceland (Sigvaldason, 1974).
7. Average of six granitic rocks from Thingmuli, Iceland (Carmichael, 1964).
8. Average of twelve granitic rocks from this report.

* Total iron reported as FeO.

All analyses reported as fluid free.

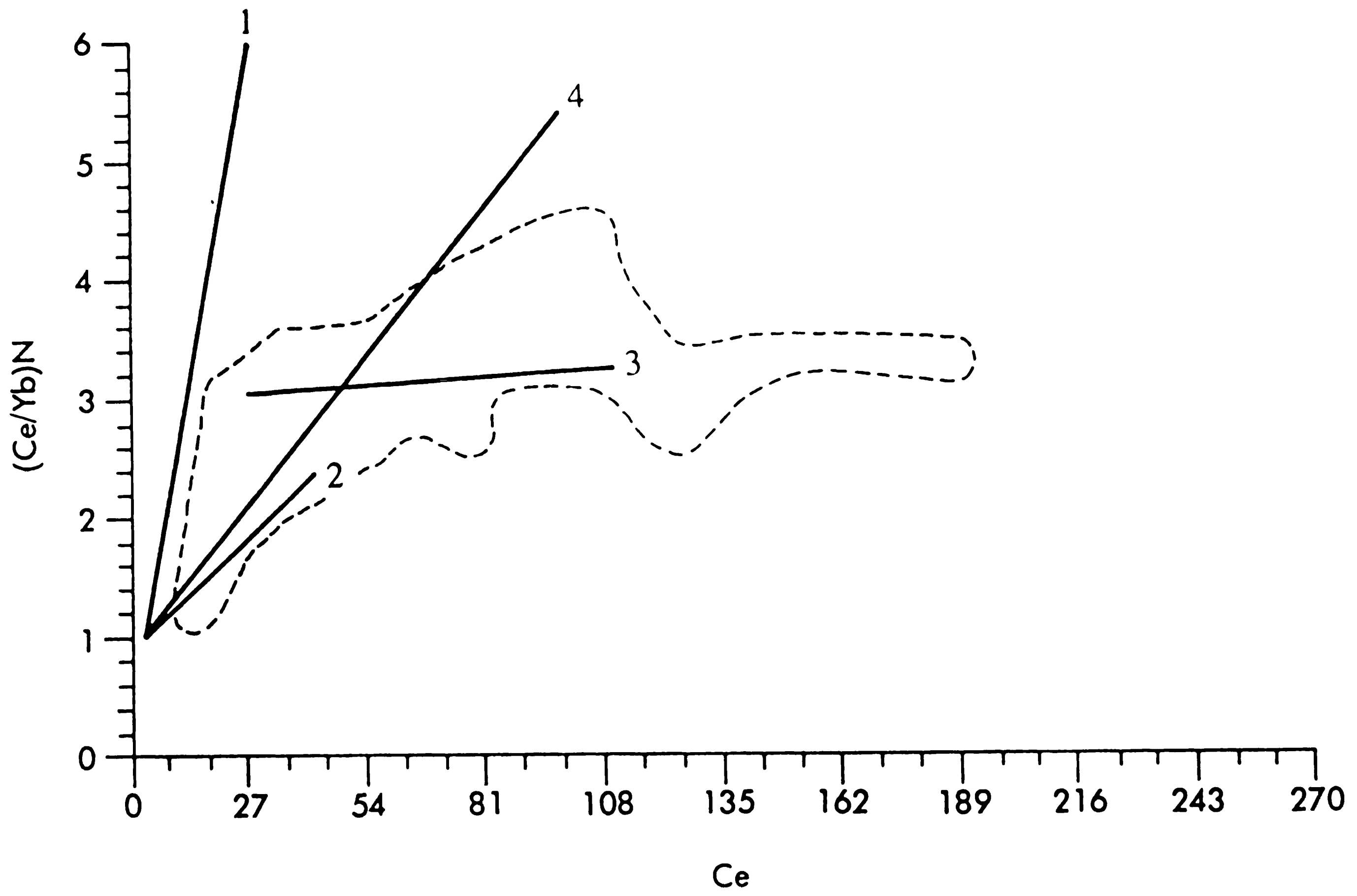

Figure 21. (Ce/Yb)N vs. Ce. Dashed field represents the variation observed in lavas from high magnesia-basalt to rhyolite. Trends 1 to 5 are from Pankhurst (1977) and Wood (1978) and are described in the text.

The model which best fits the observed positive sloped trend in the lavas is Model 4 or open-system fractionation for lava compositions ranging from high magnesia basalt though ferrobasalt. More evolved compositions (i.e., horizontal trend) are consistent with closed system fractionation or magma mixing between mafic and silicic magmas. Partial melting models may account for some of the variation observed, but these models do not account for the low (Ce/Yb)N basalts and the high (Ce/Yb)N basalts, where in general, the high (Ce/Yb)N basalts are slightly more evolved, are more abundant than the low (Ce/Yb)N basalts, and are the only basalts associated with the more evolved compositions ranging from low magnesia basalts through ferrobasaltic compositions and the evolved rocks found in the central volcanic complexes. If the low (Ce/Yb)N basalts are the result of partial melting differences in the mantle it is curious why they would never fractionate to more evolved basalts. This observation has been pointed out previously (O'Nions and Gronvold, 1973; Wood, 1978; Oskarsson, 1979). Within the more evolved compositions, which have high (Ce/Yb)N ratios, much variation is observed in the positive sloped trend (e.g., middle group IRDP) and this also cannot be attributed to partial melting models since the highest (Ce/Yb)N ratio of a high magnesia basalt is less than approximately 3.

The simple Rayleigh equilibrium fractionation equation is only valid for a closed system in which solids separate from a liquid, and no liquid is lost (Cann, 1982). Thus the model of Rayleigh fractionation presented (Model 3, Figure 23) assumes each batch of fractionated magma remains intact until its eruption with no liquid lost to eruption during the process. Modeling of (Ce/Yb)N and Ce indicates that when a small proportion of liquid is lost periodically from the magma chamber the (Ce/Yb)N ratio remains nearly constant as in other crystal fraction models. However, the Ce enrichment of the magmas is much less with increased proportion of liquids periodically leaving the system. The calculations

and assumptions used are those of Cann (1974). The calculations and plots are not presented here to conserve space. The conclusions of this analysis are that the lavas are not the product of a mafic magma chamber that has simply fractionated and erupted. Nor are they the result of a periodically erupted magma chamber which has been continuously evolving due to crystal fractionation processes because this only reduces the amount of variation which can be produced in Ce or (Ce/Yb)N.

The observed trends are believed to be most consistent with a model of open-system fractionation (positive slope trend) which is combined with a modified open-system model and simple crystal fractionation and/or mixing events with silicic magmas (horizontal trend). The volumes and field distributions of the lavas is consistent with an open-system model and not readily interpreted in terms of partial melting models. Partial melting models (Models 1 and 2, Figure 21) can only account for a limited portion of the observed trends in lavas. Primitive low (Ce/Yb)N basalts are only erupted at the fringes of the eruptive pile and high (Ce/Yb)N basalts are erupted where magmatic volumes are largest in the center of the volcanic pile.

The high (Ce/Yb)N basalts are also associated with the lavas which have higher concentrations of P_2O_5, TiO_2, K_2O, and FeO. The horizontal trend observed in the (Ce/Yb)N vs. Ce plot is attributed to magma mixing between silicic and mafic magmas which also undergo simple crystal fraction processes. This then is overprinted on the open-system trend. These lavas are the highly evolved lavas with the wide scatter observed in P_2O_5, TiO_2, K_2O, and FeO for a given FM ratio (see Figures 13, 14, and 15).

Modeling of Ce/Lu Versus La/Lu

The variation in (La/Lu)N versus (Ce/Lu)N ratios can be greatly effected by open-system fractionation or by magma mixing between silicic and mafic

magmas. These ratios, however, are relatively insensitive to simple crystallization processes. The theoretical maximun variation which can be produced in the (Ce/Lu)N or (La/Lu)N ratios by simple crystallization models, from high or low magnesium basalts to rhyolites, does not exceed two units for either ratio on such plots. These simple crystallization models include the variation from a high magnesia basalt parent through rhyolite. The phases and phase proportions of crystals used in this model are those predicted by Wood (1978) using major element models. Distribution coefficients used in these models can be found in Table 8.

Large variations in these ratios can occur if an open-system model is used (Figure 22) or if a mixing occurs between silicic and mafic magmas (Figure 20). Due to the large amount of variation observed in the evolved lavas (i.e., low magnesia basalts, ferrobasalts, basaltic andesites) in comparison to the models presented, they cannot be produced by simple crystallization processes or partial melting processes. Open-system fractionation and magma mixing processes can produce large variations in these ratios.

The mixed rock trend (Figure 20, dashed field) is only for the Austurhorn and Vesturhorn intrusions. Silicic rocks range to the extreme right of the dashed field plotted. A series of mixing lines could be drawn from silicic compositions to an individual mafic rock composition and thus produces much of the scatter observed in the intermediate lavas. Further analysis of silicic rocks and intermediate rocks should be carried out in order to test this hypothesis.

MAJOR ELEMENTS

Variations in FeO, SiO_2, P_2O_5, TiO_2, and K_2O

The variation observed in FeO and SiO_2 in lavas (Figures 17 and 18) in comparison to the experimental trend indicates that the FeO enriched and

Table 8. Distribution Coefficients Used for Mineral Phases.

La	Ce	Yb	Lu	
0.008	0.0069	0.014	0.016	Olivine
0.109	0.12	0.067	0.060	Plagioclase
0.069	0.15	0.62	0.56	Augite
0.34	0.27	0.36	0.38	Ti-Mag.
0.005*	0.0065	0.085	0.095*	Ilm.
Used for Modelling Rocks from High-Magnesia Basalt to Ferrobasalt				
0.109	0.24	0.077	0.062	Plagioclase
0.18	0.362	2.01	1.81	Augite
0.01	0.024	0.34	0.42	Opx.
10.0	16.6	9.4	7.9	Apt.
Used for Modelling Rocks from Basaltic Andesite to Icelandite				
0.02	0.01	0.03	0.08	Olivine
0.34*	0.27	0.049	0.046	Plagioclase
0.018	0.362	2.01	1.81	Augite
Used for Modelling Rocks from Icelandite to Rhyolite				

* Extrapolated

Distribution coefficients are from Luhr and Carmichael (1980), Arth (1976), Nagasawa and Schnetzler (1971), Nagasawa (1970), Higuchi and Nagasawa (1969), Philpotts and Schnetzler (1970), Schnetzler and Philpotts (1970), McKay and Weill (1976).

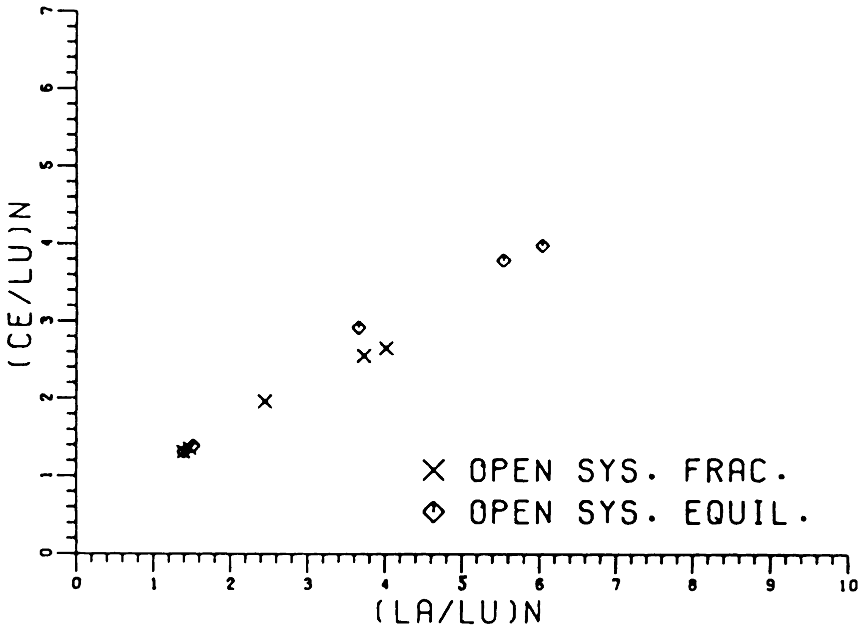

Fig. 22. (Ce/Lu)N vs. (La/Lu)N for equilibrium and fractional open system models. The model of O'Hara and Mathews (1981) and the partition coefficients in Table 7 were used to calculate the models. Models include the variation from high magnesia basalt-low magnesia basalt-ferrobasalt-basaltic andesite-Icelandite to rhyolite. The proportion of phases crystallizing in each interval used in the calculations are those estimated by Wood (1978).

elevated SiO_2 lavas, (i.e., greater than approximately 52% SiO_2) strongly depart from the expected trends for simple crystallization. This also is observable on the Ol.-Pyx.-Plag.-Qtz. projections. Lavas which depart from the iron enrichment trend at nearly constant silica contents are readily interpreted as mixed magma products from the interaction of the silicic and mafic magmas. Once the magmas have mixed, fractional crystallization processes may be superimposed on the mixed product and/or eruption.

The iron enrichment trend, by itself, lends no direct support to the modified open system fractionation model proposed, but is consistent with the model. In the laboratory modeling of replenished magma chambers hot dense magma intrudes cooler less dense magma; stratification and crystallization ensues until the liquids densities are nearly the same and this results in mixing (Huppert and Turner, 1981; Huppert et al., 1982). In Iceland, primitive, MORB-like, mafic magmas occur (Imland, 1983), but most lavas tend to be more iron enriched. In addition, enrichments in P_2O_5, K_2O, and TiO_2 occur in conjunction with the iron enrichment (Schilling, 1973; Jakobsson et al., 1978; Jakobsson, 1979; Schilling et al., 1983). The observed lava compositions are different then presumed in most laboratory experiments in that mafic magmas in the Icelandic crust are denser than more primitive MORB-like compositions which are derived from the mantle.

Due to the intrusion and rise of primitive magma into the thicker Icelandic crust and the development of hydrothermal systems, magmas are ponded and have longer residence times. Thus, a modified system of an open magmatic chamber is established under the fissure eruptions and the central volcanic complexes in Iceland. The modified open-system fractionation model is non-steady state and operates as follows. Mafic magma which has only slightly evolved toward iron enriched compositions is denser than new batches or primitive hot magma which may intrude the magma chamber. Only small temperature and viscosity

differences exist between the two magmas. The inverse density gradient allows rapid convective overturn, in the magma chamber with crystallization and fractionation soon following due to the cooling of the whole magma reservoir. This modified model of open-system fractionation would approach steady state conditions if the volume of magma from below was greatly increased and the whole chamber became more MORB-like in character. Normal open-system fractionation involves a positive density gradient (i.e., hot dense magma intruding cooler less dense magma). This involves stratification of the magma chamber, crystallization in the lower layer, and then mixing of the magmas. However, in the Icelandic environment magmas are likely ponded and evolve slightly from MORB compositions toward ferrobasalt (i.e., denser magmas). These evolved magmas are slightly cooler, but they are of higher density than the new "MORB-like" compositions which invade from below. These conditions would lead to rapid mixing and then simultaneous or subsequent crystallization. This model would explain many of the "anomalous" chemical features of Icelandic volcanism in comparison to normal MORB compositions which are affected by positive density gradients in the magma chamber.

Thus, in a similar manner to open-systems involving primitive mafic magmas, the influx of new magma provides additional thermal energy to the chamber prolonging its life (Usselman and Hodge, 1978) and modifies the chemical composition of the resultant magma. Dependent factors are the rates and volumes of new magma supply to the chamber, the rate of outflux from the chamber, and the amount and timing of crystal fractionation processes. In general, the chemical composition of the magma chamber would evolve to more FeO, TiO_2, P_2O_5, and K_2O enriched compositions if plagioclase, olivine, and pyroxene were the only fractionating phases. An idealized sample calculation is presented in Table 9 which produces enrichments in FeO, TiO_2, P_2O_5, and K_2O

Table 9. Open-system model (non-steady state).

	1 % Crystals in fractionate	4.10	7.63	3.27	2	3	4	5	6	7	8
	Lava V-10	Fo_{70} Oliv.	An_{80} Plag.	$\frac{Mg}{Mg+Fe}=0.80$ Aug.							
SiO_2	48.19	39.75	48.93	52.66	48.3782	48.2764	48.4801	48.3492	48.5850	48.4610	48.6173
TiO_2	1.91	-	-	0.61	2.2250	2.0547	2.3949	2.2057	2.5738	2.3655	2.7561
Al_2O_3	15.42	-	32.42	2.56	15.1386	15.2907	14.9865	15.1492	14.8271	15.0132	14.6358
FeO	11.13	21.16	0.57	6.94	11.7600	11.4190	12.1000	11.7187	12.4589	12.1036	12.8847
MnO	0.18	0.50	-	0.20	0.1877	0.1835	0.1918	0.1871	0.1962	0.1911	0.2005
MgO	9.06	39.59	-	16.16	8.1308	8.6331	7.6284	8.1815	7.1003	7.7153	6.5374
CaO	11.39	-	15.96	20.86	11.1693	11.2886	11.0500	11.1779	10.9250	11.0709	10.7760
Na_2O	2.31	-	2.12	-	2.5284	2.4103	2.6465	2.5148	2.7708	2.6262	2.8958
K_2O	0.23	-	-	-	0.2707	0.2487	0.2927	0.2682	0.3158	0.2889	0.3395
P_2O_5	0.18	-	-	-	0.2118	0.1946	0.2290	0.2099	0.2472	0.3037	0.3569
TiO_2/P_2O_5	10.61				10.48	-	10.46	-	10.41	-	7.72
100% Starting Volume V-10-Aphyric lava (Wood, 1978) Oliv. computed Plag.-Lava 150 (Wood, 1978) Ave. Pyx.-Lava V-12 (Wood, 1978)		Remaining Liq. Volume %			85%	185%	157.25%	257.25%	218.66%	318.66%	270.86%
		% Frac. of Crystals in Interval			15%	-	15%	-	15%	-	15%
		% Total Crystallization			15%	-	42.75%	-	81.34%	-	129.14%
		Fractions Mixed			- -	0.459459(2) 0.540544(V-10)		0.611293(4) 0.38850(V-10)		0.6861859(6) 0.3138141(V-10)	
		Processes			Frac.	Mix	Mix/Frac.	Mix	Mix/Frac.	Mix	Mix/Frac.
		Total Volume %			100%	200%	200%	300%	300%	400%	400%
		Volume % of V-10 Mixed In				100%	-	100%		100%	
		% of Remaining Liquid Fractionated				27.75%		32.799%		47.799%	

and a decrease in the TiO_2/P_2O_5 ratio due to magma mixing and fractional crystallization processes (i.e., modified open system). The proportions of ol.-pyx.-plag. are as modeled by Wood (1978) on high magnesia basalt V-10. This in part may help explain the increasing K_2O and decreasing TiO_2/P_2O_5 ratio contents measured in lavas with increasing volume of eruption pointed out by Jakobsson et al. (1978) and the high volume of evolved compositions which occur in association with the central volcanic complexes. These trends are inconsistent with simple fractional crystallization or partial melting processes (Jakobsson et al., 1978). P_2O_5, TiO_2, K_2O and FeO are thought to be controlled by a modified open-system fractionation process for mafic lava compositions and these mafic compositions may mix at any point in their evolution with silicic lavas (Figure 23).

Silicic magmas are associated in time and space with mafic magma eruption and are located at central volcanic complexes which are sites of large evolved mafic lava eruption. Once silicic magmas have developed they may exert a control on the magma evolution through stratification of the magma chamber and magma mixing processes between silicic and mafic magmas (Figure 24). The underplating of silicic magmas by mafic magmas and the stratification of the mafic magma chamber (Huppert et al., 1983) may help account for the chemical features observed, such as both high and low P_2O_5 and TiO_2 mafic pillows, in the silicic and mafic complexes of the North Atlantic Volcanic Province (Mattson et al., in prep.; Vogel, 1982) and explain why ferrobasaltic compositions are often mixed with silicic magma (Bell, 1983). That ferrobasaltic compositions are often mixed with silicic magma is lent some support, in that the most iron enriched lava compositions follow the trend of the liquidus surface on the Ol.-Plag.-Qtz. projection until the projected piercing point is reached (see Grove et al., 1982), where most of the evolved lavas deviate from the liquidus surface.

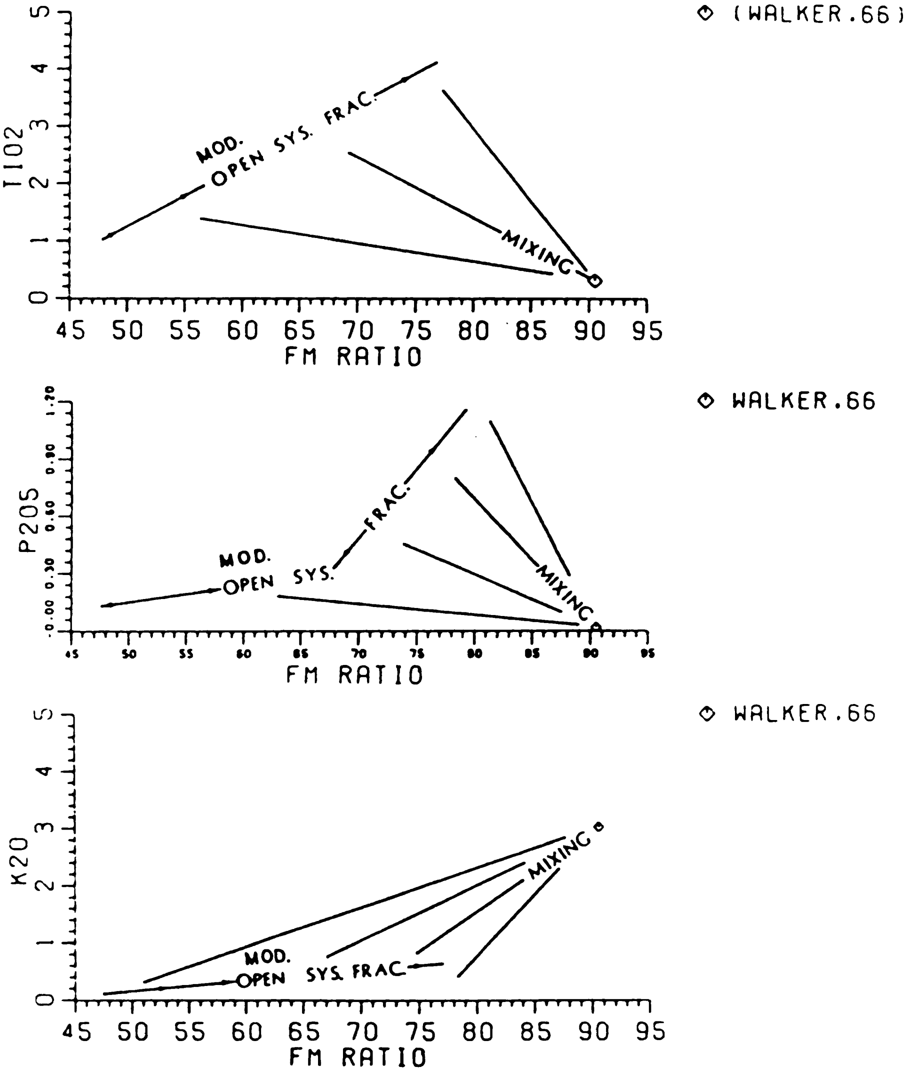

Fig. 23. Proposed model for the variation observed in TiO_2, P_2O_5, and K_2O. Mafic magmas (high and low magnesia basalts to ferrobasalts) evolve by a modified open system fractionation processes. Intermediate magmas are the result of mixing between silicic and modified mafic magmas. Crystal fractionation processes may further affect the intermediate magmas not indicated.

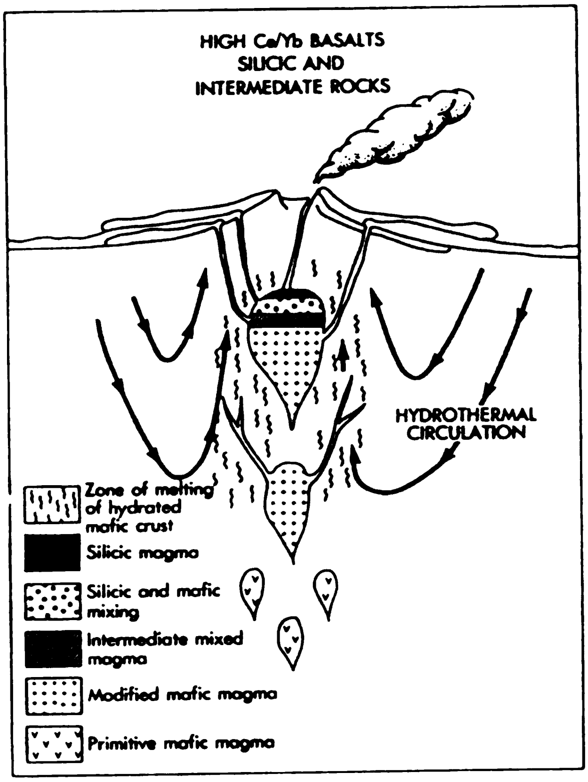

Fig. 24. Schematic diagram for an evolving zoned magma chamber beneath a central volcanic complex.

Magma Mixing for Lavas of Wide Compositional Contrast

It is commonly believed that magma mixing between mafic and silicic magmas is prohibited due to thermal differences in their liquidus temperatures. Mixing would produce compositions which should rapidly crystallize unless one of liquids is superheated. However, if thermal cusps are present in P-T-X space and mixing occurs between two compositions across the cusp, then the possibility exists, that these compositions may be at, near, or above their liquidus temperatures. Thus conditions may exist which are not prohibitive to magma mixing and these conditions may be reinforcing to the mixing process if the mixed product is above its liquidus temperature.

Figure 25 is a schematic diagram of T-X space for a binary system. Although the real geologic system is more complex, a simple binary system can be used to illustrate the concept presented. If a mafic magma, Y, at its liquidus temperature mixes with a silicic magma at its liquidus temperature, at E, then mixed magmas could be generated anywhere along the line between Y and E depending upon the proportion of endmembers mixed (Figure 25, Path 2). By mixing different proportions of silicic and mafic magmas different intermediate magmas are produced and each would have its own subsequent crystallization history.

Mixed liquids which are formed between Y and Q would be either slightly above or at their liquidus temperatures. Mixed liquids between Q and S would be significantly above their liquidus temperatures, such as, at the points U and V. Mixed products formed between S and E would be below their liquidus temperatures (Figure 25, Path 2).

Mixed compositions produced between Y and S would be more likely to form homogeneous products and erupt since they are above or at their liquidus temperatures. Mixed compositions between formed between S and E would not be

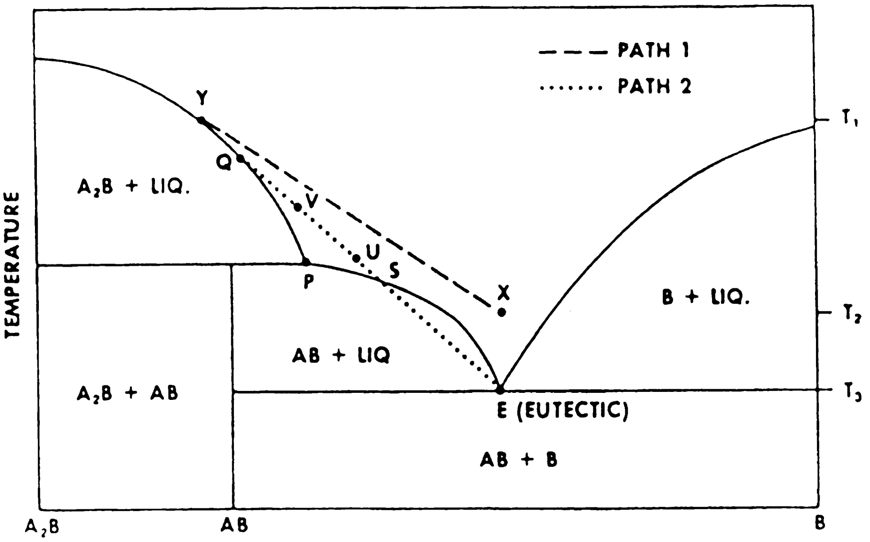

Fig. 25. Simplistic model for magma mixing between mafic and silicic magmas (see Text). Path 1 is an idealized temperature and composition path for simple mixing. Path 2 is for a mafic magma mixing with a silicic magma. The system presented is modeled after the binary Ol.-Cpx.-SiO_2 system.

as likely to homogenize and be less likely to erupt since they are well below their liquidus temperatures. Thus one would predict that mixed liquids between S and E would not occur and produce a gap in the lava record. This potentially explains the difference observed on the AFM plots (Figure 16) and the position of the "gap" in lavas in contrast to the position of the "gap" observed in the mixed rock examples. Liquids which mix between S and E freeze and do not erupt, while in the silicic and mafic complexes these mixing events take place on a localized scale (Mattson et al., in prep.) and are preserved. Compositions which form between Y and S in the silicic and mafic complexes are superheated or at their liquidus temperature and thus are allowed to mix with more silicic magma producing a "gap" in the mixed rock examples.

Mixed magma products between S and E would not be prohibited from forming and erupting if one of the liquids was superheated. If the silicic liquid, at E, was superheated to a point X then all the mixed products between X and Y would be above their lilquidus temperatures upon mixing. No gap in the lava record would be expected. Superheating of the silicic magma could occur by the underplating of the silicic magma by mafic magma. This situation is analogous to what is observed in the lava products from the 1875 Askja eruptions (Sparks and Sigurdsson, 1981), which exhibit a continuous trend on the AFM plot.

More complex situations could arise if either magma contained crystals. Crystals within the magma(s) can produce non-linearity of the chemical components within a magma (McBirney, 1979). The phenocrysts in a magma would be expected to exhibit resorbtion and/or crystal armouring relationships within the mixed magma. Instances of mixed rocks in Iceland with crystals included in either the mafic or the silicic magma are quite common (e.g., Gibson and Walker, 1963). With further equilibriation to P and T conditions the magma could evolve

toward more silicic compositions with either equilibrium or fractional crystallization.

In Iceland silicic rocks occur in association with the central volcanic vents which have the highest volumes of lava associated with them. Examples of mixing between silicic and mafic magmas are therefore limited to the central volcanoes and are result of the dynamic conditions which occur under the central volcanic complexes.

Silicic and mafic occurrences display mechanical mixing relationships, often contain xenocrysts derived from either the silicic or mafic magma, and in almost all cases the silicic volume is greater than the volume of mafic magma. The volume relationships preserved may be just as they occur in nature or may be a function of which mixed products did not homogenize and erupt due to temperature and viscosity differences in the mixed magma (i.e., between S and E on Figure 25). Mixed products which are above their liquidus temperatures (i.e., mafic magma volume greater than silicic magma volume) may homogenize and erupt leaving little trace of the mixing event except in the case where mixing triggers the eruption. Mixing of contrasting compositions below or at their liquidus temperatures may never mix homogenously due to temperature and viscosity differences. Thus the examples of composite dikes, composite flows, and silicic and mafic complexes in many cases probably represent systems which have failed to homogenize and are the least likely to erupt. Whether homogeneity and eruption develops, is a complex interaction of the volumes, viscosities, and temperatures of the contrasting magma types which may mix and the properties of the potential mixed magma which could result.

Isotopic Constraints on the Model

Of the processes invoked in the model presented, none should significantly affect the unstable isotopic values measured from Icelandic rocks. Thus unstable

isotopic values are those which are inherited from the mantle. Due to variability found in the measured unstable isotopic values mantle heterogeneities must be present beneath Iceland. Major element heterogeneity of mantle derived melts does not necessarily coincide with the isotopic heterogeneities. The process of open-system fractionation or modified open-system fraction and the generation of silicic rocks, by partial melting of a hydrated Icelandic crust or remelting of silicic compositions and then remobilization, should not signficantly affect the unstable isotopic values inherited from the mantle. Mixing between mafic and silicic magmas, therefore, will not be detectable in the unstable isotopic values.

Silicic rocks generated by either the partial melting of a hydrated mafic crust or by the remelting of previously formed silicic rock and subsequent remobilization will have similar present day ratios to the rocks from which they are derived. This is because the rocks from which they inherit their initial ratios are relatively young in comparison to the half-life of the isotopes measured. Because most of the Icelandic crust is less than 20 m.y. old, the silicic rocks will inherit isotopic values which are essentially the initial ratios of the rocks found in the Icelandic crust (Moorbath et al., 1968; Oskarason et al., 1979, 1981). Thus all rocks found in the Icelandic crust would exhibit similar Nd, Pb, and Sr variations as found in the most primitive melts which are directly derived from the mantle. Silicic rocks may show slight enrichments if the hydrated crust from which they are derived have been effected isotopically by meteoric or seawater interaction.

Stable isotopic values ($\delta^{18}O$ and $^3He/^4He$, Table 6) measured from Icelandic rocks, in contrast, indicate that substantial interaction has occurred between magmas and the intruded hydrothermally altered and older Icelandic rocks (Hattori and Muehlenbacks, 1982; Condomines et al., 1983). The $^3He/^4He$ ratios of silicic and intermediate rocks are low and probably reflect the interaction of these magmas with atmospheric helium (Condomines et al., 1983). The stable

isotope data is consistent with the formation of magma traps, hydrothermal systems, and magma mixing processes presented for Icelandic environment with which these magmas have interacted.

SUMMARY

Mafic magma evolution (high magnesia basalts, low magnesia basalts and ferrobasalts) can be accounted for by a modified open-system model. This model includes magma mixing between primitive MORB-like compositions with denser, lower temperature, and iron enriched magmas which have been ponded in the Icelandic crust due to the excess crustal thickness and hydrothermal circulation. This modified open system is dependent upon the volumes of magma influx, magma outflux, and the amounts and kind of crystal fractionation processes occurring. To produce the iron enrichment trend olivine, pyroxene and predominantly plagioclase must be the fractionating phases. This model can account for the large variations observed in (Ce/Yb)N, (La/Lu)N, and (Ce/Lu)N observed, the large continuous variations observed in K_2O, P_2O_5, and TiO_2, especially for these lavas which are related in a single lava pile such as the lavas found in the middle group lavas of the IRDP. The model can account for the relationships between increasing volumes being erupted with increasing K_2O and decreasing TiO_2/P_2O_5 ratio (Jakobsson et al., 1978), the large volumes of lava associated with the central volcanic comlexes (Walker, 1960, 1974a, 1975a; Saemundsson, 1978; Jakobsson et al., 1978), and the chemical zonation found in the erupted lenses (i.e., small volumes of high magnesia basalts with low (Ce/Yb)N ratios found on the outside of the eruptive lenses and the largest volumes associated with the evolved fissure eruptions and central volcanic complexes which have high (Ce/Yb)N ratios) (Walker, 1963, 1966, 1974a; Gibson, 1969; Sigvaldasson et al., 1974; Palmason and Saemundsson, 1974; Brooks et al., 1974;

Wood, 1978). The above observations are inconsistent with simple fractional crystallization of a primitive mafic magma and partial melting or mantle heterogeneity models which try to relate the large major element and trace elements variations observed. An important question is how much of the actual variation observed is caused by different degrees of partial melting or mantle heterogeneities? Under the model proposed it is not necessarily to invoke either of these models in order to account for the major element or trace element variations observed. It is also unknown whether the modified open-system processes occur in a single large chamber or in a series of smaller interconnected magma chambers and/or at various pressures.

In Iceland numerous examples of composite flows, composite dikes, silicic and mafic complexes, and mixed pyroclastic deposits occur in association with the central volcanic complexes. Within these occurrences a wide variety of intermediate compositions occur which are due to magma mixing processes. A comparison of these mixed intermediate compositions with intermediate lavas reveals that they have many similarities. Simple fractional crystallization models which produce intermediate lavas are inconsistent with the large variations observed in (Ce/Yb)N, (La/Lu)N, and (Ce/Lu)N, the wide scatter observed TiO_2, P_2O_5, and K_2O, the low abundance of intermediate lavas, and the deviation of intermediate lavas from experimental liquidus trends on plots of SiO_2 and FeO(T) versus FeO(T)/MgO ratio. Ol.-cpx.-plag.-qtz. projections also support this conclusion.

A model of tholeiitic volcanism and plutonism is proposed, whereby mafic magma evolution is dominated by a modified open system fractionation model for lava types ranging from high magnesia basalt, low magnesia basalt to ferrobasalt. These mafic magmas may mix at any point in their evolution with silicic magmas (Figure 26). Silicic-mafic magma mixing processes produce a wide range of

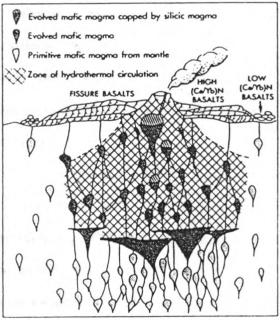

Fig. 26. Schematic diagram for an eruptive lens in the Iceland environment.

intermediate lavas. Due to the underplating of mafic magma under silicic magma a mafic zoned and stratified chamber develops. The mafic and silicic magma chamber may mix and produce silicic and mafic complexes, composite dikes, composite flows, or erupt composite pyroclastic deposits or homogeneous intermediate lava flows.

Due to crystallization in the mafic portion of the stratified magma chamber ferrobasalts may most often mix with silicic magmas (Bell, 1983). The mafic magma may also become zoned developing high and low TiO_2 and P_2O_5 intermediate compositions (Mattson et al., in prep.; Vogel, 1982). Large volumes of mafic magma have more potential for mixing with silicic magmas than vice versa unless the silicic magmas are commonly superheated (Mattson et al., in prep.; Mattson, this paper).

Derivation of silicic magmas by simple fractionation crystallization from a mafic parent is inconsistent with the major element and trace element abundances observed (Gibson, 1979; Oskarsson et al., 1979, 1982; Mattson et al., in prep.). Silicic liquid immiscibility can also be rejected (Mattson et al., in prep.). Silicic magmas can be generated by the partial melting of a hydrated mafic crust (Gibson, 1969; O'Nions and Gronvold, 1973; Oskarsson et al., 1979, 1982; Spulber and Rutherford, 1983) and/or a complex refusion history and remobilization of previously formed silicic rocks from deeper in the crust (Sigurdsson and Sparks, 1981; Sigurdsson, 1971). Crustal partial melting models are most consistent with the model presented here, the distribution and abundance of silicic rocks found in Iceland, and the abundance of low intermediate lavas.

The model presented may have many ramifications in common with other oceanic areas where rifting is occurring through thick oceanic crust, volcanism is spatially and temporally constrained, and the oceanic crust is hydrated and well

fractured. Such areas might include newly propagating rift zones and en echelon rifting areas.

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