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EVOLUTION OF SILICIC MAGMA CHAMBERS AND THEIR RELATIONSHIP TO BASALTIC VOLCANISM

by

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Abstract

Silicic volcanism is commonly preceded by eruption of basalt. Similarly, the earliest phases of granitic plutonic complexes are often gabbro or diorite. Basalt magma must play a role in the initiation of a large silicic magma system, but three lines of evidence suggest that basalt magma also enters silicic chambers and influences their further evolution: (1) Contemporaneous basalt vents flank silicic volcanic centers. (2) Thermal models of silcic bodies suggest that their heat must be replenished to maintain them in the upper crust for their observed life span. (3) Petrologic data indicate that mafic clots and "cognate" xenoliths common in granodiorite and andesite represent basalt magma quenched within active silicic magma chambers. Phase assemblages in volcanic rocks and bulk composition of volcanic and plutonic rocks in suites of this type show that much of the variation in erupted or crystallized end products is due to this interaction of basaltic and rhyolitic magmas.

It is proposed that basalt magma from the upper mantle provides heat for generating rhyolitic melt in the lower crust, and that the resulting rhyolite magma body continues to receive injections of basalt as it rises through the crust. Implications of this model are: (1) the development of a silicic system depends on the intensity of basaltic volcanism and the ability of the lower crust to produce a rhyolitic melt. (2) The relative volume of intermediate versus basaltic and rhyolitic end products depends on the extent of convective stirring. It appears that the influence of tectonic setting on crustal residence time of silicic chambers controls to what degree the system is homogenized.

batholith as mafic "forerunners" and there, too, mafic magmas invaded the later silicic bodies. Ring dike complexes commonly begin with emplacement of gabbros, followed by a copious variety of granites (e.g. Moorbath and Bell, 1965; Chapman, 1942; Modell, 1936). However, the intermingling of gabbroic and granitic rocks within some of the granite bodies suggests that mafic magmas were still present when the granites were intruded.

Essentially all volcanic fields in the western United States contain some basalt. Basalt has erupted throughout, and predominates volumetrically in part of, the Cascade Range (McBirney and others, 1975) where andesite is an important rock type. The more bimodal Snake River Plane-Yellowstone Plateau field erupts basalt before and after major caldera-forming rhyolite eruptions (Eaton and others, 1975). Relative volume of early basalt or gabbro in a complex may be underestimated because it is concealed by later lava or stoped downward by later intrusives.

In both plutonic and volcanic complexes, mafic bodies are typically satellitic to silicic complexes. Jorlin (1959) stated this general observation for discordant granitic batholiths. It has been mentioned more recently in reference to the Snoqualmie batholith (Erikson, 1969) and the Boulder batholith (Tilling, 1973). The equivalent spatial arrangement in volcanic fields is represented by silicic volcanic centers with older to contemporaneous flanking basalt vents. These include the major volcanoes of the Cascade Range (the relationship is especially clear in the southern Cascades), Long Valley Caldera (CA), San Francisco Peaks (AZ), Mt. Taylor (NM), and the Valles Caldera (NM).

Introduction

Spatial and temporal association between basaltic and more silicic rocks in both plutonic complexes and volcanic fields implies a genetic relationship. This paper discusses field evidence of this relationship and presents new petrologic data indicating that it is the interaction of basalt with initially rhyolitic magma bodies which produces much of the compositional diversity of end products. Based on this evidence from diverse complexes, a general model is proposed to explain silicic igneous activity in terms of stage of evolution and tectonic setting. Previous discussions of petrologic evidence of mixing have been presented by Eichelberger (1975) and Anderson (1976).

Relationship of Basaltic Volcanism to Silicic Magma Chambers

Most silicic (andesite-rhyolite or granodiorite-granite) igneous complexes are closely associated with basalt or gabbro. In general, intrusions of basalt magma precede, continue during, and sometimes post-date the development of silicic complexes. This observation applies both to those complexes where intermediate (andesite or granodiorite) and extreme (basalt-rhyolite or gabbro-granite) compositions predominate. For example, the earliest phases of the predominantly granodioritic Snoqualmie batholith are gabbros (Erickson, 1969), and the northern Cascade batholiths of this type were intruded by basaltic dikes late in their history (Erickson, 1969; Tabor and Crowder, 1969). Mayo (1941) referred to the earliest intrusives of the Sierra Nevada

Eaton and others (1975) and Bailey and others (1976) have used the distribution of basalt vents to infer the position of active silicic magma bodies. This is based on the assumption that dense mafic liquid can not pass upward through such a body, and on field observations at Yellowstone and Long Valley that the roof of a silicic chamber, as defined by a caldera, lacks basalt vents during the period the caldera is active. As silicic activity related to the caldera declines, basalt vents encroach on the caldera region, presumably because the underlying body is crystallizing inward. Similar observations can be made for other centers lacking calderas, but where large accumulations of silicic lava imply the presence of a large chamber.

Thus it appears that silicic magma chambers typically lie within a region of upward flux of basalt magma. Lachenbruch and others (1976) have shown that such a model could account for the discrepancy between the observed life span of the Long Valley magma chamber and the shorter life span calculated for thermal models assuming heat loss by conduction alone. Trapping of basalt magma provides an efficient means of keeping the silicic magma hot.

These observations have important petrogenetic implications. The existence of mafic forerunners to batholiths suggests that basalt magma may provide heat for development of silicic magmas by partial melting in the lower crust. Evidence that the upward flux of basalt continues after an active silicic pluton has formed suggests the possibility of direct interaction. Mass as well as heat will be added to a low density magma which traps basalt, producing a change in composition as well as temperature.

Petrologic Evidence of Interaction of Basalt and Rhyolite Magmas

Although silicic volcanic centers lack basalt vents when they are active, andesitic lavas commonly contain abundant xenoliths of basaltic composition which range in size from 1 m globules to 1 mm crystal clots and which have no exact counterparts among the country rocks. The same may be said of granodiorites in plutonic complexes. Typically there are major textural variations between, or even within (Tabor and Crowder, 1969), xenoliths but a consistent mineralogy, dominantly plagioclase + pyroxene or plagioclase + hornblende. The most common textural types are fine-grained porphyritic and medium-grained nonporphyritic. Where these textures are found in the same xenolith, the former type makes a rind on the latter (Fig. 1). In the plutonic case, the composition of phases within the xenoliths match those of the host, only the proportions differ, but in volcanic rocks there is striking evidence of disequilibrium.

Basaltic xenoliths have enjoyed a long and lively literature under such names as mafic microgranular enclaves, mafic segregations, secretions, cognate xenoliths, restites, and so forth. Probably the most common interpretation is that they are cumulates or equivalent products of fractional crystallization (for example Williams, 1931; Nicholls, 1971). Others (Piwinskii, 1973; Presnall and Bateman, 1973)

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have suggested that they are refractory residium, "restites," from partial melting of the lower crust. Joplin (1959) suggested that they are engulfed mafic forerunners. The compositionally equivalent, but genetically different, interpretation is that they are "basic pillows" (Blake and others, 1965), basalt chilled and crystallized in silicic magma.

We have studied samples of these xenoliths and their host lavas from a number of volcanic centers in the western United States and Ecuador, including a suite of Lassen lavas spanning the compositional range of basaltic andesite to rhyodacite. Several lines of evidence indicate that the xenoliths are basalt injected into, and crystallized within, silicic magma chambers; that is, that they represent the basalt magma which does not reach the surface above these chambers:

1. The xenoliths are globular in shape, sometimes with a finely contorted border.
2. Xenoliths in Lassen dacite were chilled against the host. Average grain size decreases toward the border and hornblende changes from subequant to highly elongate.
3. Many of the larger xenoliths in Lassen dacite are surrounded by a mixed rind in which partially melted or reacted phenocrysts from the host lie in a matrix similar to, but finer grained and more glass rich than, the interior of the xenolith (Fig. 1).
4. Most of the xenoliths contain interstitial vesicular glass.
5. In bulk composition the xenoliths approach the composition of associated basalt and contain as primary phenocrysts

phases which match phenocrysts in associated basalts (Table I).

Products of disaggregation of these xenoliths are so abundant on a microscopic scale that it is apparent that injection of basalt into the silicic magma body had a strong compositional effect, that the magma in the chamber was rhyolitic before mixing. For example, subtraction of basalt-derived material from the mode of Lassen dacite gives an estimate of before-mixing silica content of 75 weight percent. Confirmation of this suggestion is provided by the presence of partially reacted or resorbed phenocrysts, appropriate for magma of rhyolitic composition, in many of the intermediate lavas. Further, rhyolite-derived phenocrysts in andesites from Lassen (Fig. 2), Ecuador, and San Francisco Peaks contain inclusions of rhyolite glass in their unmelted cores.

The most common rhyolite-derived phenocrysts are sodic plagioclase and quartz. In response to injection of basalt into the magma chamber, sodic plagioclase partially melts to calcic plagioclase plus liquid, which allows diffusion inward from the surrounding mafic melt. This results in a cloudy zone consisting of calcic plagioclase, glass, pyroxene, and opaques (Fig. 3 and 4). When thermal equilibrium is reached and crystallization resumes, a normally zoned calcic overgrowth forms on the crystal. Depending on the proportion of basalt to rhyolite, quartz is either resorbed (dacite) or reacts with the liquid to form pyroxene (andesite). If the rhyolite is at its liquidus when mixing occurs, no rhyolite-derived phenocrysts will be present in the hybrid (e.g. Eichelberger, 1975). The phase assemblage of the rhyolite at the instant of mixing is shown clearly by the assemblage of rhyolite-derived phenocrysts in the porphyritic rind of basaltic xenoliths (in Lassen dacite: quartz + andesine + biotite).

Taken as a whole, the textural relationships indicate that basalt magma breaks into globules as it intrudes rhyolite magma. Mixing occurs at the interfaces, and the products of interaction are then strewn throughout the magma body by convective stirring. The basalt globules are vesicular because they are cooled to near solidus, causing vapor saturation of the residual liquid. Direct mixing of mafic and silicic liquids is minor if the proportion of introduced basalt is small because the globules are quickly crystallized. In Lassen dacite, this limited mixing is represented by the thin rinds on the xenoliths (Fig. 1). Conversely, when the proportion of basalt is large, direct mixing of liquids is more thorough. The initial mixture is still heterogeneous however, and when thermal equilibrium is reached the more basaltic portions are more crystal rich and are strewn through the magma as clots and microxenoliths. Figure 3 illustrates the products of basalt and rhyolite interaction for dacite and andesite from Lassen Park. Figure 4 shows similar features in dacite from Ecuador and andesite from Mt. Baker. It should be emphasized that these features are present in abundance in every thin section and that these samples are typical of rocks from their respective regions. Similar features have been described in the lavas of Mt. Rainier

(Fiske, Hopson, and Waters, 1963) and Glacier Peak (Tabor and Crowder, 1969). The basaltic microxenoliths in these lavas correspond to similar xenoliths in intermediate parts of associated Miocene batholiths. The similarity in texture of the latter to xenoliths in Lassen dacite is noted in Fig. 3. It is interesting to note that a large negative gravity anomaly ([illegible]), which can be interpreted as a silicic batholith in the upper crust, encompasses the hybrid vents of Lassen Park but excludes the recent basaltic vents. The areal extent of this anomaly is comparable to the Miocene batholiths of the northern Cascade Range. Erikson (1969) suggests that most of the Snoqualmie batholith, from granite to gabbro, was in a molten state at the same time. Thus the analogy between Lassen andesites and dacites, northern Cascade andesites and dacites, and northern Cascade granodiorites appears to hold. Production of the modern hybrids takes place in sizable chambers as represented by the exhumed Miocene batholiths. A test of this model in terms of major element composition of these rocks is presented in Table II. Average composition of Snoqualmie gabbro (51% SiO_2) and granite (75% SiO_2) are taken as representative of the parent magmas for Snoqualmie granodiorite. For Glacier Peak, Quaternary basalt (51% SiO_2, White Chuck Cinder Cone) of the area and average granite of the associated Miocene batholith (73% SiO_2) are used for parent compositions. Similar data have been presented previously for Lassen (Eichelberger, 1975). Church (1976) has reported isotopic data from Mt. Baker, Glacier Peak, and Mt. Shasta indicating mixing of lead from two sources, for which the upper mantle and lower crust are good candidates.

It has been suggested that quartz (Nicholls and others, 1971) and sodic plagioclase (Nash, 1973) in andesite are products of crystallization at high pressure. The presence of rhyolitic glass inclusions in the unmelted cores of these phases in andesite from Ecuador, Lassen, and San Francisco Peaks clearly rules out this possibility for these lavas. Further, Drake (1976) has demonstrated that there is no significant pressure effect to 10 kb on plagioclase-melt equilibria in dry systems of basalt to rhyolite composition. The effect of water at high pressures would shift plagioclase toward a more calcic composition (Yoder, 1969), and ascent of a hydrous magma would cause crystallization, not melting. Doe and others (1969) have found that partially melted sodic plagioclase in an andesite from the San Juan Mountains is in isotopic disequilibrium with the matrix.

Stewart (1974) has proposed that plagioclase-pyroxene crystal clots in andesites are breakdown products of high-Al amphiboles. In Lassen rocks, it is clear that the plagioclase-pyroxene clots in andesite and plagioclase-hornblende clots in dacite are simply fragments of the basaltic xenoliths, since a continuous size spectrum exists. The presence of glass, calcic plagioclase and magnesian olivine in the clots cannot be reconciled with the breakdown product hypothesis. Stewart (1974) makes a distinction between plagioclase + pyroxene + glass clots as xenoliths and plagioclase + pyroxene clots as amphibole products. However, Fo_{70} olivine and An_{85} plagioclase are present in both glass-present and glass-absent clots at Baker, and the Lassen xenoliths suggest that the amount of glass is caused by minor differences in mixing and cooling history of injected basalt. If, as the petrologic evidence suggests, northern Cascade andesite forms in a manner similar to southern Cascade andesite, then the predominance of andesite at Mt. Baker indicates that the parent magma body is well stirred. Thus it is not surprising to find the basalt represented by smaller xenoliths.

Thoroughness of Mixing and Evidence of Partially Mixed Magma Bodies

Examples such as Mt. Baker and Glacier Peak show that mixing of basaltic and rhyolitic magmas can be so thorough that end products of intermediate composition predominate, and little or no unmixed rhyolite reaches the surface. The basalt-rhyolite association as illustrated by the Yellowstone Plateau represents the opposite extreme, where mixed lavas are negligible in volume. Other volcanic and plutonic complexes represent intermediate cases where mixing is substantial but unmixed end members are still present, for example at Lassen Park and the Snoqualmie batholith. Bimodal volcanic fields tend to occur in strongly faulted terrane. This relationship has been noted previously on a large scale and correlated with plate tectonic setting (Lipman and others, 1972; Christiansen and Lipman, 1972) and it holds on a smaller scale as well, within the Cascade Range. Fields which erupt the entire spectrum of composition such as Lassen, Medicine Lake, and Newberry lie in areas of prominent faulting, while intermediate centers occur nearby where faulting is more subdued.

Christiansen and Lipman (1972) have shown that a switch from intermediate to bimodal compositions has occurred at many centers in the western United States and that this change occurred when block faulting began. Since petrologic data indicate that the diversity of end products depends on the amount of mixing of parental basalt and rhyolite, it follows that strong faulting inhibits mixing. A likely explanation is that high angle faults provide an easy path for rhyolite diapirs to leak to the upper crust or surface where they crystallize or erupt before thorough mixing with basalt can take place.

In complexes where mixing is not thorough, large plutons or volcanic units may be expected to show the effects of partial mixing. The simple case in which basalt magma enters the bottom of a rhyolite magma chamber has been described by Rice (1976). Initially, two separate convection systems will be present because of the density difference between the magmas, and a mixed (andesitic) crystal-rich layer will grow at the interface. Compositionally zoned tuff sheets in which crystal-rich dacite or andesite overlies crystal-poor rhyolite appear to represent the partial emptying of such a stratified chamber. Although such sheets have been interpreted as products of fractional crystallization (Hedge and Noble, 1976), several features are not in accord with this hypothesis:

1. The sheets are isotopically as well as compositionally zoned, and phenocrysts are in isotopic disequilibrium with the matrix in the dacitic or andesitic portions (Noble and Hedge, 1969).

2. Variations in composition are abrupt and most of the variation in bulk composition is due to a change in composition of the matrix rather than the higher proportion of phenocrysts in the andesitic portions (Lipman, 1967; Lipman and others, 1966).

Aso Caldera tuff sheets show an upward increase in partially melted plagioclase, appearance of Fo_{30-35} olivine and An_{80} plagioclase in some of the andesitic upper units, and have abundant mafic xenoliths (Lipman, 1967). Noble and Hedge (1969) found that sanidine in the quartz latite top of a zoned tuff in Nevada isotopically matches the rhyolite bottom of the sheet. These data are better explained as the product of a partially mixed, stratified magma body in which radiogenic rhyolite overlies less radiogenic basalt.

The sequence of eruption at other partially mixed centers appear to match these tuffs. Some San Juan calderas which erupted rhyolitic tuff subsequently filled with dacitic or andesitic lava (Steven and Lipman, 1975). The Long Valley caldera has erupted dacite and andesite lavas following the Bishop rhyolite tuff (Bailey and others, 1976). Centers which erupted andesite following extrusion of rhyolite domes or flows include Mt. Taylor (Baker and Ridley, 1970) and the Summer Coon Volcano (Lipman, 1968).

The latter examples may reflect the same mafic-downward zonation of magmas as the tuffs, or merely an increasingly mafic mixture with time because the rhyolite in the chamber was not replenished. The most common compositionally equivalent zonation in plutonic bodies is mafic-outward. Mafic xenolith-bearing granodiorites surround granite cores (Bateman and Wahrhaftig, 1966). These may represent a convection configuration in which the hybrid is swept up the outside of the chamber (Rice, personal communication). Another possibility is that the upward flux of basalt ceased between hybridization of the granodiorite and emplacement of the last rhyolite magma diapir.

Statement of Model

Field and petrographic evidence discussed above imply that basalt is the heat source which causes production of rhyolite melt, that continued upward flux of basalt generates the observed range in composition and that the volume distribution of end products depends on the amount of interaction of basalt and rhyolite magmas. This model is depicted in Fig. 5. The process is simply one by which upward migration of a hot melt, if there is enough of it, promotes melting out of a lower melting fraction at higher levels. Under some conditions, the cooler melt retains its identity because its physical properties differ greatly from the hot melt. In the model, the lower crust is chosen as a likely source for rhyolite melt because it is the deepest region, and therefore has the highest initial temperature, in which rocks of composition capable of producing significant amounts of rhyolite are likely to occur. The model implies that development of a silicic igneous complex is dependent on intensity of the basalt flux and ability of the lower crust to produce a rhyolitic melt. Oceanic crust will do, but can produce only trivial amounts of rhyolite compared to continental crust. Some continental basaltic fields may have insufficient rate or volume of basalt intrusion, or fail to trap enough of the basalt in the lower crust, to generate a silicic system.

Although the most compelling petrologic evidence for the model comes from volcanic fields, it is consistent with many kinds of data on batholiths. In the case of the Sierra Nevada batholith, the model provides a mechanism for mixing of components from upper mantle and lower crustal sources preferred by Doe and Delevaux (1973) on the basis of isotopic data, as well as an explanation for the mafic xenoliths in the granodiorite (Bateman and Wahrhaftig, 1966) and the high liquidus temperatures for the granodiorite observed experimentally by Piwinskii (1973).

Thermal calculations related to partial melting of the crust, modeling of the hydrodynamics of mixing, and application of the model to specific igneous complexes will be presented in subsequent papers.

Isotopic Data and Inferences Concerning the Rhyolite Source Region

Mixing of two relatively consistent parent magmas results in linear variation of whole rock composition of the products. Obviously this holds for isotopic as well as elemental abundances. Straight lines on isotope diagrams of the form $y = mx + b$ can be isochrons, mixing lines, or both. For Rb-Sr, linear variation of whole-rock initial Sr^{87}/Sr^{86} with Rb^{87}/Sr^{86} in an igneous suite can have meaning as an isochron in a two-stage model only under special conditions, because fractionation changes Rb^{87}/Sr^{86}:

1. a) Whole melting (Rb^{87}/Sr^{86} is unchanged) of an older igneous complex.
   b) Because basalt has low Rb^{87}/Sr^{86}, a close approximation to the above is bulk assimilation of material by basalt.
2. A magma differentiates and then remains in its chamber in a molten state.

In case (1a) the secondary isochron gives the age of the source complex, in case (1b) the approximate age of the contaminant, in case (2) the age of the differentiation event. Case (1a) is geologically unreasonable. Case (1b) requires unreasonable amounts of contamination to produce silicic igneous rocks. Figure 6 shows that pseudoisochrons are often too young for case (1b) and too old for case (2).

In the model proposed in this paper, parental rhyolite magma forms by partial melting of more mafic material. The rhyolite source has the same Sr^{87}/Sr^{86} value as the rhyolite but lower Rb^{87}/Sr^{86}, and therefore lies somewhere on a horizontal line to the left of the rhyolite on Fig. 6. A two-stage isochron whose slope represents the time since the rhyolite source (lower crust) and basalt source (upper mantle) were in isotopic equilibrium passes through points representing the rhyolite and basalt source or, as a close approximation, the rhyolite source and basalt initial ratio. This line has the same y intercept as the pseudoisochron but a steeper slope. Thus the pseudoisochron gives a lower limit for the two-stage model age of the lower crustal rhyolite source.

For U-Pb, linear variation of Pb^{207}/Pb^{204} with Pb^{206}/Pb^{204} in an igneous suite can be both a two-stage isochron and a mixing line, because fractionation does not affect either variable. It does not matter whether the intermediate points on the line are generated by partial melting of a different source related to the other sources in stage one, or are generated by mixing of end member parent magmas. Thus the secondary isochrons for the Kermadec Islands (Oversby and Ewart, 1972) and Tristan da Cunha (Oversby and Gast, 1970) may have meaning even though the andesites (or trachyandesites in the latter case) may be hybrids. Linear variation of U^{238}/Pb^{204} with Pb^{206}/Pb^{204} and Pb with K for Kermadec lava is consistent with the mixing model. However, plate tectonics provides a means of laterally moving shallow and deep sources independently of each other. Thus the two-stage model assumption that the shallow and deep sources evolved at the same time may not be meaningful, and in general the pseudo-isochron will give an age intermediate to the "ages" of the sources. Under some circumstances, Pb and Rb-Sr data can bracket the age of the rhyolite source material in a mixed suite. The Sierra Nevada batholith (Kistler and Peterman, 1973; Doe and Delevaux, 1973) and Skye (Moorbath and Bell, 1965; Moorbath and Welke, 1968) appear to be examples of this.

Conclusions

The model proposed here explains the origin of a variety of silicic igneous complexes and can be tested by a variety of data. It suggests that rift and subduction zone igneous activity are manifestations of similar parent magmas produced in response to a heat source, and that the variety of end products is controlled by tectonics. Although it contradicts the widely accepted intimate relationship between andesite and subducted oceanic crust, the presence of voluminous andesite in such places as Colorado demonstrates that the relationship is not intimate. Finally, by identifying the parent liquids, the model provides a means of exploring their source regions.

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TABLE I
WHOLE ROCK AND PHENOCRYST COMPOSITION OF SOME
BASALTIC XENOLITHS IN ANDESITES AND DACITES

	1	2	3	4	5
SiO_2	51.4	54.7	53.4	58.5	50
TiO_2	1.0	0.9		0.6	
Al_2O_3	18.7	18.5	19.2	17.8	17
FeO	8.6	7.0	7.5	5.9	
MgO	5.3	5.8	4.9	3.5	
CaO	10.7	8.7	9.0	7.2	
Na_2O	3.2	3.0	2.9	3.4	
K_2O	0.5	1.0	1.0	1.5	
Olivine	Fo_{70-80}	Fo_{80}	Fo_{80}	Fo_{80}	Fo_{70}
Plagioclase	An_{80}	An_{70-80}	An_{90}	An_{30}, An_{90}	An_{80-85}

1. Average of xenoliths in Modern Series, Santorini Volcano, Greece (Nicholls, 1971).
2. Xenolith in dacite, Medicine Lake Highland, California (Anderson, 1941; Eichelberger, 1975).
3. Xenolith in dacite, Lassen Volcanic National Park, California (Williams, 1931).
4. Porphyritic rind on xenolith in dacite (Fig. 1), Lassen Volcanic National Park, California. Analyst: John Husler, University of New Mexico.
5. Microxenolith in andesite, Mt. Baker, Washington. Silica and alumina content estimated from mode. Bytownite occurs as cores of some plagioclase grains.

TABLE II
COMPARISON OF OBSERVED BULK COMPOSITIONS WITH COMPOSITIONS CALCULATED FOR MIXTURES OF RHYOLITE AND BASALT

	Snoqualmie		Glacier Peak			
	1	2	3	4	5	6
SiO_2	65.6	65.3	57.0	57.4	63.4	63.9
TiO_2	0.5	0.6	0.8	0.9	.07	0.6
Al_2O_3	15.7	15.0	18.0	17.1	16.9	15.9
FeO	4.5	5.0	5.9	6.1	4.4	4.3
MgO	2.3	2.5	4.9	5.2	2.9	3.2
CaO	4.5	4.9	7.0	7.2	4.8	4.9
Na_2O	3.4	3.1	3.6	3.4	4.1	3.7
K_2O	2.3	2.0	1.2	1.2	1.8	2.0

1. Average granodiorite (33 analyses).
2. Mixture: three parts rhyolite (9 analyses) to two parts basalt (6 analyses,.
3. Andesite of Gamma Ridge (1 analysis).
4. Mixture: three parts rhyolite (3 analyses to seven parts basalt (2 analyses).
5. Average dacite (11 analyses).
6. Mixture: three parts rhyolite (3 analyses) to two parts basalt (2 analyses).

All data are from Erickson (1969) and Tabor and Crowder (1969). See text for discussion of selected basalt and rhyolite parent compositions.

Fig. 1. Portion of large zoned plagioclase-hornblende xenolith (dark gray) and dacite host (light gray) from Chaos Crags, Lassen Volcanic National Park, CA. From left to right are medium-grained core, porphyritic fine-grained rind (Table I, analysis 4), and dacite host. Note small fragments of both zones of xenolith in dacite at far right. For plutonic equivalent, see Didier (1973, p. 228). Bar length is 2 cm.

Fig. 2. Average normative composition of glass inclusions in andesine and quartz phenocrysts in dacite and andesite from Lassen Volcanic National Park, based on complete electron microprobe analyses. Location of glasses are:

1. Core of unmelted plagioclase in Chaos Crags dacite (8 analyses).
2. Unmelted core of partially melted plagioclase in porphyritic rind of basaltic xenolith (Fig. 1), Chaos Crags dacite (3 analyses).
3. Core of quartz in Chaos Crags dacite (5 analyses).
4. Unmelted core of partially melted plagioclase in Prospect Peak andesite (3 analyses).
5. Core of quartz in Prospect Peak andesite (2 analyses).

The position of the rhyolite glasses in the andesite with respect to the clustered analyses for the dacite is apparently due to expansion of the liquid stability field in the hotter andesite hybrid. Phenocrysts representative of locations 3, 4, and 5 are shown in Fig. 3.

Fig. 3. Comparison of basaltic xenoliths and rhyolite-derived phenocrysts in dacite (line 1) and andesite (line 2). Column A is basaltic xenoliths, B is partially melted plagioclase, C is quartz. The dacite is from Chaos Crags and represents approximately four parts rhyolite to one part basalt, by weight. The andesite is from Prospect Peak and represents approximately two parts rhyolite to three parts basalt, by weight.

<u>Dacite</u>: Basaltic xenoliths are plagioclase plus hornblende plus glass (1A). Chilled margin is 1A' (compare with Tabor and Crowder, 1969, p. 13). Plagioclase (1B) has An_{28-40} core, thin partial melt zone (dark), and normally zoned An_{75-50} overgrowth.

Plagioclase which did not encounter hot basalt globules has An_{28-40} core, no partial melt zone and An_{50} rims (not shown). Quartz (1C) is resorbed.

<u>Andesite:</u> Basaltic xenoliths are plagioclase + pyroxene + glass (2A). Plagioclase (2B) has An_{28-40} core, wide partial melt zone, and normally zoned $An_{[illegible]-55}$ overgrowth. All sodic plagioclase in the andesite has a partial melt zone. Quartz (2C) has a pyroxene reaction rim. Bar length is 0.5 mm.

Fig. 4. Features analogous to those of Fig. 3 in dacite from vicinity of Nevado Antisana, Ecuador (line 1) and andesite from Mt. Baker, WA (line 2).

<u>Dacite:</u> Basaltic microxenoliths are plagioclase + hornblende (1A). Plagioclase (1B) has An_{35}, partial melt zone, and normally zoned An_{65-50} overgrowth. Quartz (1C) is resorbed.

<u>Andesite:</u> Basaltic microxenoliths are plagioclase + pyroxene + glass (2A). Plagioclase (2B) is partially melted throughout, with a normally zoned An_{75-50} overgrowth. Bar length is 0.5 mm.

Fig. 5. A model for evolution of silicic igneous complexes:

I. Basalt from the upper mantle heats the crust.

II. Partial melting in the lower crust produces rhyolite liquid which gathers into diapirs and ascends. In a strongly faulted (upper case) region the diapirs reach the upper crust rapidly and little mixing occurs (e.g., Yellowstone Plateau). In areas lacking extensional tectonics (lower case), mixing is thorough (e.g. Mt. Baker). The middle case is intermediate, mixing occurs but some unmixed rhyolite reaches the surface (e.g. Lassen Park). Large chambers in these centers are compositionally zoned as shown (e.g. San Juans). Activity may cease with eruption or emplacement of silicic bodies if the basalt flux declines.

III. If rhyolite is not replenished due to depletion of the lower crust, but basaltic activity continues, magma in the chamber becomes more mafic and basalt vents encroach on the silicic center (e.g. Long Valley).

Fig. 6: Whole rock initial $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ for several volcanic suites:

Number	Suite	Location	Pseudo-isochron "Age" in MY	Number of Analyses	Reference
1	Doggie Spring Member Superstition Tuff (compositionally zoned tuff)	Arizona	33	3	Stuckless and O'Neil (1973)
2	Barroso Volcanics	Peru	400	8	James and others (1976)
3	Fantale Volcano	Ethiopia	3	12	Dickinson and Gibson (1972)
4	Aden Volcano - Main Cone Series	Yemen	35	8	Carter and Norry (1976)
5	Aden Volcano - Shamson Caldera Series	Yemen	12	5	Carter and Norry (1976)

Letters denote composition of samples at extremes of each data set.

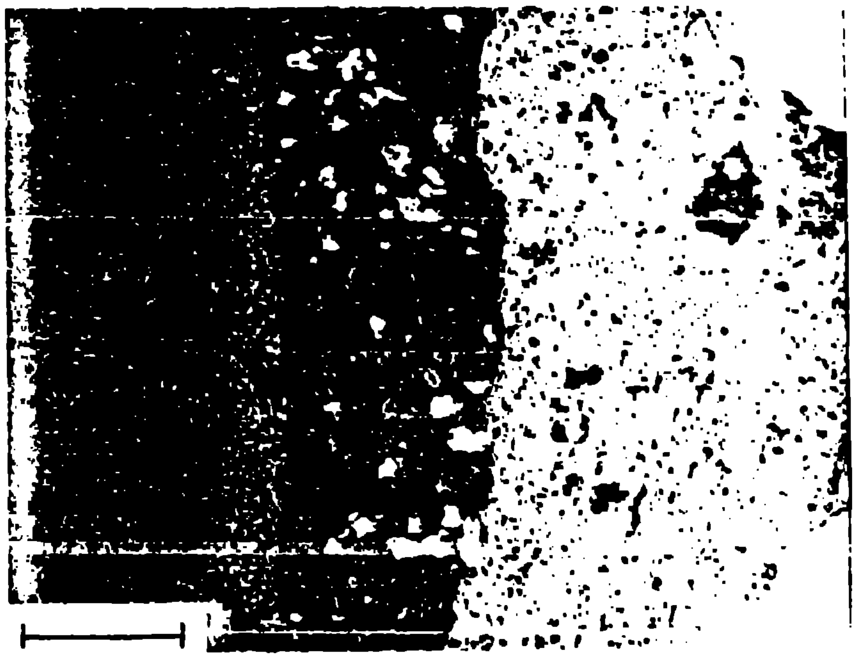
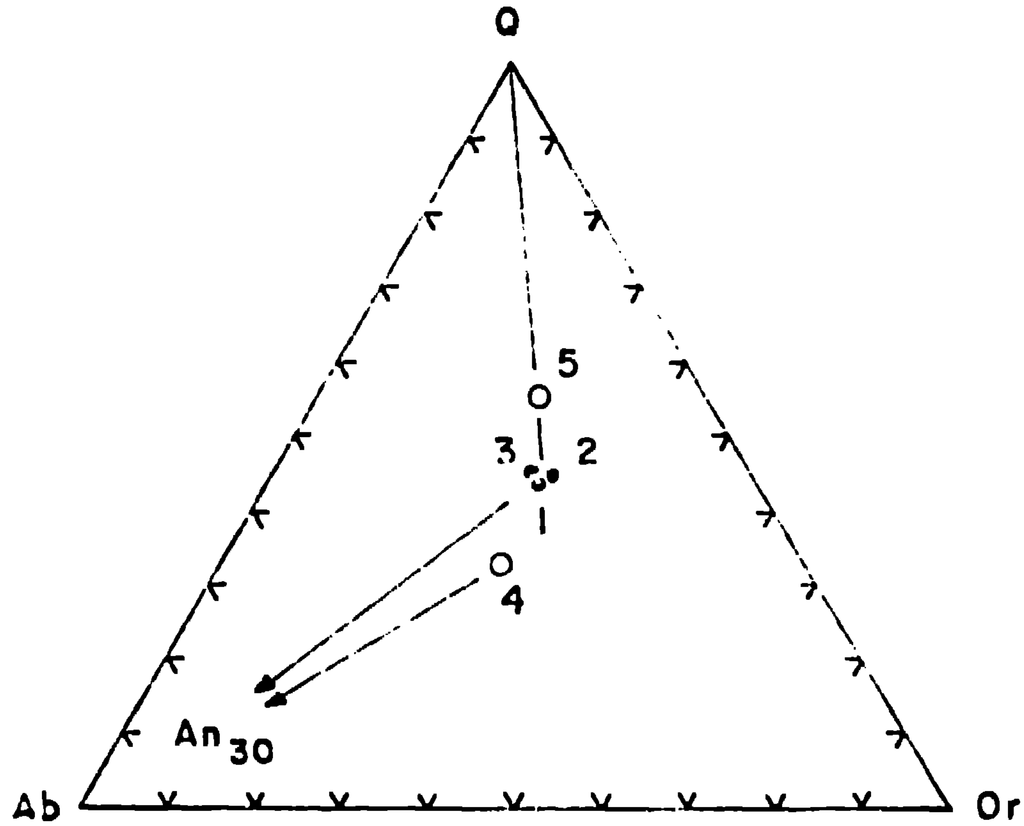


Fig. 1


Q
5
3
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Or

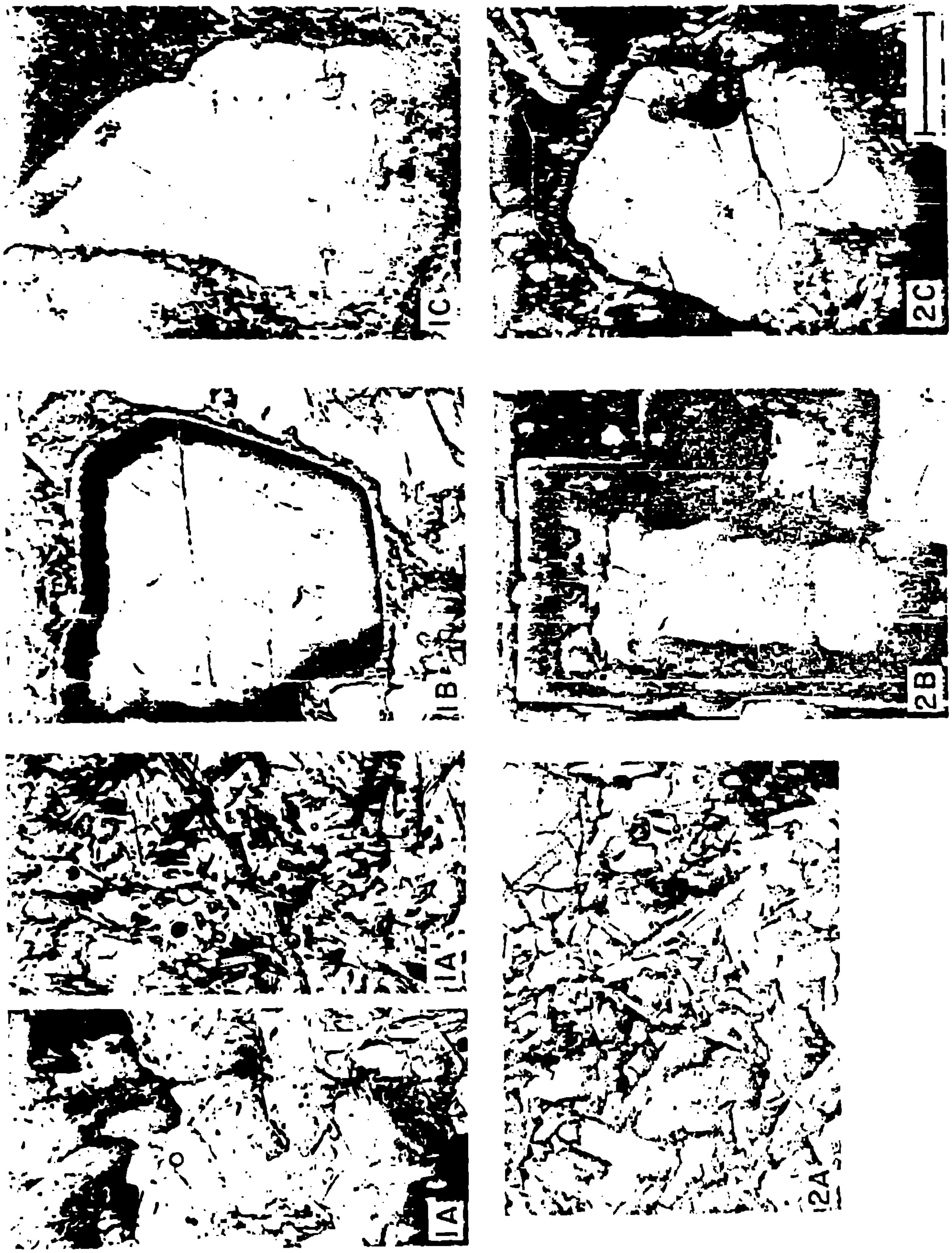


Fig. 3

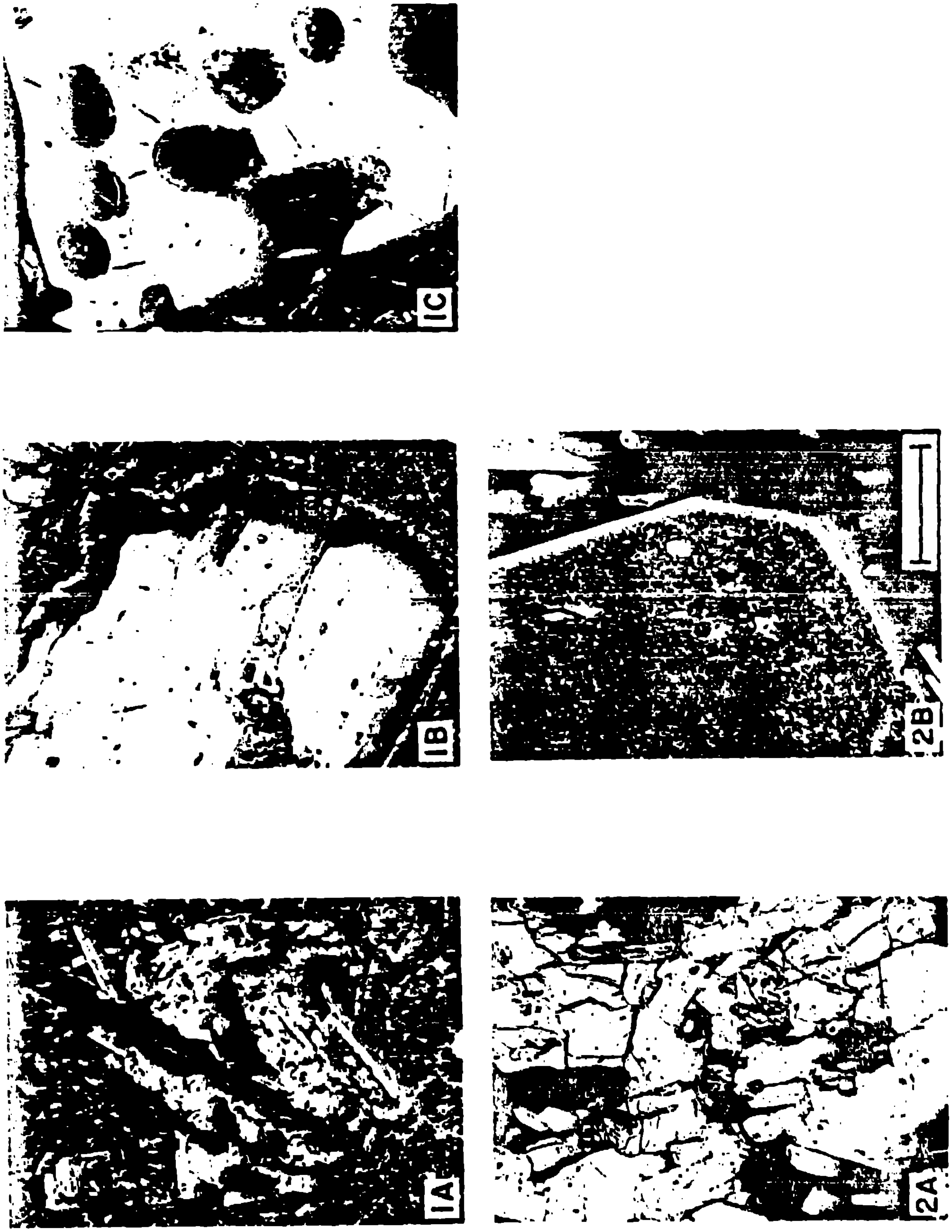
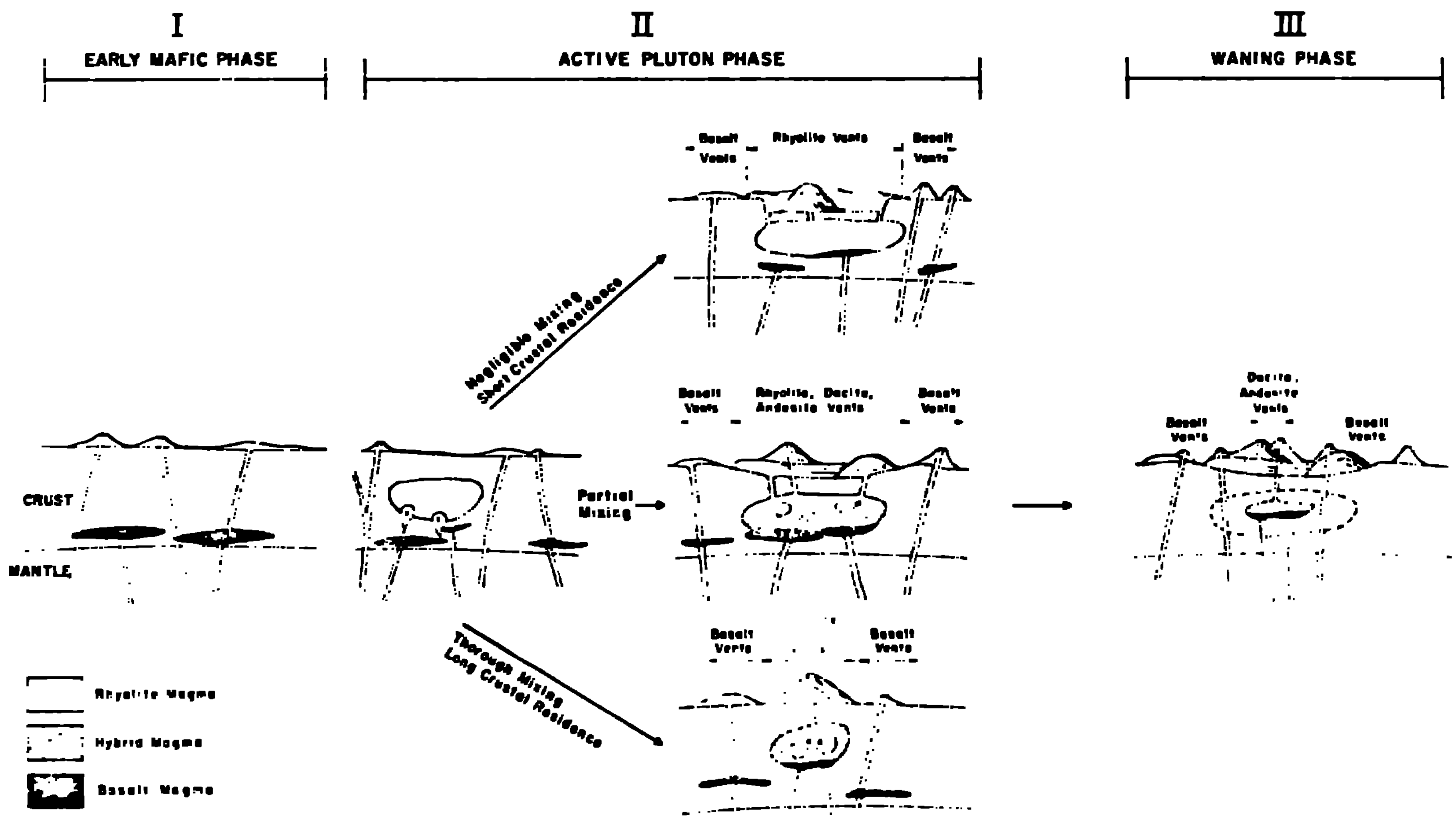
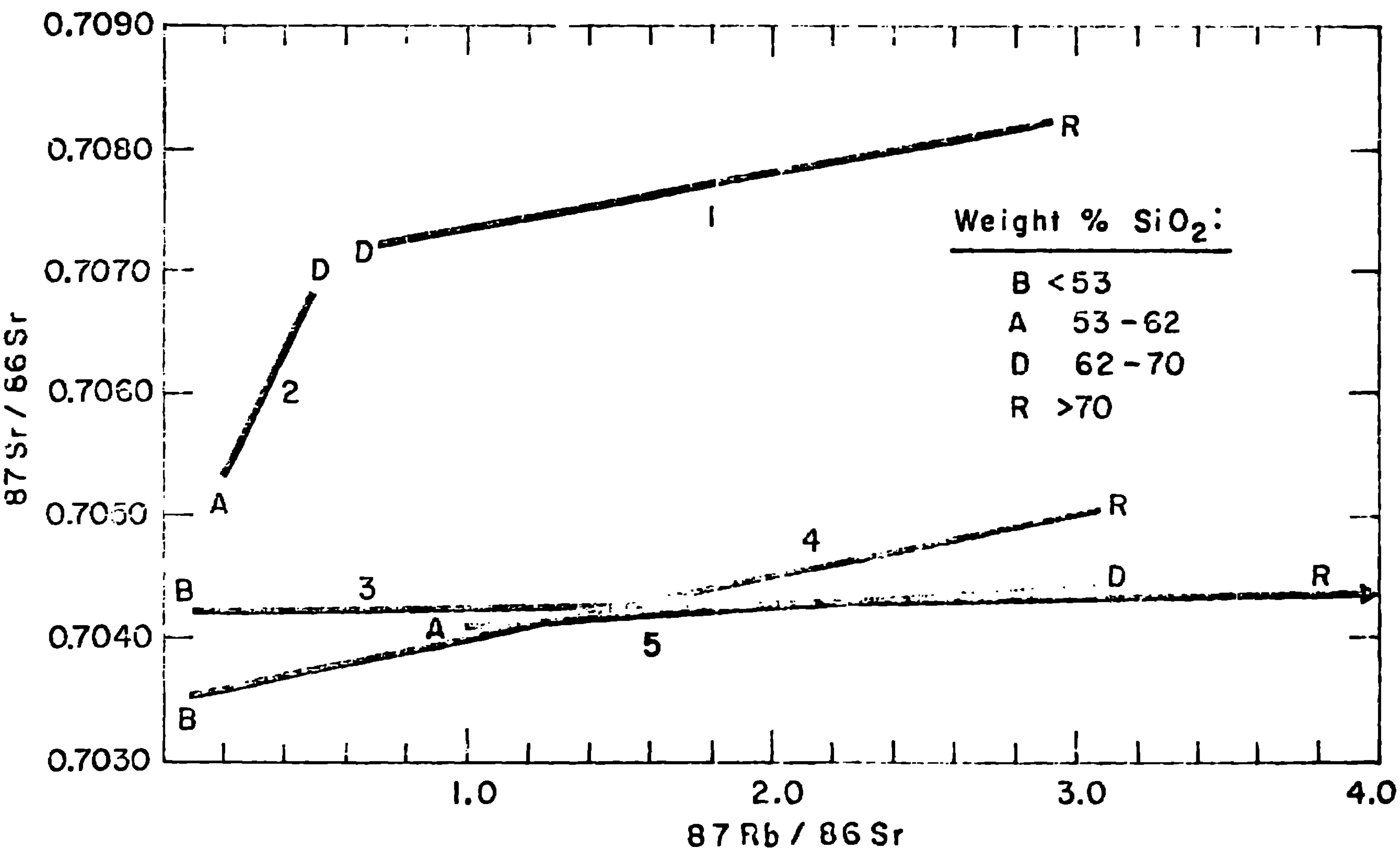


Fig. 4

Fig. 5



I
EARLY MAFIC PHASE
II
ACTIVE PLUTON PHASE
III
WANING PHASE
CRUST
MANTLE
Negligible Mixing
Short Crustal Residence
Partial Mixing
Thorough Mixing
Long Crustal Residence
Basalt Vents
Rhyolite Vents
Rhyolite, Dacite, Andesite Vents
Dacite, Andesite Vents
Rhyolite Magma
Hybrid Magma
Basalt Magma



0.7090
0.7080
0.7070
0.7060
0.7050
0.7040
0.7030
87 Sr / 86 Sr
1.0
2.0
3.0
4.0
87 Rb / 86 Sr
Weight % SiO_2:
B <53
A 53 - 62
D 62 - 70
R >70
1
2
3
4
5