

## Contemporaneous Basaltic and Rhyolitic Magmas<sup>1</sup>

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### Abstract

The common interbedding of basalt and rhyolite indicates that such magmas were available at the same place contemporaneously. Field observations support the view that two magmas of highly contrasting compositions coexisted at least for limited periods and were erupted simultaneously throughout geologic time. The paucity of intermediate rocks casts doubt on the production of contrasting magmas by fractional crystallization. Previous explanations either have assumed the existence of separate basaltic and rhyolitic magmas or of remobilization of pre-existing granites, or have appealed to liquid immiscibility.

The thermal properties of natural rhyolite and basalt do not support the concept of immiscibility, and melts formed by the fusion of mixtures of common natural basaltic and rhyolitic rocks as well as their glasses are completely miscible. Additional experiments illustrate that H<sub>2</sub>O-saturated rhyolitic and basaltic melts may maintain an interface for short periods of time, and some hybridization appears to take place between such coexisting magmas. The similarity of concentration gradients of elements near the interface, as determined by electron microprobe analysis, suggests that element interactions play a dominant role in the diffusive transfer of material. The asymmetry of the concentration gradients relative to the optical interface indicates more extensive transfer in the basaltic liquid than in the rhyolitic liquid.

A new hypothesis involving fractional melting illustrates one possible way in which two magmas of highly contrasting composition may be generated successively from the same parental material. Small batches ( $\approx 10$  km<sup>3</sup>) of parental material are partially melted as a result of adiabatic decompression. Each magma is extracted at separate invariant points, essentially isothermally, in an interval of several thousand years. No liquids of intermediate composition are produced. The paucity of intermediate rocks, the "Daly gap," is attributed to the fractional melting process without regard to the time interval between contrasting magmas.

Removal of small amounts of liquid from the parental material is presumed to take place with the same efficiency as the removal of residual liquids from monomineralic cumulate layers in layered intrusions. Alternatively, rhyolitic liquid may be removed in one batch even though removal of basaltic liquid would have to take place continuously. Variations imposed by the H<sub>2</sub>O content and its initial disposition are manifold; however, if a hydrous mineral is retained in the parental material during formation of both magmas, the products are rhyolite and andesite. If the H<sub>2</sub>O of the parental material is consumed in the first stage of fractional melting, the products are rhyolite and tholeiite.

Trace element contents of each magma are dependent on (1) the kinds and proportions of major phases in the parental material, (2) which major phase is consumed at the first stage of fractional melting, (3) the presence of accessory minerals, and (4) the distribution coefficients effective under the conditions of magma formation. The extent of hybridization of contiguous contrasting magmas depends on the geometry of the interface, the degree of turbulence, and the storage period, and is not necessarily confined to producing liquids along normal lines of descent. A hydrous, olivine-rich parental material capable of producing quartz-normative liquids is assumed on the basis of experimental evidence from synthetic systems and natural rocks; however, the hypothesis is equally applicable under anhydrous conditions and to parental materials having other normative characteristics.

### Introduction

One of the oldest problems in petrology is the contemporaneous extrusion or intrusion of magmas of great contrast in composition with intermediate

members absent or of negligible volume. Bunsen in 1851 recognized the highly contrasting compositions of basalt and rhyolite<sup>2</sup> in Iceland. He proposed two independent parental magmas, which when mixed in

<sup>1</sup> Presidential Address, Mineralogical Society of America. Delivered at the 53rd Annual Meeting of the Society, 14 November 1972.

<sup>2</sup> Bunsen (1851, p. 199) described the extreme members as a normal trachyte and a normal pyroxenite and indicated in a footnote that these were to be taken as a silica-rich trachyte and a silica-poor basalt or dolerite, respectively.

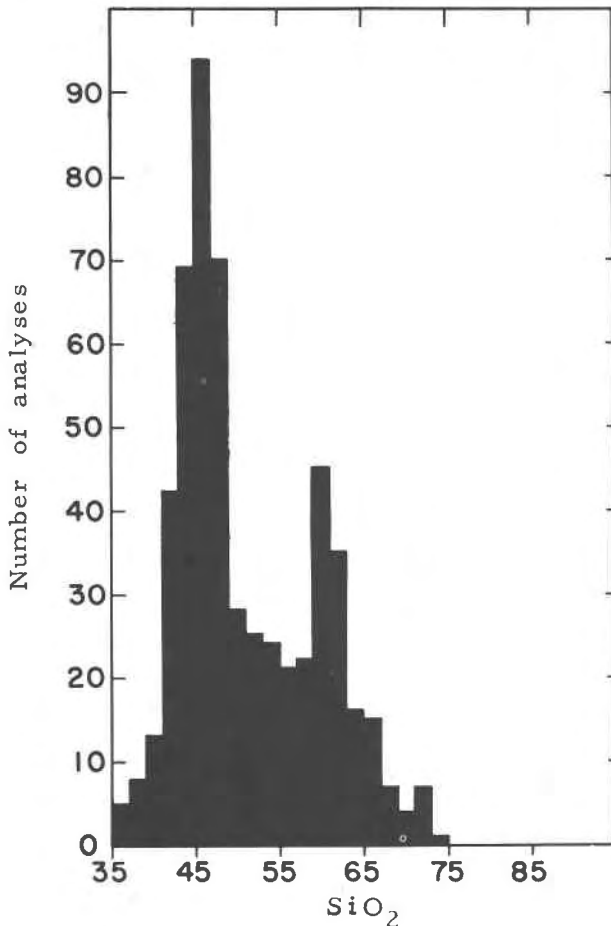


FIG. 1. Distribution of  $\text{SiO}_2$  (abscissa) in 551 analyses of rocks of the oceanic basalt-trachyte association (Chayes, 1963, p. 1523, Fig. 1A). Note paucity of specimens having intermediate silica contents.

various proportions produced the wide variety of igneous rocks.<sup>3</sup> Although the concept of magma mixing did not survive as a major process in petrogenesis, the contrast of magmas has since been recognized as a world-wide phenomenon.

Chayes (1963) has illustrated the compositional contrast in a quantitative way by various plots of oxides and normative minerals of associated oceanic basalts and trachytes. The time relationships of the associated rocks are not known; however, the relevance of the data to contemporaneous basalt and trachyte will become evident. One example (Fig. 1) is sufficient to show that there is indeed a division of these igneous rocks into two major groups with a

<sup>3</sup> The mixed magmas were described by Durocher (1857) as hybrids in the strictest sense, although "hybrid" is sometimes used to describe the liquid resulting from the assimilation of crystalline materials.

minimum of intermediate compositions. The relative paucity of intermediate rocks has often been described as the "Daly gap" (Daly, 1925).

The bimodal frequency distribution in composition has been raised as a serious objection to the formation of igneous rocks primarily as a consequence of crystal fractionation. In general, the volume of successive liquids, and hence the rocks crystallized therefrom, would be expected to decrease in a petrogenetic process controlled primarily by crystal fractionation. Furthermore, no major gap or hiatus in liquid composition would be anticipated in an anhydrous crystal fractionation process (see Chayes, 1963, Appendix);<sup>4</sup> however, sudden loss of volatiles in a hydrous fractionation process may produce major gaps in liquid composition.<sup>5</sup>

Because the question bears heavily on the presently accepted framework of igneous petrology, it is desirable to review the field evidence bearing on the contemporaneity of magmas outside the compositional gap, examine the relative thermal relations of the contrasting magmas, review previously proposed hypotheses of origin, present some new exploratory data on the coexistence of two melts, and outline a new hypothesis for their generation from a single parent.

#### Field Evidence of Contemporaneity

Most field geologists have observed rhyolitic lava, pumice, tuffs, or ash interbedded with basalt flows. Less commonly observed is an array of field associations which suggest that at times these magmas of highly contrasting composition have actually coexisted and were erupted contemporaneously.

1. *Mixed welded tuffs* containing glass shards with indices of refraction of approximately either 1.516 or 1.545 corresponding to  $\text{SiO}_2$  contents of about 67 percent and 56 percent, respectively, are known

<sup>4</sup> Attention is called to the compositional gap generated by fractional crystallization between the crystal residua and the last liquid. Starting with a melt of  $\text{Ab}_{50}\text{An}_{50}$  composition in the Ab-An system, for example, the last liquid is of Ab composition yet the average composition of the zoned crystal accumulate may be  $\text{Ab}_{50}\text{An}_{50}$ . The apparent anomalous hiatus between phenocrysts and groundmass compared to equilibrium crystallization in some igneous rocks can be ascribed to the fractional crystallization process, or crystal accumulation, or both.

<sup>5</sup> See Yoder (1969, p. 83 and Fig. 4). Emphasis was placed on the change of crystal composition with release of volatiles; however, the abrupt change in liquid composition is equally significant.

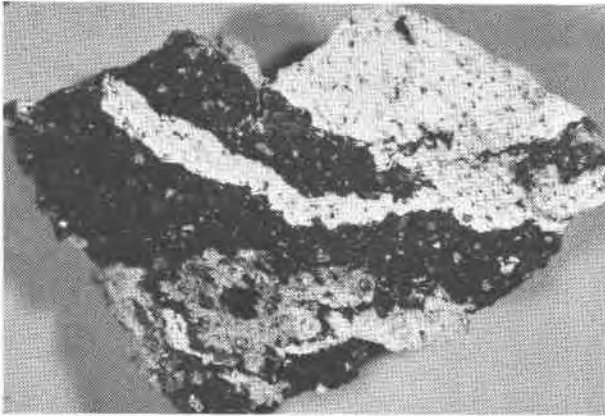


FIG. 2. Photograph of sawed surface of hand specimen of banded pumice from base of Novarupta, Katmai area, Alaska. Rhyolite, white; andesite, black. Specimen No. 54 ACU 36, courtesy of Dr. G. H. Curtis. Longest dimension of sawed surface is 10 cm.

(Costa Rica; Williams, 1952). Some shards show "hair-fine" banding of both types. The implication is that a single vent was simultaneously producing volcanic products of distinctly different composition. Approximately 15 percent phenocrysts were present, and, therefore, crystallization had commenced before eruption.

2. Particularly striking are the *banded pumice* blocks consisting of light bands of dacite and dark bands of andesite ejected from Mt. Lassen (Macdonald and Katsura, 1965) and those of rhyolite and andesite (Fig. 2) from Novarupta at Katmai, Alaska (Curtis, 1968). The imperfectly blended or hybridized magmas, presumably gas-charged, reached the surface and erupted without entirely losing their identity.

3. A unique *tuff-lava* has been found at the volcano Breiddalur in Iceland (Walker, 1963; Blake *et al.*, 1965), which exhibits an emulsion-like texture on a scale of millimeters of nearly equal proportions of a black basic glass and a clear acid glass (Fig. 3). (The composition of the glasses and their thermal behavior are described below.) The "emulsion" contains phenocrysts of two kinds of feldspar; according to Blake *et al.* (1965, p. 43), the more basic plagioclase is mantled by basic glass, and the more sodic plagioclase is enclosed in acid glass. One may confidently conclude from this occurrence that the liquids with their respective phenocrysts issued from the same vent, although no firm conclusion can be drawn that they came from the same source. The two liquids could have been generated in separate

chambers and mixed in the duct during simultaneous eruption. Other similar localities are known in Iceland, and another such "emulsion" has been found in the caldera of the volcano Fantale in Ethiopia (Dr. I. L. Gibson, personal communication, 1970).

(Some tektites consist of two or more glasses of contrasting composition [E. C. T. Chao in O'Keefe, 1963, pp. 60–62]; however, they are not necessarily of volcanic origin.)

4. *Composite dikes* having basic margins and acid cores are of common occurrence in the Tertiary volcanic region of eastern Iceland and in Great Britain (Blake *et al.*, 1965). The field relationships suggest that a basic magma first occupied the dike and while still molten was eviscerated by the later inflow of acid magma. The basic rock locally shows chilled borders against the acid center as well as the country rock.

The converse relations are also observed, although more rarely, in central Scotland (Buist, 1952, p. 53), Skye (Harker, 1904, p. 208), Arran (Judd,

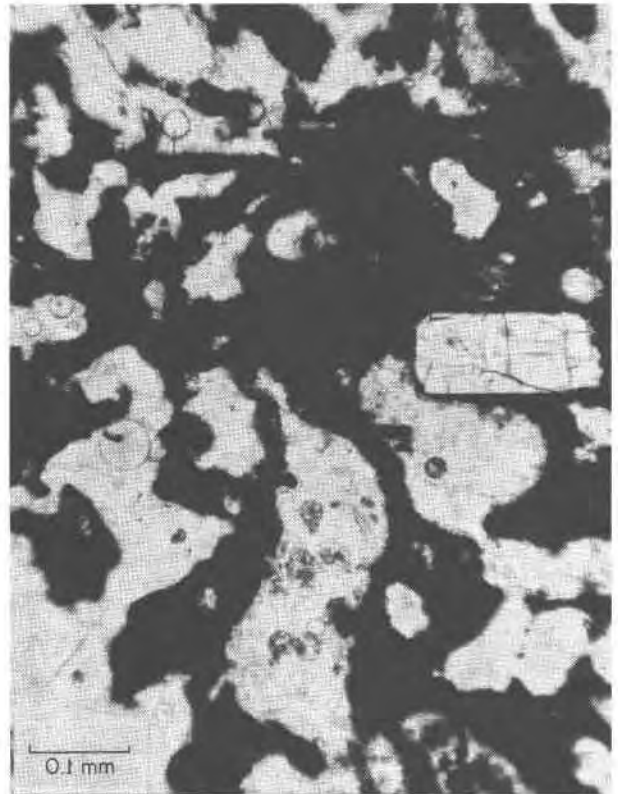


FIG. 3. Photograph of thin section of tuff-lava "emulsion" rock from Breiddalur, Iceland. Specimen No. 05368, courtesy of Dr. G. P. L. Walker. Clear glass,  $\text{SiO}_2 = 73.05\%$ ; black glass,  $\text{SiO}_2 = 52.40\%$ . Note phenocrysts in each glass.

1893, p. 561), and south Greenland (Upton *et al.*, 1971, p. 165), where the basic rock occupies the central portion and acid rock forms the margins.

The contiguous borders of the members of the composite dike may exhibit mechanical mixing, with blobs of basaltic liquid trapped in rhyolitic liquid, or streaks of each intermingled in a flow structure. Hybridization may also be evident at the interface. A spectacular exhibit of mechanical mixing of hydrous magmas was found by Dr. R. A. Wiebe (personal communication, 1970) in a dike in northern Cape Breton Island, Nova Scotia. This body consists of pillow-like inclusions of hornblende gabbro in a granitic matrix (Fig. 4).

5. Some composite dikes have been traced into *composite lava flows* (Gibson and Walker, 1963), the basic unit usually underlying the more acid unit of the flow.

The converse relationship of units is found in the volcano Tejada of Gran Canaria (Schmincke, 1967, p. 7), where a composite flow consists of a lower ignimbrite of quartz-trachyte composition and an upper columnar basalt. The quartz-trachyte component is mixed with the basaltic component in a zone up to several meters thick and covers a vast area (300 km<sup>2</sup>). The clots of basaltic magma are not uncommonly formed into "micropillows" (Fig.

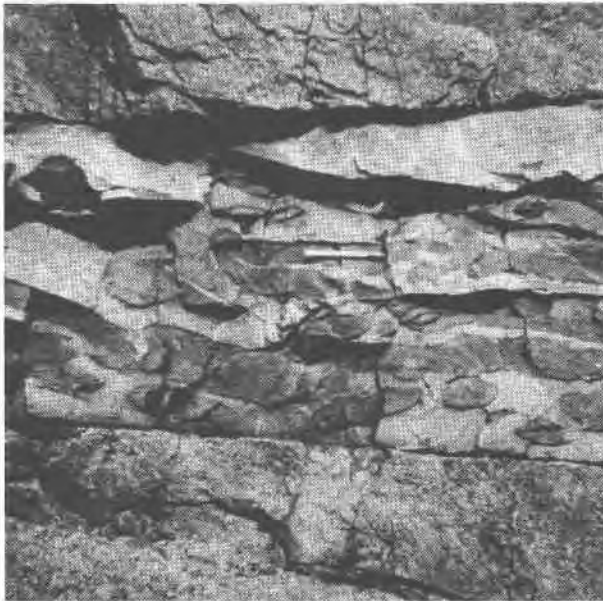


FIG. 4. Photograph of mixed composite dike of hornblende gabbro (black) and granite (light gray) at northern Cape Breton Island, Nova Scotia. Courtesy of Dr. R. A. Wiebe.

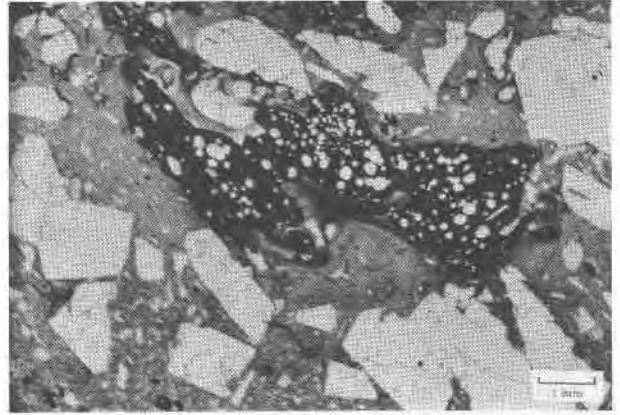


FIG. 5. Thin section of mixed zone between quartz trachyte and basalt,  $P_1$  composite flow on Gran Canaria, Canary Islands. Micropillows of basaltic glass in trachytic glass with large phenocrysts. Note vesiculation and diffusion aureole around micropillows. Specimen No. 994, courtesy of Dr. H. U. Schmincke.

5) in the quartz trachyte ash flow or ignimbrite, and each component contains phenocrysts.

Such flows are distinct (1) from "multiple" intrusions in which the inner portions chill against the outer portions, which in turn chill against the country rock, (2) from flows that have undergone in situ gravitative differentiation, and (3) from flows that have undergone gravitative differentiation in the conduit prior to eruption. The last two types of flow show no chilling effects between the components and less compositional contrast, but often have portions distinguished by the presence or absence of phenocrysts. The basalt-mugearite flows of Kennedy (1931) and the complex sill of Upton and Wadsworth (1967) appear to result primarily from a gravitative differentiation process.

6. "Emulsions" are known on a grander scale where meter-sized blobs or "pillows" of basalt with crenulate or cumulus borders are found within rhyolite. The *mixed lavas* of the Yellowstone Park region of Wyoming are familiar to most petrologists as a result of the Wilcox-Fenner debate (Fenner, 1938, 1944; Wilcox, 1944; Boyd, 1961). The mixing of contemporaneous basalt and rhyolite was considered by Hawkes (1945) to have taken place before extrusion of basalt and rhyolite and was believed by Wilcox (1944) to have occurred after extrusion of the lavas. The critical observation, first made by Wilcox, is that the basaltic magma was quenched or chilled against the rhyolitic magma, showing clearly that they were in contact as liquids. Later Wager

and Bailey (1953) suggested that pillow-like masses represent basic magma chilled against cooler but liquid acidic magma at St. Kilda, Hebrides, and at Slieve Gullion, Ireland.

7. Other intrusive forms indicative of liquid-liquid relationships include net-veined complexes and pipes (Walker and Skelhorn, 1966, p. 95). Even some large plutons in batholiths are believed to be the result of magma mixing and hybridization (Piwinski and Wyllie, 1968, p. 231).

8. Further documentation of the contemporaneity of some basaltic and rhyolitic magmas comes from the *direct observation* of eruption. The 1707 eruption of Fujiyama (Tsuya, 1955) is especially noteworthy because of its almost simultaneous production of an acid pumice ( $\text{SiO}_2 = 68\%$ ) and a basic ash ( $\text{SiO}_2 = 51\%$ ) from close but separate craters. The 1947 Hekla eruption (Thorarinsson, 1954, pp. 33, 38) initially produced a pumice with 63 percent  $\text{SiO}_2$ , *abruptly* changing to ejecta having 56 percent

$\text{SiO}_2$ , and then gradually changing to a lava with 54 percent  $\text{SiO}_2$ . This sequence of chemical changes in eruptions at Hekla appears to reoccur in a periodic way (Thorarinsson, 1954, p. 43, Fig. 7).

There can be little doubt, therefore, that two magmas of greatly contrasting composition—whether basalt (or andesite) versus rhyolite (or dacite) or alkali basalt (or hawaiiite) versus trachyte (or mugearite)—coexisted at the same locality and erupted from the same vent (or were intruded into the same dike) and at the same time. These magmas have retained their identity with a minimal amount of mechanical mixing or chemical diffusion. The key question is, "How are two magmas of such great contrast in composition generated and maintained at the same place at the same time?"

### Relative Thermal Behavior of Basaltic and Rhyolitic Magmas

The question becomes even more puzzling when the thermal properties of the magmas of contrasting composition are considered. Rhyolite and basalt will be used as examples; however, similar arguments are applicable to the alkali basalt-trachyte association.

Rhyolites are usually explosive (*e.g.*, ash, tuffs, pumice, ignimbrites), and gas, mainly  $\text{H}_2\text{O}$ , is considered to be the chief propellant. The minimum melting curve of granite in the presence of an excess of water may be used as an approximation of the lower limit of stability of a potential rhyolitic magma (Fig. 6). Similar lower limits of stability describe the behavior of trachytic and phonolitic magmas (Millhollen, 1971; Barker, 1965). In each of these cases the melting behavior is of either the minimum type or the eutectic type because the compositions of such magmas lie approximately at invariant points in their respective systems. This implies that the crystal + liquid interval between the crystalline rock and the wholly liquid magma ( $\text{H}_2\text{O}$ -saturated) is moderately small ( $<100^\circ\text{C}$ ) or negligible (Piwinski and Wyllie, 1970).

In contrast, the eruption of basalt is usually quiet. The absence of hydrous minerals, of course, does not necessarily indicate the absence of water. Andesites, which may contain hydrous minerals, often erupt explosively. The mixed welded tuffs of Costa Rica and the banded pumices of Novarupta, Katmai area, Alaska, and of Lassen Peak, California, attest to the presence of volatiles in both magmas. For these reasons the lower limit of liquid in a basalt (olivine tholeiite) in the presence of an excess of

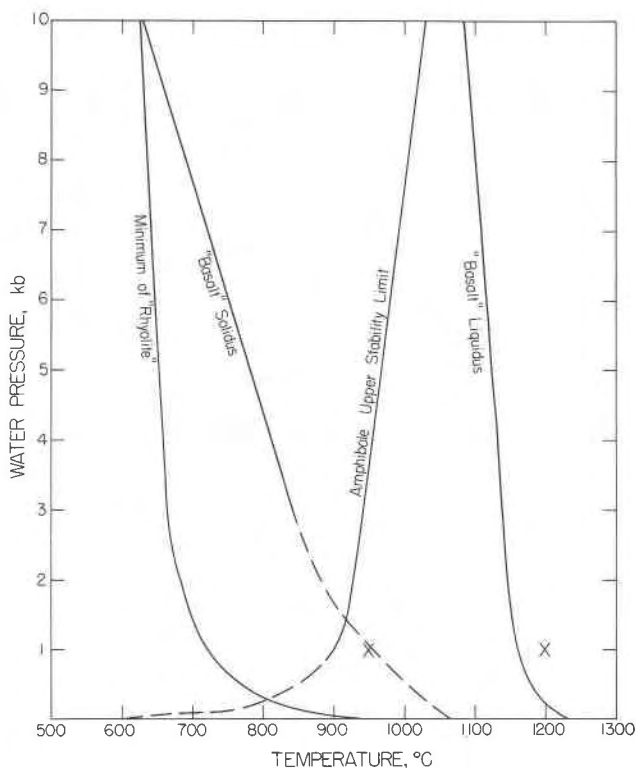


FIG. 6. Minimum melting curve of rhyolite composition (= granite of Tuttle and Bowen, 1958; Luth *et al.*, 1964) and the liquidus, solidus, and upper stability curve of amphibole for the olivine tholeiite composition (Yoder and Tilley, 1962) in the presence of excess  $\text{H}_2\text{O}$ . Conditions studied experimentally for other materials are marked with an X, above the liquidus of rhyolite and basalt, respectively.

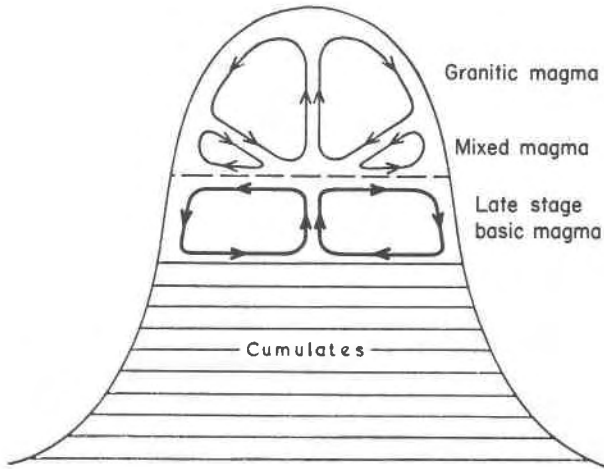


FIG. 7. Schematic representation of cupola-shaped magma reservoir produced by melting of overlying granitic layer by convecting basic magma. Mechanical mixing develops hybrid magma and fractional crystallization yields cumulates. From Wager *et al.* (1965, p. 303, Fig. 35b).

water is also given in Figure 6 along with the liquidus curve and the  $H_2O$ -saturated melting curve of the predominant hydrous phase, amphibole. The large region of crystals + liquid for basaltic compositions is evident. Quartz tholeiites, tholeiites, high-alumina basalts, and alkali basalts exhibit similar stability limits in the same pressure range (Yoder and Tilley, 1962).

It is of interest to note that if basaltic magma ( $H_2O$ -saturated) is to crystallize as basalt or gabbro and not hornblende gabbro, the water pressure cannot exceed approximately 1.5 kbar.<sup>6</sup> The dike from Cape Breton, Nova Scotia, mentioned above, contains pillow-like inclusions of hornblende gabbro in granite, suggesting that the mixing and crystallization of the magmas (assuming  $H_2O$  saturation) took place at water pressures in excess of 1.5 kbar.

The critical features illustrated in Figure 6 are that (1) under conditions where the rhyolitic magma ( $H_2O$ -saturated) is just all liquid below 1.5 kbar, that is, immediately above its liquidus, the basalt is completely crystalline; and (2) if the basaltic magma

<sup>6</sup> At water pressures less than the total pressure, basalt liquid would crystallize at total pressures higher than 1.5 kbar within certain limits of  $H_2O$  content. No attempt will be made here to include a discussion of all the many options introduced by insufficient  $H_2O$  to saturate the magma or by the presence of other gaseous components. Some of the determined effects are outlined by Holloway and Burnham (1972) and Egger (1972). Also see discussion in section below entitled "Water distribution and the role of hydrous phases."

( $H_2O$ -saturated) is just all liquid in the same pressure range, then the rhyolitic magma is superheated approximately  $250^\circ C$  at 1 atm and  $450^\circ C$  at 1 kbar  $P_{H_2O}$ . Because both natural magmas contain phenocrysts, the possibility of such excessive superheating is most unlikely. Moreover, the natural basaltic magma is commonly chilled against the rhyolitic magma, but the reverse relationship has not been recorded in localities of mixed magmas. Only rarely is the remelting or resorption of the phenocrysts in contaminated rhyolite observed (Wilcox, 1944, p. 1054). Herein lies the heart of the problem and the dilemma. The generation of the contrasting magmas at or near their own liquidus temperature imposes a serious constraint on their modes of origin.

### Previously Proposed Hypotheses

Some previously proposed solutions to the problem will now be reviewed briefly.

1. The simplest solution is obtained by invoking two separate chambers or reservoirs, one containing rhyolitic magma and the other basaltic magma at their respective liquidus temperatures, perhaps at different depths. An earthquake may provide horse-tail cracks that vent both chambers and lead to a common vent. This fortuitous arrangement must be repeated worldwide, and the solution ignores the question of how the two magmas arose in the first place.

2. Another solution to the problem was suggested by Holmes (1931), whereby a basaltic magma invades a region of granitic composition. The basaltic magma, through convective heat transfer, melts a portion of the granitic region, forming a cupola at the upper region of contact. Fractures may occur that tap either layer of magma—the layers being maintained by gravity and separate convective systems—and feed into a common conduit. A single fracture venting the cupola would yield first a rhyolitic flow, followed by a basaltic flow.

The suggestion of Holmes was embellished by Wager *et al.* (1965) with the addition of a mixed zone, or hybridized region, between the two convecting cells and a cumulate zone at the base of the invading basaltic member (Fig. 7). Schmincke (1969) appealed to a similar arrangement to explain the composite flows of soda rhyolite and basalt of Gran Canaria; however, he reversed the convective circulation in the soda-rhyolitic magma chamber.

Blake *et al.* (1965) proposed a related mech-

anism whereby the granitic layer is remelted by the passage of basalt through a fracture (Fig. 8a). The mobilized granitic magma chokes off the flow of basaltic magma (Fig. 8b) and uses the molten center of the basaltic dike as an easy access route to the surface (Fig. 8c). The interrupted flow of basaltic magma piles up as pillows or forms a net-veined complex in which pillows predominate.

These suggestions of Holmes, Wager and coworkers, Schmincke, and Blake and coworkers depend on a rather unusual crust or upper mantle in oceanic volcanic areas.

3. Another simple solution is a chamber with two immiscible liquids. Of necessity the liquids at equilibrium would have to be at the same temperature, at least along the interface. Both magmas could contain phenocrysts; however, the thermal and chemical properties of such a conjugate rhyolitic magma would be most unusual compared with those of known rhyolitic magmas. The principle may be illustrated by the simple systems  $\text{FeO-SiO}_2$  (Bowen and Schairer, 1932, p. 200, Fig. 4) and  $\text{K}_2\text{O-FeO-Al}_2\text{O}_3\text{-SiO}_2$  (Roedder, 1951, p. 283, Fig. 1). In the latter system two immiscible liquids in equilibrium with tridymite terminate in a conjugate line at  $1140^\circ\text{C}$ ; a separated "basic" liquid would crystallize completely at one eutectic, and the isolated "acidic" liquid would undergo reaction and with fractionation proceed to another eutectic at a lower temperature ( $<990^\circ\text{C}$ ). The final separate products would have different liquidus temperatures on remelting. Roedder (1956) emphasized the dependence of immiscibility on special compositions and noted that this property of liquids is suppressed in complex systems.

Nevertheless, two glasses of unusual composition have been identified in the residua of some lunar rocks. Roedder and Weiblen (1971) described co-existing glass globules as evidence of immiscibility in the residual liquid. The normative compositions are approximately those of potassic granite and iron-rich pyroxenite (*op. cit.*, p. 519). They reported similar observations in the residua of six terrestrial basalts, and in one example the crystal content is about 56 percent. The late-stage nature of the immiscibility deduced from the normative compositions of glasses and crystal content, therefore, precludes the simple application of this process to the generation of early-stage basalt and rhyolite.

The data available on hydrous systems with distinguishable liquid and gas phases indicate that the relative volume relations of these two phases are

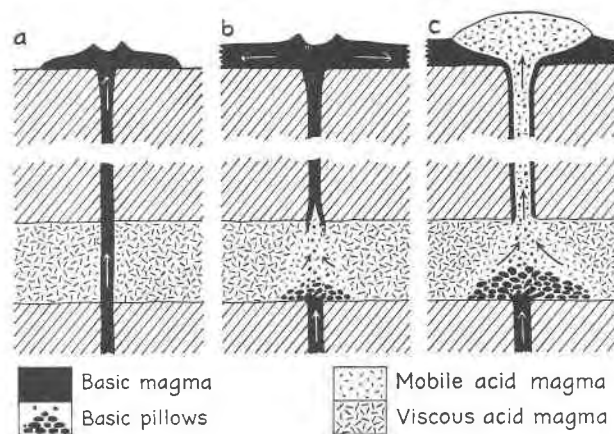


FIG. 8. Schematic representation of the evolution of a basic magma passing through a preexisting crystalline granitic layer (a), mobilizing the granite which terminates the flow of basic magma (b), and the granitic magma then eviscerates the basic magma in the dike producing a composite dike and flow (c). The interrupted flow of basic magma forms pillows in a net-veined complex. From Blake *et al.* (1965, p. 4, Fig. 2) with permission of the authors and the Geological Society of London.

inadequate to provide separate magmas from a homogeneous fluid phase.

Fenner (1948, p. 500) appealed to immiscibility at the mixed magma localities of Katmai, Alaska, and Gardiner River, Wyoming, and suggested that the intermediate magmas were produced by the assimilation of the basaltic magma by the rhyolitic magma. He believed that the assimilation was effected by exothermic gas reactions. One may recall Bowen's (1922) argument that rhyolite can assimilate basalt exothermically dry, but by reacting and freezing liquid, not by generating more liquid. Similar arguments hold when water is involved, except that the accompanying release of  $\text{H}_2\text{O}$  may be an endothermic process (see Khitarov *et al.*, 1963). The net heat balance has not as yet been ascertained for a specific case; however, the writer believes that exothermic gas reactions, if any, are inadequate for generating more magma.

No doubt there are more complex schemes for producing two liquids. However, most suggestions, excepting that involving immiscibility, presuppose the existence of the two contrasting compositions. Preliminary data have led to the consideration of a new hypothesis for the production of contemporaneous rhyolite and basalt liquids, and these data will now be presented.

## Exploratory Experiments

Some exploratory experiments were carried out to ascertain the behavior of rhyolite and basalt under the liquidus conditions most likely to obtain for each. The intent was to obtain some notion as to the relevant physicochemical parameters and to test the miscibility of basalt and rhyolite.

### Experimental Conditions

All experiments were performed at  $P_{H_2O} = 1$  kbar and at temperatures of 950°C for 2 hours and 1200°C for 1 hour to avoid the formation of amphibole, as indicated in Figure 6. One set of conditions was chosen to be above the liquidus of rhyolite and below the solidus of basalt, and the other set of conditions, above the liquidus temperatures of both rock types. Two physical arrangements of the specimens were tested at each of the two sets of conditions. One arrangement consisted of equal proportions by weight of the powders of contrasting compositions, which were intimately ground together for 1 hour and placed in a platinum tube with  $H_2O$  in excess of that required to saturate the liquid. The second arrangement consisted of cylinders of the rock or glass, or of the two powders of contrasting composition, packed end-to-end in a platinum tube with excess  $H_2O$ . The tubes lay horizontal in the furnace under pressure with the interface of end-to-end specimens vertical. Thermal quenching was accomplished in the internally heated, gas-media pressure apparatus (Yoder, 1950) in less than 30 seconds at constant pressure.

### Materials

Natural materials were chosen because of their close relationship in the field or because of their special chemical or physical properties even though unrelated in the field. The samples used were unadulterated except for the addition of water, a constituent known to be present in the analyzed materials.

#### I. Field-related materials used.

*Craignurite, Mull:* Composite cone sheet (Skelhorn *et al.*, 1969).

A. Craignurite ( $SiO_2 = 71.80\%$ ). Analysis given by Skel-

horn (1962, p. 139). Central acid component "closely allied to granophyre."

B. Dolerite ( $SiO_2 = 48.25\%$ ). Complete analysis made (R. R. Skelhorn, unpublished data, 1970). Lower basic member.

*Scallastle Bay, Mull:* Composite cone sheet (Skelhorn *et al.*, 1969; see Fig. 10).

A. Craignurite ( $SiO_2 = 71.50\%$ ). Complete analysis made (R. R. Skelhorn, unpublished data, 1970). Central acid member.

B. Dolerite ( $SiO_2 = 49.85\%$ ). Complete analysis made (R. R. Skelhorn, unpublished data, 1970). Lower basic margin.

*Breiddalur, Iceland:* Tuff-lava "emulsion" (Walker, 1963; Blake *et al.*, 1965, p. 33; see Fig. 3), No. 05368.

A. Colorless acid glass ( $SiO_2 = 73.05\%$ ). Partial electron microprobe analysis given in Table 1.

B. Black basic glass ( $SiO_2 = 52.40\%$ ). Partial electron microprobe analysis given in Table 1.

*Novarupta, Katmai area, Alaska:* Banded pumice (Curtis, 1968; see Fig. 2), Specimen No. 54 ACU 36.

A. Rhyolite, unanalyzed.

B. Andesite, unanalyzed.

*Socorro Island, Mexico:* Oxidized hawaiite-pantellerite association (Bryan, 1970).

A. Pantellerite ( $SiO_2 = 68.91\%$ ; Bryan, 1970, p. 199, Table 13, No. 1, S138).

B. Oxidized hawaiite ( $SiO_2 = 46.96\%$ ; Bryan, 1970, p. 195, Table 10, No. 2, S141).

*Pantelleria Island, Italy:* Titaniferous basalt-pantellerite association (Zies, 1960, 1962).

A. Hyalopantellerite ( $SiO_2 = 69.56\%$ ; Zies, 1960, p. 307, Table 1, PRC 2007).

B. Titaniferous basalt ( $SiO_2 = 46.31\%$ ; Zies, 1962, p. 178, Table 1, PRC 2006).

*Gran Canaria Island, Spain:* Composite flow  $P_1$  (Schmincke, 1967, 1968, 1969).

A. Quartz trachyte. No. 979; upper half of lower member of flow ( $SiO_2 = 67.5\%$ ).

B. Oxidized basalt. No. 983; "least contaminated sample" of upper member ( $SiO_2 = 49.5\%$ ).

#### II. Materials not field-related but with special properties.

*Analytical reference samples:* (Fairbairn *et al.*, 1951).

A. Granite, Westerly, R.I. U. S. Geological Survey Standard Sample G-1 (consensus mean  $SiO_2 = 72.45\%$ ).

B. Diabase, Centerville, Va. U.S.G.S. Standard Sample W-1 (consensus mean  $SiO_2 = 52.50\%$ ).

*Glass cylinders and powder:*

A. Rhyolitic obsidian, Lake Naivasha, Kenya (Bowen, 1935, p. 493, Table 1, No. 1). ( $SiO_2 = 75.55\%$ ).

B. Basaltic tachylite, Kilauea, Hawaii (Adams and Gibson, 1926, p. 276). ( $SiO_2 \approx 49.7\%$ ).

## Results

Because of the similarity of results, only the response to the conditions applied to four pairs of samples will be described in detail on this occasion. The exploratory nature of the experiments is obvious; however, the behavior of the samples is clear

TABLE 1. Electron Microprobe Analyses of Clear and Black Glass in Tuff-Lava Emulsion Rock, Breiddalur, Iceland\*

	Clear Glass	Black Glass
$SiO_2$	73.05	52.40
$TiO_2$	0.19	1.62
$Al_2O_3$	11.23	16.10
"FeO"***	1.30	9.27
MgO	0.18	6.14
CaO	0.61	9.04
$Na_2O$	3.90	3.77
$K_2O$	3.78	0.54
	94.24	98.86

\* From Walker (1963) and Blake *et al.* (1965), p. 33. Average of three areas each: 45  $\mu m$  beam, 0.02  $\mu A$ .

\*\* Total Fe converted to FeO.



and the directions for further systematic research are indicated. The results for the pair of analytical reference samples will be described first.

### I. Mixtures of the analytical reference samples.

Equal proportions by weight of the G-1 granite and W-1 diabase were ground together for 1 hour and placed in a platinum tube with  $H_2O$  in excess of that required for saturating the liquid. After hydrothermal treatment at  $1200^\circ C$  for 1 hour a homogeneous brown glass was obtained. There was no optical evidence (resolution no greater than  $1 \mu m$ ) of immiscibility under these conditions. There is need, however, to examine the glass quenched from liquids formed at temperatures greater than  $1200^\circ C$  to ascertain whether a possible immiscibility loop exists and is closed before reaching the liquidus. Although similar results were obtained in the absence of water by Ginsberg and Nikogosyan (1924), who heated mixtures of granite and iron-rich diabase at  $1400^\circ C$ , an electron microscope search for incipient globule formation such as that observed by Ohlberg *et al.* (1962) would be desirable, even though opalescence was not observed.

In another hydrothermal run at  $950^\circ C$  for 2 hours the products from a mixture of the analytical reference samples were clinopyroxene, plagioclase, opaques, and a glass of relatively uniform index of refraction. It was evident that with intimate mixing intermediate compositions could be obtained. Hybridization under these conditions and for these materials is, therefore, a demonstrable process if mechanical mixing is adequate.

In another set of experiments powdered G-1 granite and powdered W-1 diabase and  $H_2O$  were packed in a platinum tube so that the separate but equal proportions by weight of the powders lay end-to-end with a single common interface. After hydrothermal treatment at  $1200^\circ C$  and 1 hour the products consisted of a colorless glass in the position of the granite and a dark brown glass in the position of the diabase, the two being separated by an exceedingly sharp cusped interface convex toward the granitic glass. A photograph of the undisturbed charge after the platinum container has been peeled back is given in Figure 9A. Figure 9B shows the basalt-rhyolite contact of the Ornálfjall composite flow in eastern Iceland as photographed from a polished hand specimen by Gibson and Walker (1963) and reproduced with their kind permission. The photograph of the charge in Figure 9A was rotated  $90^\circ$  for comparison

with the basalt-rhyolite contact as observed in the field. The similarity of the cusped, crenulate interface as well as its sharpness is readily discerned. Based on the sharp contact observed optically and its assumed correlation with compositional contrast, the diffusion is *apparently* slow even when the gra-

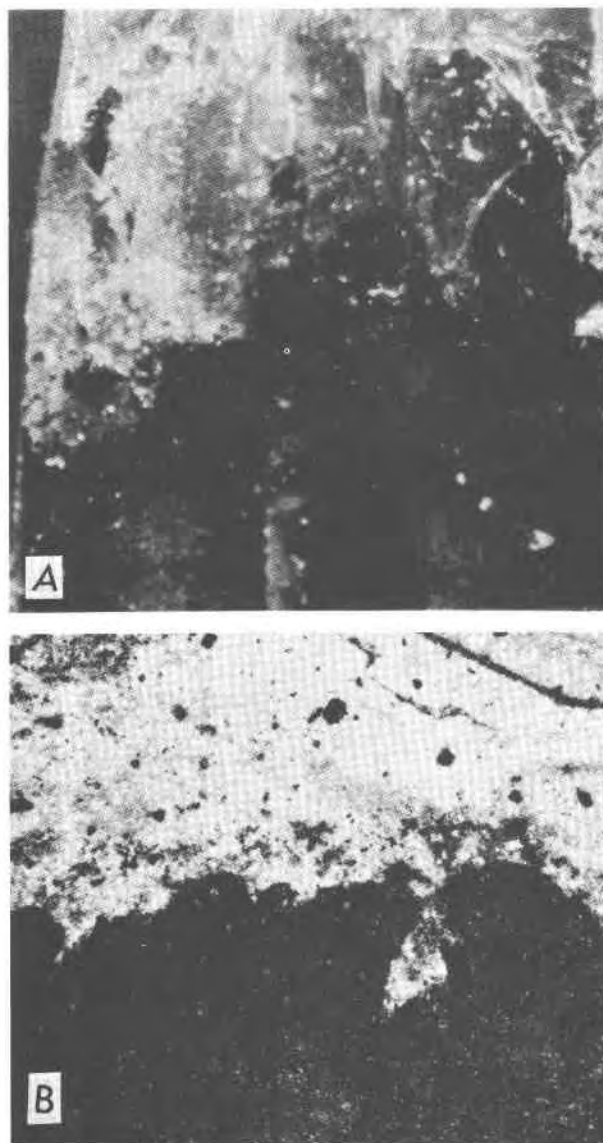


FIG. 9. (A) Photograph of products resulting from the hydrothermal treatment of G-1 granite (top) and W-1 diabase (bottom) at  $1200^\circ C$  for 1 hour at  $P_{H_2O} = 1$  kbar. Turned  $90^\circ$  from run position for comparison below. Width = 3 mm. (B) Photograph of rhyolite (top)-basalt (bottom) contact of the Ornálfjall composite flow in eastern Iceland reproduced from Gibson and Walker (1963, after p. 315, Plate 8A) with permission of the authors and Benham and Co., Ltd. Width = 5 cm.

nitic magma is highly superheated and  $H_2O$ -saturated. It is concluded that liquids of greatly contrasting composition, even when saturated with  $H_2O$ , can be maintained in contact at least for a limited amount of time. Additional observations on this point will be presented below.

Interpretation of the cusped interface is especially intriguing. The initial temptation is to conclude that the hydrous diabase liquid is more viscous than the hydrous granitic liquid.<sup>7</sup> One, however, would draw the opposite conclusion if the cusps are traces of the surface of convective cells. On the other hand, the interface possibly records the sequence of quenching, diabasic liquid quenching to a glass ( $\sim 10^{13}$  poises) before the granitic liquid, thereby recording relative viscosities at different temperatures and not those

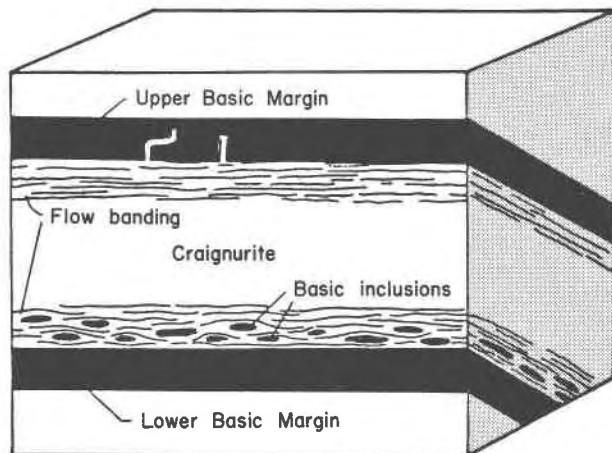


FIG. 10. Diagrammatic section of composite intrusion at Altcrich Cottage, Scallastle Bay, Mull, illustrating relationship of craignurite to basic margins of dolerite. From Skelhorn *et al.* (1969, p. 33, Fig. 12A) with permission of the authors and Benham and Co., Ltd.

<sup>7</sup> The conclusion is drawn intuitively from the interfacial tension where the pressure on the concave side is greater than that on the convex side. Viscosity usually increases with pressure; therefore, the viscosity, discounting important compositional effects, is presumed to be greater on the concave side of the interface. To the best of the writer's knowledge, there is no known *direct* relationship between interfacial tension and viscosity. A comparison of viscosity data obtained on rhyolitic liquids with 4.3–6.2 percent  $H_2O$  extrapolated to  $1200^\circ C$  (Shaw, 1963, 1972) with that measured on anhydrous basalts at the same temperature (Murase and McBirney, 1970) suggests the viscosities may be about the same. If those basaltic liquids were hydrous, the viscosity would probably be less than that of the hydrous rhyolitic liquids—a conclusion opposite to that drawn from the interfacial tension argument.

prevailing at  $1200^\circ C$ . Dr. S. Bhattacharji (personal communication, 1972) suggested that the cusps are related to differential volumetric thermal expansion due to volatiles. The cusped interface is indeed a phenomenon worthy of detailed theoretical analysis.

Samples similarly packed and held at  $950^\circ C$  for 2 hours yielded a colorless glass in the position of the granite and a recrystallized hard cake in the position of the diabase. The interface was sharp, though some of the granitic liquid had flowed around the end of the basaltic cake. Based solely on the lack of coloration of the granitic glass, no reaction appeared to take place during the short time of the run.

Further experiments were conducted at the same temperatures and time periods using powdered obsidian from Lake Naivasha and powdered tachylite from Kilauea mixed intimately and packed in a platinum tube with excess  $H_2O$ . In addition, cylinders of the two natural glasses were cut and placed end-to-end in the platinum tube with excess  $H_2O$ . The results for both physical conditions were comparable to those obtained from the G-1 granite and W-1 diabase. An experiment analogous to that with the cylinders of glass at  $1200^\circ C$  was performed under anhydrous conditions by Bowen (1921). He heated a crucible containing a layer of plagioclase glass over a layer of diopside glass at about  $1500^\circ C$  for periods of 17 to 48 hours and measured the extent of diffusion by the changes of index of refraction from top to bottom of the resulting partially homogenized glass. The extensive diffusion observed by Bowen is not directly comparable to the results of short runs at lower temperatures using obsidian and tachylite cylinders.

## II. Mixtures of field-related materials.

The experiments described above involve materials unrelated in the field, and experiments on materials that are intimately related in the field will now be described. A well documented pair of samples was kindly provided by Dr. R. R. Skelhorn from the Craignurite composite intrusion of Mull (*cf.* Fig. 10). The most interesting results of the experiments run at the two temperatures and two physical arrays were those from the powders packed end-to-end at  $P_{H_2O} = 1$  kbar and  $1200^\circ C$ . One cusp of the cusped interface between the resulting glasses is shown in polished section (Fig. 11). The gray portion at the bottom of the figure is basaltic (dolerite) glass and the black portion, containing highlights from vesicles and inclusions, is the rhyolitic (craignurite) glass. The rhyolitic glass is conspicuously free of vesicles and

inclusions near the interface. The basaltic glass (gray) has a bright border of 20  $\mu\text{m}$  and then a broad band of darker material about 150  $\mu\text{m}$  wide. A continuous compositional profile at an angle to the trace of the interface (vertical line in Fig. 11), in a plane essentially normal to the interface, was obtained by electron microprobe. The horizontal portions of the curve (Fig. 12) extending to the edge of the figure were assigned the values obtained by wet chemical analysis, and the electron microprobe results were scaled linearly to these oxide values. The change in index of refraction of the two glasses suggests, however, that some hybridization had already been achieved.

Attention is called to the slight but obvious rise in values for  $\text{TiO}_2$ ,  $\text{MgO}$ ,  $\text{CaO}$ , and "FeO" (total Fe reported as FeO) above the initial amount in the basalt some 100–150  $\mu\text{m}$  from the observed interface. A similar rise appears to take place for  $\text{K}_2\text{O}$  in the rhyolitic glass. However, inclusions may ac-

count for this deviation as well as the large drop in  $\text{K}_2\text{O}$  content at about 400  $\mu\text{m}$  on the arbitrary scale.

It is now realized that what appeared to be a sharp contact on visual inspection is in fact a diffusion zone involving at least 300  $\mu\text{m}$ , although most of the compositional changes take place within 60  $\mu\text{m}$ . (The electron beam, as adjusted, averages over a 5- $\mu\text{m}$  region.) The concentration gradients were most likely due to diffusion in the liquid; however, other mechanisms, such as vapor transport, might have been operative. The general similarity of the concentration gradients for each element measured indicates the great influence of element interactions. The concentration gradients appear to be consistent with the concept that multicomponent diffusion operates to maintain constant volume and to preserve local electrical charge neutrality. These factors are presumed to be accommodated by the diffusion of units of structure in the liquid related to species or subspecies of minerals.<sup>8</sup> The asymmetry of the gradients relative to the optical interface suggests that the rate of diffusion is greater in the basalt than in the rhyolite. When time dependence and accurate compositions are obtained, it will be possible to determine the effective diffusion coefficients. Experiments evaluating the diffusion characteristics of these contrasting liquids at higher pressures, particularly where basalt and rhyolite are themselves no longer stable assemblages, would also be of interest.

For glass in other fragments exhibiting the same type of interface, partial electron microprobe analysis at some distance from the interface indicated some

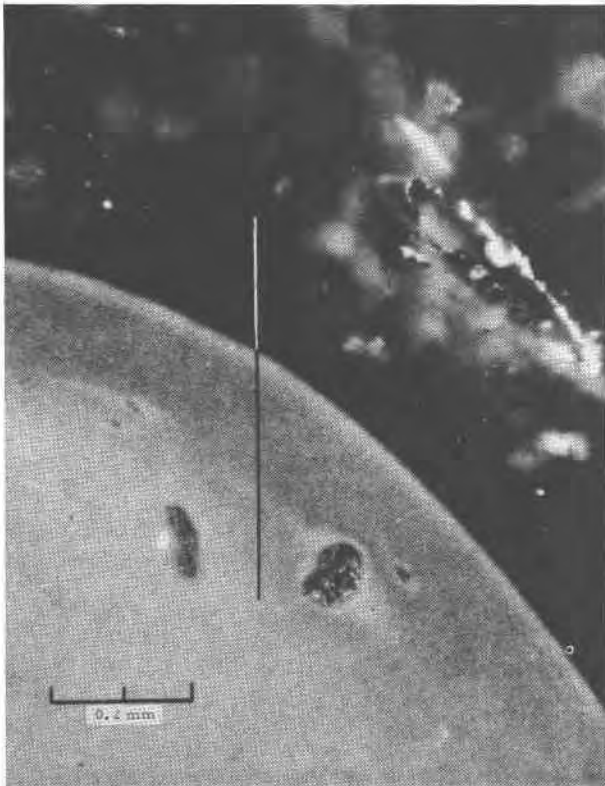


FIG. 11. Polished section of part of the interface formed between melts of basalt (bottom, gray) and rhyolite (top, black) from the Caignure, Mull, composite intrusion. Vertical line marks the approximate position of the electron microprobe traverse (see Fig. 12). Conditions of the experiment were 1200°C and 1 hour at  $P_{\text{H}_2\text{O}} = 1$  kbar, with powdered samples of each rock type placed end-to-end in a platinum tube.

<sup>8</sup> The units of structure in the liquid no doubt change with temperature. It is common practice at the Geophysical Laboratory to "acclimate" a glass prior to crystallization by quenching liquids from successively lower temperatures with intermediate crushing of the glass. After such treatment, crystallization below the liquidus takes place rapidly, usually without intermediate precursors. Crystallization of a glass formed by quenching a liquid from the high temperatures required to achieve solution of the constituents and homogenization usually yields few crystals or metastable phases. Relatively abrupt changes in viscosity of silicate liquids with temperature are also known, and the structure of the liquid is assumed to have changed accordingly. Diffusion rates of the structurally related elements would be expected to change as well. Additional support for the view that the multicomponent diffusion is structurally related is found in the vapor transport experiments of Morey and Hesselgesser (1951). They found that components were transported in the vapor for the most part in the proportions of known mineral species. A structural study of silicate liquids as a function of temperature would be of considerable interest.

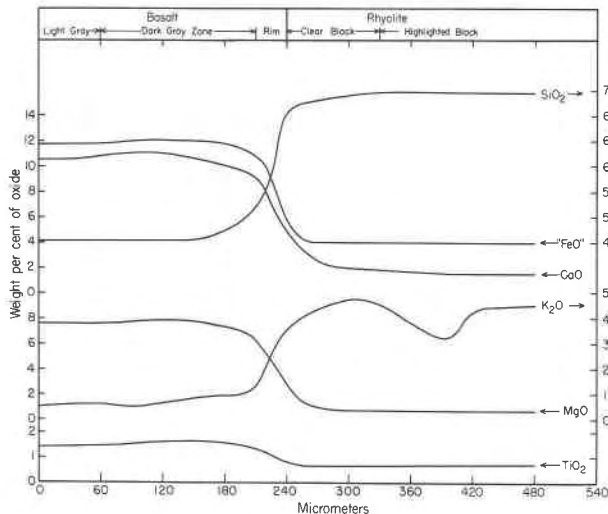


FIG. 12. Schematic presentation of compositional changes across the melted basalt-rhyolite interface near the path shown in Figure 11. Oxide changes calculated from electron microprobe traverses are correlated with optical observations. Origin of micrometric scale is arbitrarily chosen.

heterogeneity or hybridization. In general, the analyses of the elements measured lay on or near straight lines on a  $\text{SiO}_2$ -variation diagram, with the exception of  $\text{Al}_2\text{O}_3$ , which is higher than expected, and  $\text{K}_2\text{O}$ , which is lower than expected, from a straight-line extrapolation. The lack of discoloration of the rhyolitic glass may, in fact, be deceiving. It is suspected that transfer of material takes place through the interface (not necessarily the original contact of the two materials) and that the optical demarcation becomes diffuse only after much of the compositional contrast has been reduced. It is also possible that iron in one electronic state (*i.e.*,  $\text{Fe}^{3+}$ ) is diffused preferentially into rhyolitic liquid and no discoloration is produced (*cf.* Fig. 5). Mössbauer studies of the glasses would, no doubt, resolve that issue.

Of considerable interest was the distribution of  $\text{H}_2\text{O}$  between the two liquids. An attempt was made to map the  $\text{H}^+$  with an ion probe. Qualitatively the rhyolitic glass contained more  $\text{H}^+$  than the basaltic glass. However, dewatering of the glasses along cracks after quenching was evident, giving rise to highly variable distributions.

The interface of a natural "emulsion" of basaltic and rhyolitic glass was studied for comparison. The specimen from Breiddalur, Iceland (courtesy of Dr. G. P. L. Walker), is illustrated in thin section in Figure 3. The bulk composition of each glass phase was obtained by electron microprobe (Table 1) by

averaging several points measured with a broad beam ( $45 \mu\text{m}$ ) and low current ( $0.02 \mu\text{A}$ ). The sharpness of the interface was determined by traversing for the elements Ti, Fe, and Si simultaneously with a  $5\text{-}\mu\text{m}$  beam and was equal to or less than the beam diameter. The remarkable sharpness of the interface, even without correcting for possible edge effects in the electron microprobe analysis, signifies that unique conditions existed under which the liquids were unable to diffuse or mix. These conditions cannot be defined; however, they might include (1) immiscibility, (2) short time in contact, and (3) high viscosity occasioned by volatile loss. Immiscibility is not likely because the powders of each glass phase, with phenocrysts removed, interdiffused and became homogeneous when mixed and held at  $1200^\circ\text{C}$  for 1 hour under  $P_{\text{H}_2\text{O}} = 1$  kbar. If the time of contact was short, the mixing presumably took place immediately before eruption and the quench closely followed. The electron microprobe analyses have low totals, and it is presumed that most of the missing material is  $\text{H}_2\text{O}$ . Some  $\text{H}_2\text{O}$  would have been lost during the eruption; on the other hand, in view of the absence of vesicles,  $\text{H}_2\text{O}$  may have been gained after quenching.<sup>9</sup> It is considered unlikely, therefore, that the coexistence of the two glasses of contrasting composition can be attributed solely to high viscosity attending loss of volatiles.

It may be concluded from the experiments using pairs of natural materials, related and unrelated in the field, and from the published field interpretations that the identity of two contiguous magmas of divergent composition may be maintained for at least a limited amount of time.

### Tentative Hypothesis

It is of interest to inquire whether such contiguous magmas of contrasting composition can actually be generated from the same parent without intermediate members rather than from separate independent sources. The mechanism to be presented stems from the belief that the heterogeneity of the mantle may

<sup>9</sup> The  $\text{Sr}^{87}/\text{Sr}^{90}$  of Breiddalur basalt ( $0.7089 \pm 0.0010$ ) is anomalous and about that of sea water (Moorbath and Walker, 1965). Isotopic exchange with sea water may have accompanied the absorption of water.

The identification of juvenile water and determination of the extent of mixing with meteoritic water are formidable tasks still facing the geochemist. Geothermal systems investigated with present methods indicate little or no magmatic component. In addition, primary hydrous minerals of igneous rocks may have exchanged their OH with ground-water.

be large with respect to the amounts of phases; however, as long as the kinds of phases do not change within a mantle province, the liquids produced by fractional melting will be relatively uniform in composition (see Yoder and Tilley, 1962, p. 518). The uniformity of magma types produced around the world results primarily from the singularity of the physicochemical "invariant" conditions that determine the composition of the first liquids in such heterogeneous systems. The great floods of basalt clearly require some physicochemical control to account for their uniformity. The close relationship of major rock types with the assemblage of phases at the invariant points in a pertinent five-component system was considered strong support for this concept by Schairer and Yoder (1964, pp. 70–74). For these reasons a dominant role is assigned to fractional fusion in the generation of magmas of contrasting composition. A careful geometrical analysis of fractional fusion has been made by Presnall (1969), and some of the principles outlined by him are applied here.

The data of Kushiro (1969) on the diopside-forsterite-silica system at  $P_{H_2O} = 20$  kbar serve as a suitable example to illustrate a possible mechanism for the generation of both magmas from a common parent. The pressure of 20 kbar may be slightly excessive relative to the depths of origin presumed for such magmas; however, the principles involved are informative, and the relations in the simple system will not change drastically at somewhat lower pressures. Consider a parental material of quartz-normative composition analogous to  $X$  in Figure 13. If the temperature is raised to  $960^\circ\text{C}$ , melting of composition  $X$  in the presence of excess  $H_2O$  begins and yields an initial liquid of the composition at point  $A$  in Figure 13. Removal of that initial melt as soon as it is formed causes the bulk composition of the parent to move away from the liquid composition. Continuous isothermal removal of liquid of the composition  $A$  eventually causes the bulk composition to move to  $C$ . Alternatively, the liquid may be left in equilibrium with the parental material and removed after all possible liquid is produced at  $960^\circ\text{C}$ . The residual crystals would also have the bulk composition of  $C$ . In either event the critical observation is that the bulk composition of the remaining parental material has changed to a point on the  $Di$ - $En$  join. Here the phase quartz of the parental material is exhausted, and melting ceases after about 20 percent of siliceous liquid has been removed from the original bulk composition. The liquid, occupying a larger volume,

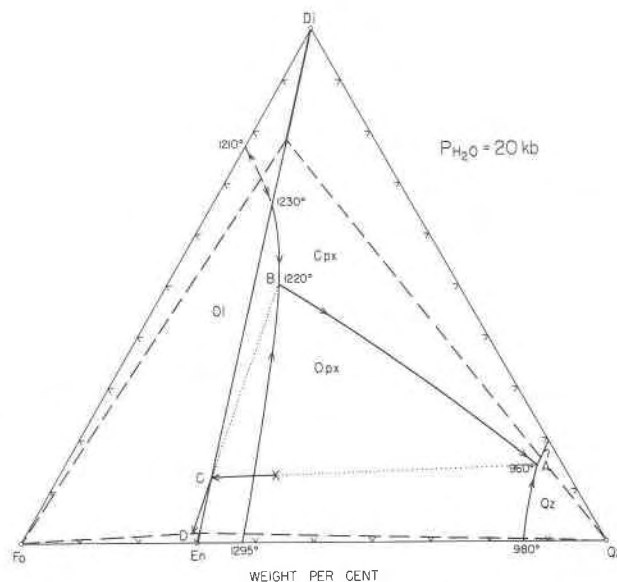


FIG. 13. The diopside-forsterite-silica system at  $P_{H_2O} = 20$  kbar (Kushiro, 1969). The  $X$  marks an assumed parental composition, and the arrows from it indicate the change of its composition resulting from continuous removal of liquids  $A$  and  $B$  with heating. The dotted lines are construction lines. Dashed lines indicate limits of three-phase assemblages stable immediately below invariant point temperatures of  $A$  and  $B$ .  $Di$ , diopside;  $Cpx$ , clinopyroxene;  $En$ , enstatite;  $Opx$ , orthopyroxene;  $Fo$ , forsterite;  $Ol$ , olivine;  $Qz$ , quartz.

may migrate up a fracture away from the site of generation or find a suitable reservoir.

Before the resumption of melting of the remaining parental material, which now has the composition  $C$ , it is necessary to raise the temperature to  $1220^\circ\text{C}$  (point  $B$  in Fig. 13). Continuous removal of liquid  $B$  in a similar way drives the bulk composition of the remaining parental material toward  $D$ , where depletion of another major phase, diopside solid solution ( $Cpx$ ), occurs. About 22 percent of parental material with the composition  $C$  has been removed from the parental material as basic liquid having the composition  $B$ . The basic liquid  $B$  may follow up the fracture behind the siliceous liquid  $A$ , occupy the same reservoir as the siliceous liquid  $A$ , or seek a separate reservoir. Further melting of the residual parental material  $D$  produces a series of liquids along the olivine-orthopyroxene boundary curve until the temperature of  $1295^\circ\text{C}$  is reached on the  $En$ - $Qz$  join.

In brief, two homogeneous liquids have been removed from a common parent without the production of liquids of intermediate composition. The analogy of rhyolitic magma to liquid  $A$  and andesite to liquid

*B* is evident and has already been drawn by Yoder (1969).<sup>10</sup> The parental residuum *D* can be described as a pyroxenite or saxonite.

Some of the critical aspects of this hypothesis require examination with regard to (1) volume of parental material involved, (2) heat requirements, (3) time involved, (4) extraction and storage of magmas, (5) water distribution and role of hydrous phases, (6) trace element partition and isotopes, (7) hybridization potential, (8) eruptive sequence, and (9) normative character of parental material.

1. *Volume of parental material involved.* A single eruptive event rarely exceeds 2 km<sup>3</sup> in volume. On the basis of the simple system described and the choice of bulk composition, the fractional melting process need involve only 10 km<sup>3</sup>, for example. Volumes of an order of magnitude larger would probably be required if the parental material is peridotite. The small volume of residual parental material, eventually reduced to pyroxenite or saxonite, could not contribute significantly to the production of rhyolite or basalt. Small volumes of parental material would be readily accommodated in cyclical processes involving conduction of heat, diffusion of volatiles, or mechanical transport.

2. *Heat requirements.* The ever-present problem of providing essentially a local source of heat for production of successive small batches of magma can possibly be resolved by successive adiabatic decompressions of relatively flat plates (Yoder, 1952, pp. 370–373). Alternatively, a convective cycle may carry new parental material within range of a fixed hot spot. Based on present-day earth plate motions (1 to 10 cm per year), the rate of supply may, however, be too slow, depending on the geometry of

the block of parental material relative to the isotherms, to meet the requirements of observed eruptive cycles. D. K. Bailey (in Newall and Rast, 1970, pp. 177–186) suggested that melting is effected by heat focusing and fluxing by volatiles in zones of lower pressure or tension.

3. *Time involved.* The time required for raising the temperature between the respective liquidus temperatures of the associated magmas and supplying the latent heat of melting would probably exceed several thousand years.<sup>11</sup> The temperature interval between the liquidus temperatures at relevant depths may be much greater than that in the simple system, depending on the water content of the parental material. The time required to achieve the liquidus temperature of the basic melt is, however, not particularly relevant because the hybridization process would not become significant until the basic magma began to evolve and the magmas were brought into contact. The Daly gap is not, in fact, time dependent. The time interval does become important in the composite intrusions and extrusions because of the storage problem discussed immediately below.

4. *Extraction and storage of magmas.* The difficulty of removal of small amounts of magma continuously from parental material has been of considerable concern to many igneous petrologists. The removal of the residual liquid from monomineralic cumulates in layered intrusions as well as in the crucible would indicate that the process is not only possible but efficient. In any case, the batch removal of the first-stage liquid, in part or in its entirety, an alternative already mentioned above, would alleviate the problem. Brace *et al.* (1968, p. 21) indicate in their experiments on the onset of melting of granite under an effective confining pressure that a few percent melting is sufficient to form interconnecting passageways between grain boundaries. Movement of the liquid no doubt takes place in response to thermal expansion on melting, density difference, compressional stresses, and the pressure drop accompanying fracture.

Storage of the generated magmas for frequent eruptive cycles introduces other problems. The H<sub>2</sub>O-saturated siliceous liquid has essentially a minimum-like or eutectic-like behavior. Generally the melting

<sup>10</sup> The formation of "rhyolite" at eutectic *A* in the synthetic system is compatible with the known thermal behavior of natural rhyolite; however, the formation of "andesite" at reaction point *B* may not at first glance appear to be compatible with the thermal behavior of natural andesite in the presence of excess H<sub>2</sub>O. This apparent anomaly is readily explained by considering the *crystallization* of liquid *B*. The course of crystallization follows the Opx-Cpx boundary curve, and final crystallization occurs at the eutectic *A*. The large temperature range of *crystallization* of "andesite" *B* is in accord with that observed in natural andesites in the laboratory and in the field. On the basis of this simple system, the temperature of the beginning of melting of "rhyolite" and its associated "andesite" should be the same. A comparison of the hydrous melting curves of unrelated granite and basalt (Yoder and Tilley, 1962, p. 463, Fig. 33) suggests that this relationship is closely approached at high water pressures.

<sup>11</sup> An exact calculation of the time required is not possible because of the many variables involved. Some of the parameters are discussed by Jaeger (1964), and estimates may be made for specific geometries of parental material having assigned thermal properties.

and crystallization interval may be of the order of 30°-100°C in natural siliceous systems, depending on the composition (see Piwinskii and Wyllie, 1970). Thus, cooling, of necessity, must be limited to prevent freezing in the conduit. Although the time interval required for the parental residua to reach the liquidus of the basaltic or andesitic magma is relatively small, a small drop in temperature below the liquidus of the separated siliceous liquid would produce a large amount of crystallization.<sup>12</sup> On the other hand, the cooling problem is not critical in the associated basaltic or andesitic liquid (e.g., liquid *B*, Fig. 13) because of the large temperature interval between liquidus and solidus (Yoder and Tilley, 1962). Heat transfer from the basaltic magma may maintain the thermal state of the siliceous magma, as suggested by Holmes (1931), but not without thermal effects on the basaltic magma.

5. *Water distribution and the role of hydrous phases.* Variations imposed by the H<sub>2</sub>O content and its initial disposition (free phase or in hydrous minerals) are manifold. It is perhaps useful to record one set of conditions as a basis for discussion. It is assumed that water is not a free phase in the mantle but is contained in a common hydrous mineral (e.g., phlogopite) present in rocks believed to come from the mantle (see Yoder and Kushiro, 1969). The hydrous mineral is probably of sufficient quantity to produce rhyolitic magma without being consumed in the first stage of the fractional melting process.<sup>13</sup> If, however, the hydrous mineral is the phase that is consumed in the first stage of fractional melting, subsequent liquids produced at the next thermal level of melting will be anhydrous. That is, basalt would be expected rather than andesite (Yoder, 1969).

If the second stage of melting proceeds without

H<sub>2</sub>O, the parental material would then have to be raised to a much higher temperature to produce a liquid analogous to hydrous liquid *B* (Fig. 13). Kushiro (1969, p. 282) has studied a portion of the Di-Fo-SiO<sub>2</sub> system at *P* = 20 kbar under anhydrous conditions, and the relevant invariant point on the Di-En join for the bulk composition *C* has a temperature close to 1650°C. The larger temperature interval between melting stages increases the heat requirements and the time involved.

Vesiculation of the rhyolitic magma on pressure reduction (Yoder, 1965) as it rises to higher levels in the crust probably initiates the explosive eruptive phase. Preservation of phenocrysts unique to each magma (e.g., "emulsion" tuff lava from Breiddalur, Iceland) indicates that the mixing took place primarily during the turbulent period of simultaneous eruption. Release of volatiles may also be initiated as the hydrous rhyolitic magma reacts with phenocrysts of the basaltic magma. The schematic albite-anorthite-H<sub>2</sub>O system at *P*<sub>H<sub>2</sub>O</sub> = 5 kbar and 800°C, in Figure 14, is particularly instructive in this connection. If 20 percent of a basic plagioclase (An<sub>70</sub>) or a basic hydrous mineral (e.g., lawsonite) is added to a relatively albite-rich, H<sub>2</sub>O-saturated magma (*A*), the bulk composition shifts into the crystal + liquid + gas region (*X*) and gas is released. A thorough analysis

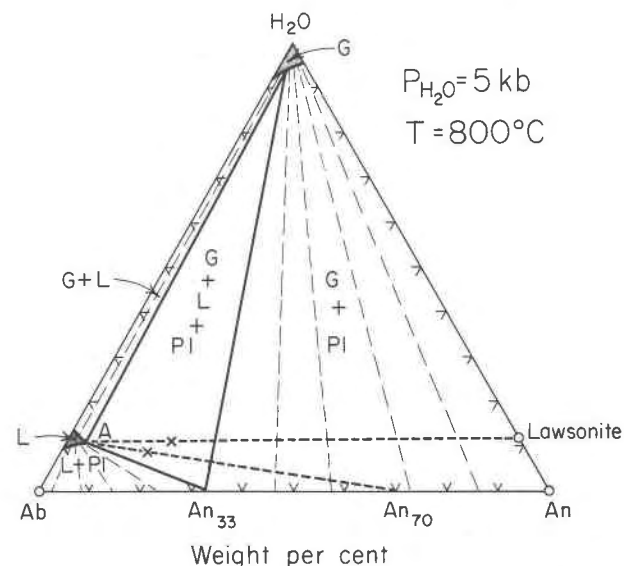


FIG. 14. Estimate of the albite (Ab)-anorthite (An)-H<sub>2</sub>O system at *P*<sub>H<sub>2</sub>O</sub> = 5 kbar and *T* = 800°C based on data of Yoder *et al.* (1957, p. 207, Fig. 36). Bulk composition obtained by addition of 20 percent basic plagioclase, An<sub>70</sub>, or a basic hydrous mineral (e.g., lawsonite) to a saturated albite-rich magma, *A*, marked with an X. G, gas; L, liquid; Pl, plagioclase.

<sup>12</sup> In addition, the lowering of pressure on adiabatic rise of the separated, H<sub>2</sub>O-saturated magma to shallower depths would produce a large amount of crystallization. Magmas undersaturated with regard to H<sub>2</sub>O would, on the other hand, melt sufficiently on pressure reduction to offset cooling.

<sup>13</sup> Kushiro *et al.* (1972) melted a mixture of natural garnet lherzolite minerals and 2 percent synthetic fluorophlogopite in which the initial K<sub>2</sub>O = 0.25 percent. All of the mica was consumed in the liquid at 1500°C and 30 kbar when the liquid content reached about 10 percent (see their Table 2, p. 21). It would appear, therefore, that the mica content of the parental material would have to exceed several percent to satisfy this requirement. This amount of mica and its K<sub>2</sub>O content may not be acceptable in some models of the mantle because of excessive radiogenic heat production from K<sup>40</sup>.

of the assimilative process in various types of hydrous systems is needed but will not be undertaken here.

6. *Trace element partition and isotopes.* The trace element partitions will depend first on whether the elements are saturated or undersaturated. Exhaustion of phases in the parental material on fractional melting will produce subsequent discontinuous changes in trace element composition in the liquid. Initially, the first liquid formed will concentrate those elements which preferentially partition into the liquid. The parental mineralogy in kind and proportions will obviously have great influence on the distributions. Magma produced in successive stages will be greatly reduced in those preferred elements.

These deductions appear to account in general for the trace element distributions in depleted oceanic tholeiites. In addition, the production of alkali basalts in the oceans implies that a mica, or equivalent phase, was retained in the parental material after the first stage of melting. There are, however, obvious difficulties in correlating these deductions with depth of origin in the mantle, degree of melting, and determined partition coefficients in crystal-liquid equilibria. Future tests of this hypothesis will no doubt rely heavily on the trace elements.

Differences in  $\text{Sr}^{87}/\text{Sr}^{86}$  should be small between rhyolitic and basaltic magmas derived by fractional melting from the same parent. The similarity of this ratio for some of the associated rhyolites and basalts (and andesites) of Central America (McBirney and Weill, 1966) and Iceland (Moorbath and Walker, 1965) lends support to this hypothesis. H. P. Taylor (in McBirney and Weill, 1966, pp. 11–12) has determined the  $\text{O}^{18}/\text{O}^{16}$  for rhyolite obsidians and basalts in Central America and concluded that the rhyolite obsidians could not have been derived by remelting of the basement rocks and are more directly related to the associated basalts. The sensitivity of these isotopes to exchange may temper interpretation in other areas.

7. *Hybridization.* The contiguous magmas (Fig. 7) may hybridize if the storage period is long or the interface large as outlined by Wager *et al.* (1965). Contiguous magmas confined to a dike system would have limited opportunity to hybridize until flow began in the eruptive stage. The hybrid rocks observed at Gardiner River, Wyoming, Gran Canaria Island, and in the Katmai area suggest that mechanical mixing and diffusion between magmas had taken place. Bowen (1928, p. 121) argued that hybridization of the reactive type (magma consuming foreign crys-

tals) only tends to reinforce the normal lines of liquid descent. However, an examination of the  $\text{SiO}_2$  variation diagram of a magma series produced by fractional crystallization indicates that magmas obtained by liquid-liquid mixing, hybridization in the strict sense of Durocher (1857), are not initially confined to the normal lines of descent (see Harker, 1904, p. 232, Figs. 50 and 51). A chemical study of the glassy rocks may reveal whether magma mixing or fractional crystallization (and its corollative reactive assimilation) is more applicable to the evolution of the calc-alkaline series.

8. *Eruptive sequence.* In general the compositional sequence of eruption is rhyolitic followed by basaltic magma, and the fractional melting hypothesis satisfies this observation. On the other hand, the composite dikes and composite lava flows more often indicate the reverse sequence of magma emplacement. The conduits may no doubt feed the magmas in the latter sequence, but such fortuitous plumbing does not have worldwide application. Buist (1952) attributed the sequence to viscosity differences, the less viscous basic magma progressing more rapidly to the surface. Similarly, Gibson and Walker (1963, p. 317) believe that viscous siliceous magma is "rendered more fluid" by the passage and incorporation of the hotter basic material that precedes the siliceous magma to the surface. The volumetric predominance of acid intrusives over basic intrusives would appear to support their view; however, a wholly satisfactory solution to the sequence problem is not at hand.

9. *Parental material.* The assumption of a parental material capable of producing quartz-normative liquids is not without some foundation. Studies of simple *hydrous* systems involving olivine, clinopyroxene, orthopyroxene, and spinel, a possible mantle assemblage, indicate that the first liquids ( $\text{H}_2\text{O}$ -saturated) are quartz-normative (Yoder and Chinner, 1960, p. 79; Yoder, 1971, p. 178). Direct determination of the composition of the liquids derived from the hydrous partial melting of natural peridotite demonstrated that the liquids are quartz-normative (Kushiro *et al.*, 1972). In the latter experiments the liquids were described as andesitic or dacitic after 20 percent melting had occurred at 25 kbar. At somewhat lower pressures and with a smaller degree of melting, it is believed that the  $\text{H}_2\text{O}$ -saturated liquid would be analogous to liquid *A* in Figure 13, that is, rhyolitic. Olivine would of necessity be present in that assemblage at high pressure in the natural multi-component system.



The basic principle of the hypothesis is equally applicable to a nepheline-normative parental material. For example, the relations in Figure 15 illustrate a eutectic at *C*, analogous in assemblage to phonolite, and a reaction point at *B*, analogous in assemblage to basalt. Two liquids of the compositions *B* and *C* could be removed by fractional melting from a nepheline-normative ultrabasic parent without intermediate members. The contrast in SiO<sub>2</sub> content of the anhydrous liquids at *B* and *C* is obviously small in the simple system, but the principle remains clear in its application to nepheline-normative natural materials.

It is probably evident that a simple ternary eutectic system is equally capable of yielding two liquids of contrasting composition. Presnall (1969, p. 1180, Fig. 1) demonstrated that the ternary eutectic composition and any one of the three possible binary eutectics would yield liquids of considerable contrast on fractional melting of any composition in the system. The exhaustion of a phase in the parental material is the critical event that brings about the hiatus in extracted liquid compositions.

### Concluding Remarks

There is little doubt that the principal framework of igneous petrology is the piezochemical "flow sheet" for liquids that occur in the natural multicomponent system. Fractional crystallization provides the mechanism for extending the liquid line of descent. The paucity of some members of the magma series has been attributed to the imperfect way in which the mechanism operates. The tentative hypothesis advanced above outlines one possible way in which liquids of high contrast in composition originate. Fractional melting also operates imperfectly, and the extent to which each process obtains from province to province and from time to time remains to be seen. The criteria for identifying these processes from the products alone have yet to be enumerated.

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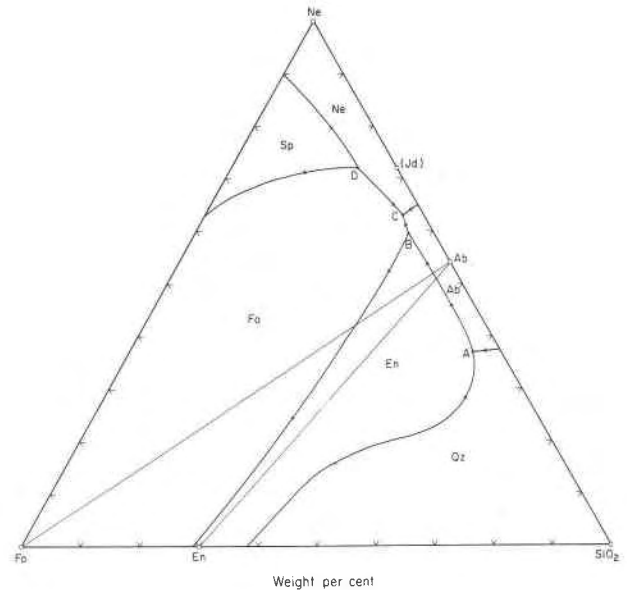


FIG. 15. Hypothetical representation of the nepheline (Ne)-forsterite (Fo)-silica system at  $P \approx 15$  kbar, based in part on findings of Kushiro (1965, p. 106, Fig. 24), illustrating possible existence of invariant points *B* and *C*, representing compositions of contrasting magmas which could be extracted from a nepheline-normative parental material by fractional melting. En, enstatite; Qz, quartz; Ab, albite; Sp, spinel; Jd, jadeite. From Yoder (1964, p. 100, Fig. 25).

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### References

- ADAMS, L. H., AND R. E. GIBSON (1926) The compressibilities of dunite and of basalt glass and their bearing on the composition of the earth. *Proc. Nat. Acad. Sci. USA*, **12**, 275-283.
- BARKER, D. S. (1965) Alkalic rocks at Litchfield, Maine. *J. Petrology*, **6**, 1-27.
- BLAKE, D. H., R. W. D. ELWELL, I. L. GIBSON, R. R. SKELHORN, AND G. P. L. WALKER (1965) Some relationships resulting from the intimate association of acid and basic magmas. *Quart. J. Geol. Soc. London*, **121**, 31-50.

- BOWEN, N. L. (1921) Diffusion in silicate melts. *J. Geol.* **29**, 295-317.
- (1922) The behavior of inclusions in igneous magmas. *J. Geol.* **30**, 513-570.
- (1928) *The Evolution of the Igneous Rocks*. Princeton University Press, Princeton, N. J., 332 pp.
- (1935) "Ferrosilite" as a natural mineral. *Amer. J. Sci.* **30**, 481-494.
- , AND J. F. SCHAIRER (1932) The system FeO-SiO<sub>2</sub>. *Amer. J. Sci.* **24**, 178-213.
- BOYD, F. R. (1961) Welded tuffs and flows in the rhyolite plateau of Yellowstone Park, Wyoming. *Geol. Soc. Amer. Bull.* **72**, 387-426.
- BRACE, W. F., W. C. LUTH, AND J. D. UNGER (1968) Melting of granite under an effective confining pressure (abstr.). *Geol. Soc. Amer. Spec. Pap.* **115**, 21.
- BRYAN, W. B. (1970) Alkaline and peralkaline rocks of Socorro Island, Mexico. *Carnegie Inst. Washington Year Book*, **68**, 194-200.
- BUIST, D. S. (1952) A contribution to the petrochemistry and petrogenesis of the composite sill of South Bute. *Trans. Edinburgh Geol. Soc., Campbell Vol.*, **15**, 52-68.
- BUNSEN, R. W. (1851) Über die Prozesse der vulkanischen Gesteinsbildungen Islands. *Ann. Phys. Chem.* **83**, 197-272.
- CHAYES, F. (1963) Relative abundance of intermediate members of the oceanic basalt-trachyte association. *J. Geophys. Res.* **68**, 1519-1534.
- CURTIS, G. H. (1968) Stratigraphy of the ejecta from the 1912 eruption of Mount Katmai and Novarupta, Alaska. *Geol. Soc. Amer. Mem.* **116**, 153-210.
- DALY, R. A. (1925) The geology of Ascension Island. *Proc. Amer. Acad. Arts Sci.* **60**, 1-80.
- DUROCHER, J. (1857) Essai de pétrologie comparée. *Annales des Mines, Memoires (Paris), Ser. 5*, **11**, 217-259.
- EGGLER, D. H. (1972) Amphibole stability in H<sub>2</sub>O-undersaturated calc-alkaline melts. *Earth Planet. Sci. Lett.* **15**, 28-34.
- FAIRBAIRN, H. W., *et al.* (1951) A cooperative investigation of precision and accuracy in chemical, spectrochemical, and modal analysis of silicate rocks. *U. S. Geol. Surv. Bull.* **980**, 71 pp.
- FENNER, C. N. (1938) Contact relations between rhyolite and basalt on Gardiner River, Yellowstone Park. *Geol. Soc. Amer. Bull.* **49**, 1441-1484.
- (1944) Rhyolite-basalt complex on Gardiner River, Yellowstone Park, Wyoming: A discussion. *Geol. Soc. Amer. Bull.* **55**, 1081-1096.
- (1948) Immiscibility of igneous magmas. *Amer. J. Sci.* **246**, 465-502.
- GAST, P. W. (1968) Trace element fractionation and the origin of tholeiitic and alkaline magma types. *Geochim. Cosmochim. Acta*, **32**, 1057-1086.
- GIBSON, I. L., AND G. P. L. WALKER (1963) Some composite rhyolite/basalt lavas and related composite dykes in eastern Iceland. *Proc. Geol. Ass.* **74**, 301-318.
- GINSBERG, A. S., AND C. S. NIKOGOSYAN (1924) The fusion of diabase and granite. *Bull. Geol. Comm., Leningrad*, **43**, 735-765 [in Russian; French summary].
- HARKER, A. (1904) The Tertiary igneous rocks of Skye. *Mem. Geol. Surv. U.K.*, J. Hedderwiche and Sons, Glasgow, 481 pp.
- HAWKES, L. (1945) The Gardiner River rhyolite-basalt complex. *Geol. Mag.* **82**, 182-184.
- HOLLOWAY, J. R., AND C. W. BURNHAM (1972) Melting relations of basalt with equilibrium water pressure less than total pressure. *J. Petrology*, **13**, 1-29.
- HOLMES, A. (1931) The problem of the association of acid and basic rocks in central complexes. *Geol. Mag.* **68**, 241-255.
- JAEGER, J. C. (1964) Thermal effects of intrusions. *Rev. Geophys.* **2**, 443-466.
- JUDD, J. W. (1893) On composite dykes in Arran. *Quart. J. Geol. Soc. London*, **49**, 536-564.
- KENNEDY, W. Q. (1931) On composite lava flows. *Geol. Mag.* **68**, 166-181.
- KHITAROV, N. I., A. S. KADIK, AND E. B. LEBEDEV (1963) Estimate of the thermal effect of the separation of water from felsic melts based on data for the system albite-water. *Geochemistry (USSR)*, **7**, 637-649.
- KUSHIRO, I. (1965) The system forsterite-nepheline-silica. *Carnegie Inst. Washington Year Book* **64**, 106-109.
- (1969) The system forsterite-diopside-silica with and without water at high pressures. *Amer. J. Sci., Schairer Vol.*, **267-A**, 269-294.
- , N. SHIMIZU, Y. NAKAMURA, AND S. AKIMOTO (1972) Compositions of coexisting liquid and solid phases formed upon melting of natural garnet and spinel herzolite at high pressures: A preliminary report. *Earth Planet. Sci. Lett.* **14**, 19-25.
- LUTH, W. C., R. H. JAHNS, AND O. F. TUTTLE (1964) The granite system at pressures of 4 to 10 kilobars. *J. Geophys. Res.* **69**, 759-773.
- MACDONALD, G. A., AND T. KATSURA (1965) Eruption of Lassen Peak, Cascade Range, California, in 1915: Example of mixed magmas. *Geol. Soc. Amer. Bull.* **76**, 475-482.
- MCBIRNEY, A. R., AND D. F. WEILL (1966) Rhyolite magmas of Central America. *Bull. Volcanol.* **29**, 435-448.
- MILLHOLLEN, G. L. (1971) Melting of nepheline syenite with H<sub>2</sub>O and H<sub>2</sub>O + CO<sub>2</sub>, and the effect of dilution of the aqueous phase on the beginning of melting. *Amer. J. Sci.* **270**, 244-254.
- MOORBATH, S., AND G. P. L. WALKER (1965) Strontium isotope investigation of igneous rocks from Iceland. *Nature (London)*, **207**, 837-840.
- MOREY, G. W., AND J. M. HESSELGESSER (1951) The solubility of some minerals in superheated steam at high pressures. *Econ. Geol.* **46**, 821-835.
- MURASE, T., AND A. R. MCBIRNEY (1970) Viscosity of lunar lavas. *Science*, **167**, 1491-1493.
- NEWALL, G., AND N. RAST (1970) Mechanism of igneous intrusion. *Geol. J., Spec. Issue* **2**.
- OHLBERG, S. M., H. R. GOLOB, AND D. W. STRICKLER (1962) Crystal nucleation by glass in glass separation. In, *Symposium on Nucleation and Crystallization in Glasses and Melts*, American Ceramic Society, Inc., Columbus, Ohio.
- O'KEEFE, J. A. (1963) *Tektites*. University of Chicago Press, Chicago, Illinois, 228 pp.
- PIWINSKII, A. J., AND P. J. WYLLIE (1968) Experimental

- studies of igneous rock series: A zoned pluton in the Wallowa batholith, Oregon. *J. Geol.* **76**, 205–234.
- , AND ——— (1970) Experimental studies of igneous rock series: Felsic body suite from the Needle Point pluton, Wallowa Batholith, Oregon. *J. Geol.* **78**, 52–76.
- PRESNALL, D. C. (1969) The geometrical analysis of partial fusion. *Amer. J. Sci.* **267**, 1178–1194.
- ROEDDER, E. (1951) Low temperature liquid immiscibility in the system  $K_2O$ - $FeO$ - $Al_2O_3$ - $SiO_2$ . *Amer. Mineral.* **36**, 282–286.
- (1956) The role of liquid immiscibility in igneous petrogenesis: A discussion. *J. Geol.* **64**, 84–88.
- , AND P. W. WEIBLEN (1971) Petrology of silicate melt inclusions, Apollo 11 and Apollo 12 and terrestrial equivalents. *Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl.* **2**, **1**, 507–528.
- SCHAIRER, J. F., AND H. S. YODER, JR. (1964) Crystal and liquid trends in simplified alkali basalts. *Carnegie Inst. Washington Year Book* **63**, 65–74.
- SCHMINCKE, H. U. (1967) Cone sheet swarm, resurgence of Tejada caldera, and the early geologic history of Gran Canaria. *Bull. Volcanol.* **31**, 153–162.
- (1968) The geologic framework and origin of alkali trachytic to alkali rhyolitic ignimbrites on Gran Canaria, Canary Islands. In, *Abstracts, International Symposium on Volcanology, Spain—Canary Islands, Int. Ass. Volcanol. Chem. Earth's Interior*.
- (1969) *Petrologie der phonolytischen bis rhyolitischen Vulkanite auf Gran Canaria, Kanarische Inseln*. Habilitation Schrift, Ruprecht Karl Universität zu Heidelberg, Heidelberg, Germany.
- SHAW, H. R. (1963) Obsidian- $H_2O$  viscosities at 1000 and 2000 bars in the temperature range 700–900°C. *J. Geophys. Res.* **68**, 6337–6343.
- (1972) Viscosities of magmatic silicate liquids: an empirical method of prediction. *Amer. J. Sci.* **272**, 870–893.
- SKELHORN, R. R. (1962) Quartz after tridymite in an acid intrusion from Mull. *Mineral. Mag.* **33**, 138–144.
- , J. D. S. MACDOUGALL, AND P. J. N. LONGLAND (1969) The Tertiary igneous geology of the Isle of Mull. *Geol. Ass. Guides, No. 20*, Geologists' Association, London, Benham and Co., Ltd., 35 pp.
- THORARINSSON, S. (1954) The tephra-fall from Hekla on March 29th 1947. In, *The Eruption of Hekla 1947–1948*, Vol. II, No. 3, Soc. Sci. Island, 68 pp.
- TSUYA, H. (1955) Geological and petrological studies of Volcano Fuji. V. On the 1707 eruption of Volcano Fuji. *Bull. Earthquake Res. Inst., Tokyo Univ.*, **33**, 341–384.
- TUTTLE, O. F., AND N. L. BOWEN (1958) Origin of granite in the light of experimental studies on the system  $NaAlSi_3O_8$ - $KAlSi_3O_8$ - $SiO_2$ - $H_2O$ . *Geol. Soc. Amer. Mem.* **74**, 153 pp.
- UPTON, B. G. J., J. E. THOMAS, AND R. MACDONALD (1971) Chemical variation within three alkaline complexes in south Greenland. *Lithos*, **4**, 163–184.
- , AND W. J. WADSWORTH (1967) A complex basalt-mugearite sill in Piton des Neiges volcano, Reunion. *Amer. Mineral.* **52**, 1475–1492.
- WAGER, L. R., AND E. B. BAILEY (1953) Basic magma chilled against acid magma. *Nature (London)*, **172**, 68–69.
- , E. A. VINCENT, G. M. BROWN, AND J. D. BELL (1965) Marscoite and related rocks of the Western Red Hills complex, Isle of Skye. *Phil. Trans. Roy. Soc. London*, **257**, 273–307.
- WALKER, G. P. L. (1963) The Breiddalur central volcano, eastern Iceland. *Quart. J. Geol. Soc. London*, **119**, 29–63.
- , AND R. R. SKELHORN (1966) Some associations of acid and basic igneous rocks. *Earth-Sci. Rev.* **2**, 93–109.
- WILCOX, R. E. (1944) Rhyolite-basalt complex on Gardiner River, Yellowstone Park, Wyoming. *Geol. Soc. Amer. Bull.* **55**, 1047–1080.
- WILLIAMS, HOWEL (1952) Volcanic history of the Meseta Central Occidental, Costa Rica. *Calif. Univ. Publ. Geol. Sci.* **29**, 145–180.
- YODER, H. S., JR. (1950) High-low quartz inversion up to 10,000 bars. *Trans. Amer. Geophys. Union*, **31**, 827–835.
- (1952) Change of melting point of diopside with pressure. *J. Geol.* **60**, 364–374.
- (1964) Genesis of principal basalt magmas. *Carnegie Inst. Washington Year Book*, **63**, 97–101.
- (1965) Diopside-anorthite-water at five and ten kilobars and its bearing on explosive volcanism. *Carnegie Inst. Washington Year Book*, **64**, 82–89.
- (1969) Calcalkalic andesites: Experimental data bearing on the origin of their assumed characteristics. In, *Proceedings of the Andesite Conference*, Ed. A. R. McBirney, *Oregon Dep. Geol. Mineral. Ind. Bull.* **65**, 77–89.
- (1971) The join diopside-pyrope- $H_2O$  at 10 kb: Its bearing on the melting of peridotite, the ACF metamorphic facies, and the gedrite-hornblende miscibility gap. *Carnegie Inst. Washington Year Book*, **69**, 176–181.
- , AND G. A. CHINNER (1960) Grossularite-pyrope-water system at 10,000 bars. *Carnegie Inst. Washington Year Book*, **59**, 78–81.
- , AND I. KUSHIRO (1969) Melting of a hydrous phase: phlogopite. *Amer. J. Sci., Schairer Vol.*, **267-A**, 558–582.
- , D. B. STEWART, AND J. R. SMITH (1957) Ternary feldspars. *Carnegie Inst. Washington Year Book*, **56**, 206–214.
- , AND C. E. TILLEY (1962) Origin of basalt magmas: An experimental study of natural and synthetic rock systems. *J. Petrology*, **3**, 342–532.
- ZIES, E. G. (1960) Chemical analyses of two pantellerites. *J. Petrology*, **1**, 304–308.
- (1962) A titaniferous basalt from the Island of Pantelleria. *J. Petrology*, **3**, 177–180.