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Introduction

Boqueron Volcano is a composite cone which is the central and youngest part of the San Salvador volcanic center. Boqueron is located 1.5 km. west of the capital city of San Salvador, El Salvador. It is a low-broad cone at the summit of which is a 500 meter deep crater with near-vertical walls. A section of lava flows exposed in the walls of the crater span almost the entire history of the Boqueron cone.

Rittmann (1933), Wilcox (1954), Savelli (1967), Rose (1977), Newhall (1977), and others have used lava trends over periods of years to centuries to infer petrogenetic processes. They have shown knowledge of chemical changes over time to be superior in explaining lava genesis to generalized trends uncontrolled along the time dimension. Using the time-trend approach, a series of lavas, whose relative temporal relations are established by superposition, was taken from the crater walls and the recent flows on the volcano's north and south flanks. The rock-types collected were all vesicular, augite-olivine-plagioclase basalts and andesites.

The Boqueron lavas were examined for temporal chemical and mineralogic trends in an investigation of several volcanologic and petrologic issues. Among the findings of the study are:

- 1) The occurrence of fractionation beneath the volcano.
- 2) The relationship between shallow and deep processes, particularly the timing of magma transfer between them.
- 3) Fractionation processes operating during a single, prolonged eruption.
- 4) The origin of the andesitic lavas.

Regional Geology

Approximately 40 kilometers inland from the Pacific Coast of Central America is a belt of quaternary volcanic centers which extends in a northwest-southeast direction parallel to the coast (Figure 1, after Stoiber and Carr, 1973). Associated with this volcanic chain are many of the regional tectonic features characteristic of the circum-Pacific region. Among them are:

- 1) A deep-sea trench parallel to the coast (The Middle America Trench) (Fisher, 1961).
- 2) Earthquakes concentrated in an inclined zone which begins at the trench and dips beneath the active volcanic belt (Schultz, 1961; Molnar and Sykes, 1969; Stoiber and Carr, 1973).
- 3) Increases in the alkali content of volcanic rocks with increasing distance from the trench (Pichler and Weyl, 1973).

The seismicity of the region has been investigated by Schultz (1963), Molnar and Sykes (1969), Stoiber and Carr (1973), and Carr (1976). Earthquakes are concentrated in two zones. One is the inclined seismic zone, which strikes about north 60 degrees west and dips 30 to 60 degrees northeast. The other zone is a narrow belt of shallow earthquakes which coincides with the volcanic belt. There is a gap in seismicity in the inclined seismic zone directly below the lines of active volcanoes (Stoiber and Carr, 1973) and, typically, concentrations of intermediate depth earthquakes are found a few tens of kilometers seaward of the active volcanoes (Carr and Stoiber, 1973). Foci of these earthquakes range in depth from 70 to 110 km.

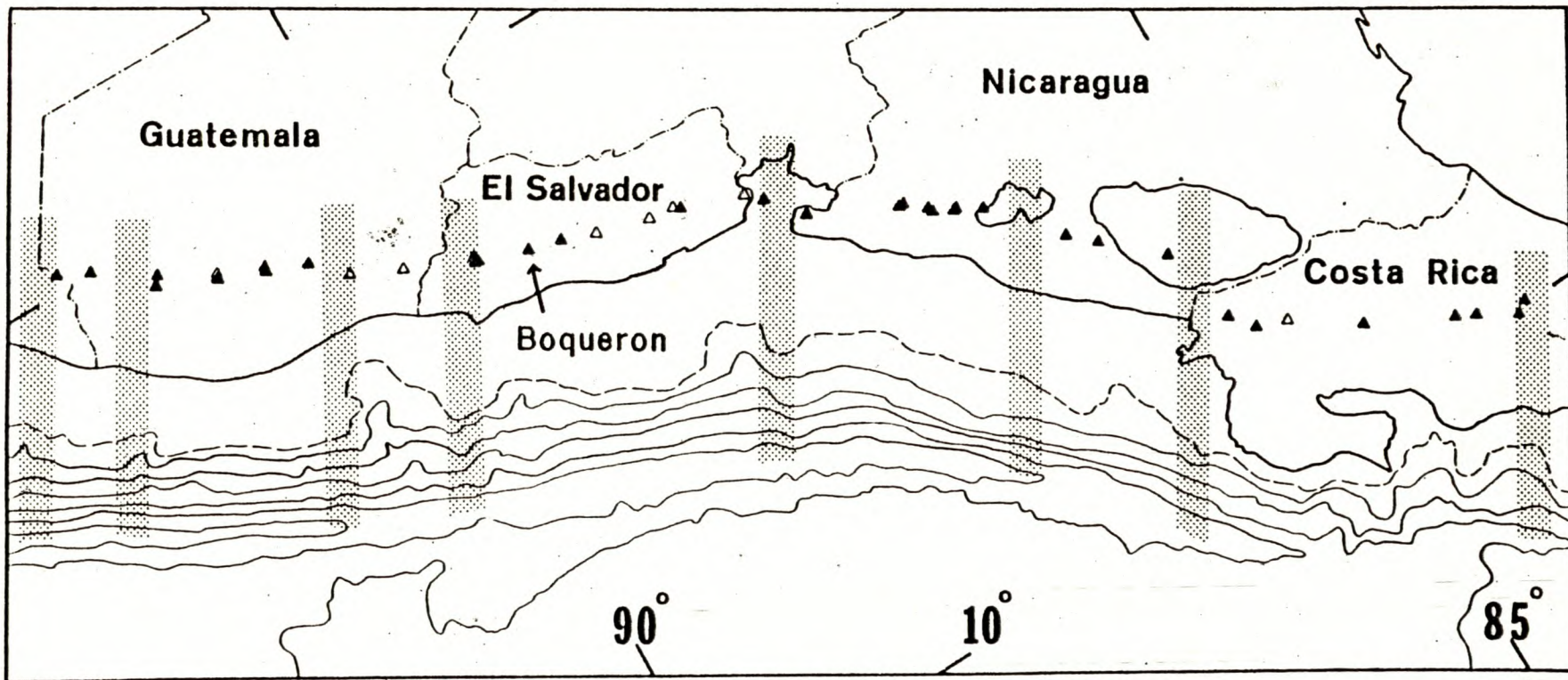


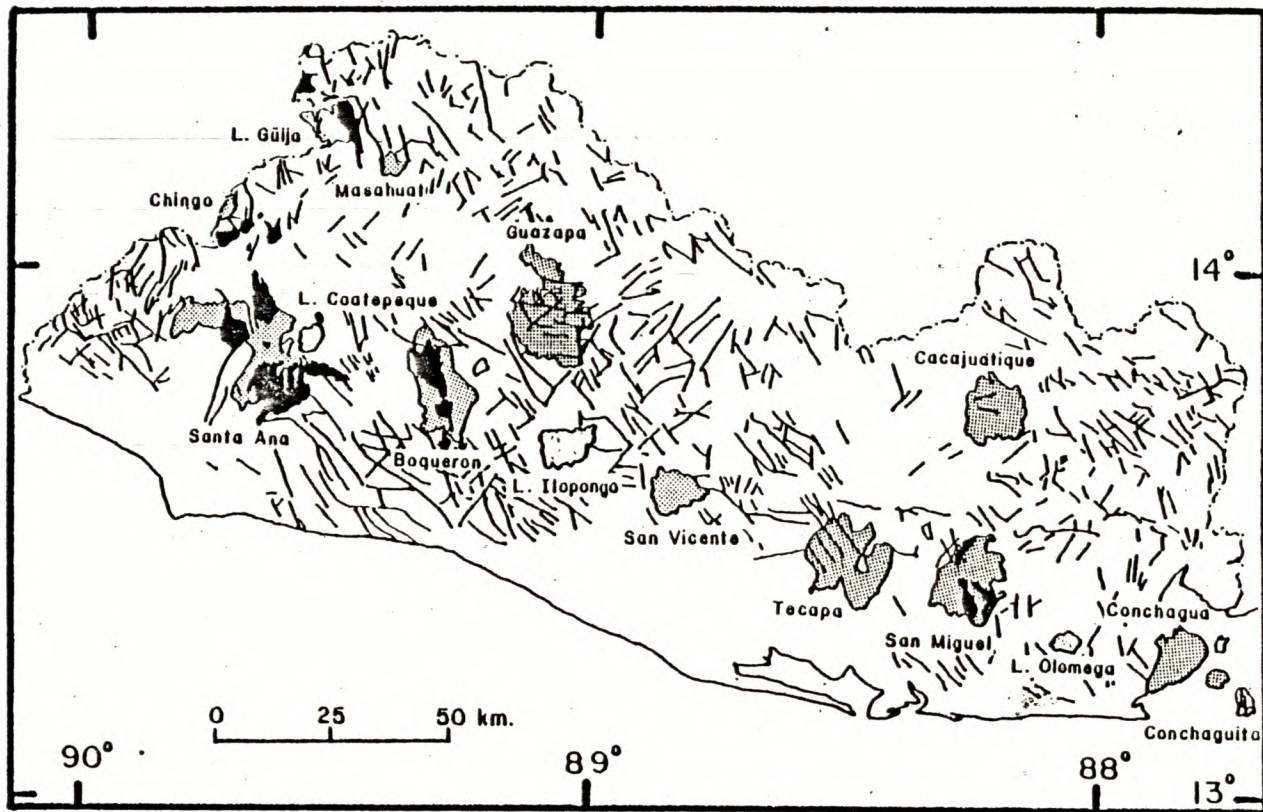
Figure 1 - Generalized map of the southwestern edge of Central America. Solid triangles are volcanoes with historic eruptions. Open triangles are volcanoes with solfataric activity. The dashed contour is the 100 fathom contour. The next contour is the 500 fathom contour, and subsequent contours have a 500 fathom interval. Stippled areas represent boundary areas between the volcanic segments (from Stoiber and Carr, 1973).

Stoiber and Carr (1973), and Carr (1976) have pointed out transverse structures and offsets in the volcanic chain that divide this plate margin into segments (Figure 1). All but the westernmost edge of El Salvador lies within the El Salvador segment, whose proposed boundaries pass through the Santa Ana volcanic complex in the west and through the Gulf of Fonseca in the east. Stoiber (1976) has suggested that volcanic behavior varies with position relative to the segment boundaries.

Most prominent of the regional geologic features in El Salvador is the Salvador Graben, or Trough, which extends east-west across the Republic. It is 20-30 km. wide and is filled with Quarternary volcanics originating at the volcanic centers of the active belt. Lakes Ilopango and Olomega are isolated remnants of the unfilled graben (Williams and Meyer-Abich, 1955). The graben continues to the southeast as the Nicaragua Depression. To the northwest in Guatemala only the southern boundary of the graben is seen as the Jalpatagua Fault scarp (Wiesemann, 1975). Williams and Meyer-Abich proposed in 1955 that the graben represented the foundered crest of a broad geanticline which was formed by Pliocene volcanoes. The trough was subsequently filled with the products of the Quaternary volcanic chain, except at Lake Ilopango, where renewed collapses occurred until a few thousand years ago. Wiesmann (1975) has modified this scheme, interpreting the graben as a series of En-Echelon basins formed along east-west and northwest-southeast structural trends. Major volcanic centers of the main volcanic chain are located at the intersection of these two structural trends. Pleistocene and Recent volcanism has been concentrated in the basins, although it

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- Quaternary basaltic effusive rocks
- Quaternary andesitic and basaltic effusive rocks; pyroclastic rocks

Figure 2 - Structural map of El Salvador with recent lava flows (from Bosse, et. al., 1974).

has not been restricted to it. Within the trough the Quarternary volcanic chain extends WNW-ESE over the entire length of the Republic (figure 2). From west to east, the historically active volcanoes are the Santa Ana group, San Salvador/Boqueron, Lake Ilopango (Islas Quemadas), San Vicente, Tecapa, San Miguel, Conchagua, and Conchaguita. An earlier generation of volcanoes is represented by the Chingo Cluster, Guazapa, Cacagatique, and Masahuat.

Another prominent structural trend is seen in faults striking northwest-southeast with faults spread throughout the country. Boqueron/San Salvador, San Vincente and its parasitic cones, and the volcanoes north of the Gulf of Fonseca are also aligned along these faults. Other fault systems strike north-south and northeast-southwest, being especially prominent around Lakes Coatepeque and Ilopango. Carr (1976) recognizes three primary fault directions in northern Central America—NE-SW (transverse), N-S (tensional), and NW-SE (volcanic chain).

Structure, History, and Petrography of Boqueron

Immediately west of the city of San Salvador is a Pleistocene to Recent compound stratovolcano variously called San Salvador, Quetzaltepeque, and Boqueron. (see Figures 1 and 2). The ancestral volcano, San Salvador, began to grow in the previously established Salvador graben sometime before the formations of Lake Coatepeque. Collapse of the cone left a caldera four miles in diameter, within which the cone of Boqueron grew. Remnants of the old volcano are seen as the peaks of Picacho and Jabali, to the east and northwest of Boqueron (see Figure 3 and Plate I).

Boqueron contains a 500 meter deep crater, at the bottom of which is a small, 30 meter high cinder cone called Boqueroncito. The crater of Boqueron is roughly square, with a diameter at the top of 1500 m. The bottom of the crater is between 1340 and 1350 m., and the rim is between 1780 and 1890 m. The slopes of the ancient volcano, San Salvador, can be seen below 1300 m., where they are inclined 15 degrees. Above 1300 m. only the gentler slopes (7.5 degrees) of Boqueron are seen. Since the crater floor is at 1340 m., the walls of the crater must contain almost the entire history of the Boqueron cone subsequent to the filling of the San Salvador caldera. Williams and Meyer-Abich (1955) consider the crater to be a subsidence feature, but it is equally possible that the crater is an explosion phenomenon.

Boqueron's active vents are controlled by three prominent fracture zones oriented WNW-ESE, NW-SE, and NNW-SSE (Wiesemann, 1975). The first is parallel to the main volcanic axis. Along it lie the central crater of Boqueron, and four explosion craters, including Laguna de Chanmico. Along the NW-SE fracture lie several boccas and craters

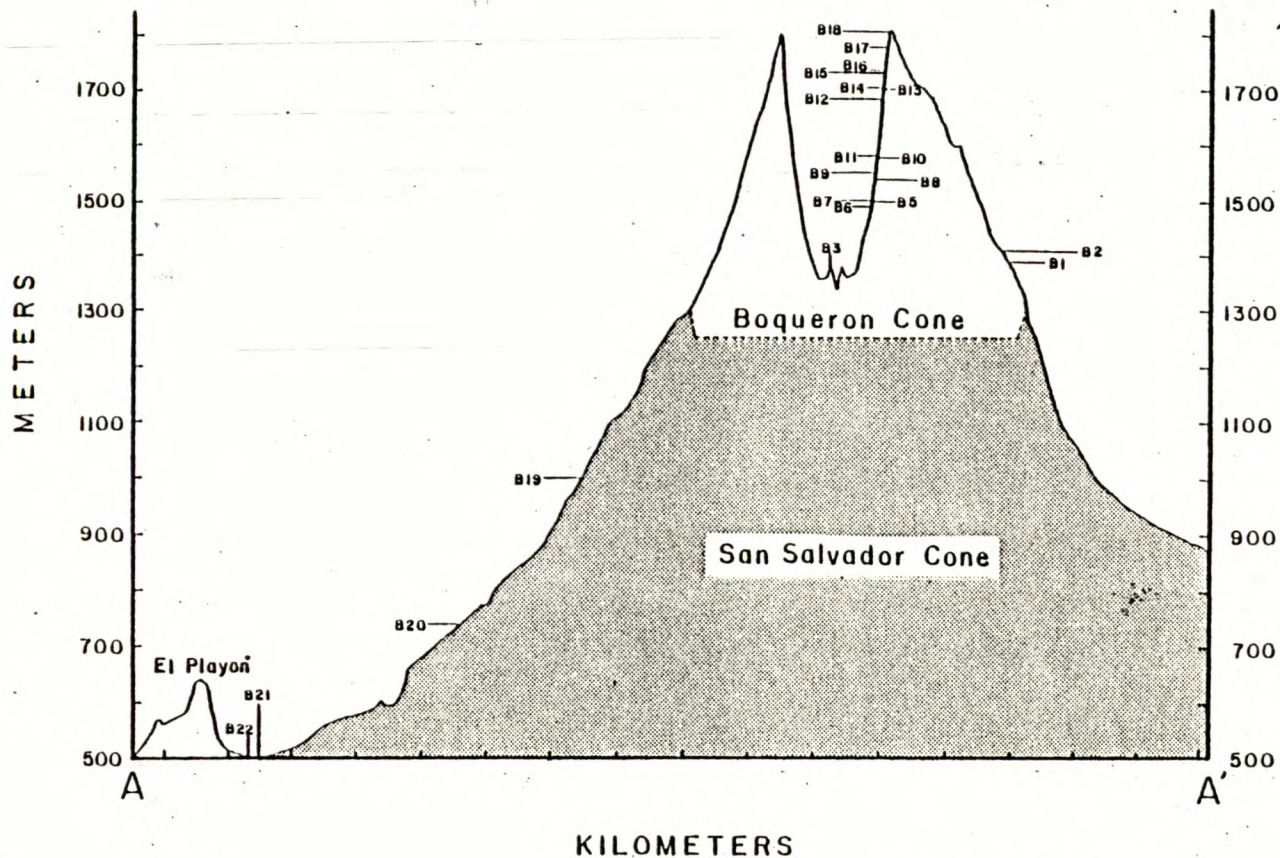


Figure 3 - NE-SW cross-section through Boqueron, with sample locations. Stippled area is the inferred volume of the ancestral volcano.

including the Los Chintos cones, the historically active cinder cone of El Playon, the three cinder cones called the Boqueroncitos, the parasitic cone of La Joya, and the collapse pit of Puerto de Laguna (see Plate I). Along the NNW-SSE fracture lie the bocca of the 1917 eruption on the NNW side, and a cinder cone and an explosion crater on the SSE side at 1200 and 800 m. respectively (Williams and Meyer-Abich, 1955; Mooser, et. al., 1958).

Williams and Meyer-Abich propose that late in Boqueron's history there was a prolonged series of andesite pumice eruptions from the summit vent, contemporaneous with similar eruptions at Lake Ilopongo. The best exposures of pumice deposits which may have erupted from Boqueron are seen on the western flanks of the cone, where up to 84 layers and many zones of weathering are exposed in a 400 ft. section. Weyl (1954) has estimated the time necessary for the ashes to accumulate, based on the total thickness of the weathered zones seen in this section. Given a total thickness of the weathered zones of 100 ft., and assuming a weathering rate of 1670 years/ft., the period of eruption must have been at least 160,000 years. The composition of the ejected material is primarily dacitic, with some andesitic material, and it occurs chiefly as a pumiceous glass. Dominant minerals include plagioclase, hornblende, hypersthene, augite, and magnetite. Identification of the Boqueron pumice is based mainly on the presence of angular lithic fragments mingled with the pumice, which are composed chiefly of pyroxene andesite, and olivine-bearing basalt and andesite. These were presumably torn from the crater walls of Boqueron. Their number and size generally decrease with increasing distance away from the crater (Williams and

Meyer-Abich, 1955).

Last of these pumice layers to be erupted was the "Tierra Blanca", which is a thick, white mantle draping a vast area around Boqueron, Lake Ilopongo, and the city of San Salvador. Contained within the latest layers to be erupted are many human artifacts, found at several sites. Ages of these are estimated at 2993 plus or minus 360 years, based on radiocarbon dating of charcoal fragments found in a humus layer containing ceramic fragments (Williams and Meyer-Abich, 1955). The Tierra Blanca layer is not found within Boqueron's central crater. Whether there is a causal relationship between the voluminous pumice eruptions and the formation of the Boqueron crater is not clear, but the possibility exists. Until 1917 the crater contained a small lake at the bottom.

The Recent, prehistoric flows of the Boqueron cone began with a flow extruded from a fissure on the northeast slope of Picacho. Other flows were erupted on the flanks of Boqueron, primarily on the northern flanks. Sample B-24 (see Plate 1) was taken from the most prominent of these. During this time the Boqueroncitos and the Los Chintos cones were formed over a period of not more than a thousand years (see Plate I). The latest of these is El Playon, a basaltic cone which formed in 1658. Following a period of explosive eruption accompanied by a strong earthquake, the cone erupted a flow from its eastern base, the volume of which is estimated at approximately 0,01 cubic km. Sample B-22 was collected from this flow. Williams and Meyer-Abich (1955) describe this unit as an augite olivine basalt on a petrographic basis, but sample B-22 has been classified by chemical criteria under the Irvine and Baragar (1971) scheme for volcanic rocks as a tholeiitic

andesite.

In 1671 El Playon erupted again with a period of explosive activity and the recorded destruction of arable land (Larde Y Larin, 1948, Mooser, et. al., 1958). Mooser, et. al. (1958), citing Ximenez (1722), and Meyer-Abich (1955), regard the Talpetate Layer, a prominent ash layer, as having been formed by this eruption. Explosive activity was observed again in 1806.

On June 6, 1917 the NW-trending fissures on the north flank of Boqueron opened (Schultz, 1963) to release a voluminous flow (Approx. 0.01 cubic km.) of black, vesicular tholeiitic andesite. Simultaneously, a chain of cinder cones formed parallel to the Boqueroncitos. On June 10, the lake in the summit crater began to boil and it disappeared altogether by June 28. In the same place, eruptions of tholeiitic andesite (Sample B-3), described by Williams and Meyer-Abich (1955) as olivine-augite basalt, were observed until November. The result of these eruptions was the small cinder cone, Boqueroncito. Williams and Meyer-Abich reported in 1955 that hot vapors still issued from near its base, as did Weyl in 1961, but none were observed in May, 1976, during field collection for the present study.

In recent years considerable attention has been given to the relations between earthquakes and volcanic eruptions (Blot and Priam, 1963; Carr and Stoiber, 1973; Carr, 1976; Kimura, 1976). Both large historic eruptions of Boqueron have been accompanied by strong earthquakes. Ballore (1884) mentions an earthquake associated with the 1659 eruption, which is described as having completely destroyed San Salvador. The temporal relations of the eruption and the earthquake are not mentioned, but from the description it appears that the eruption

came first. A strong earthquake caused extensive damage to San Salvador on June 6, 1917, the same day that the eruption began.

The Lavas of Boqueron

1) Data Collection

The section in the Boqueron crater walls is composed of layers of highly altered ash and laharic material alternating with lava flows. A prominent ash and pumice layer extends from 1580 to 1680 m. In places vesicular boundaries can be recognized on the lava flows, but such features are generally obscured by alteration, slumping, and vegetation. Within the section 15 samples were collected from massive flow interiors (see Figure 3). In addition, two flows exposed in a stream channel on the southeast flank were sampled (B-1 and B-2), and 5 samples were collected from recent flows erupted on the north flank. Of these, three were taken from the 1917 flow (B-19, B-20, and B-21), one from the 1659 El Playon eruption (B-22), and one from a recent prehistoric flow (B-24). Figure 3 and the map of Boqueron (see Plate I) show the field relations of the samples.

Most samples were collected from unaltered rock of the massive, central parts of fresh flows. Near the base of the section weathering had proceeded to such an extent that unaltered rock could not be found. Samples B-6 (1490 m.), B-7 (1500 m.) and B-8 (1540 m.) have moderately high water contents (0.99 to 1.54) and varying degrees of alteration of olivines, groundmass pyroxenes, and glass in thinsection.

Modal analyses were made using 1000 point counts. Bulk chemical data were collected using the atomic absorption method of Medlin and Shur (1969). All analyses added to 100.0%, plus or minus 0.9%. Variation diagrams were made from normalized analyses that were recalculated on a water-free basis. Normative mineral compositions were

calculated using the CIPW program (Fortran IV) of Niekirk and Backstrom (1966), as modified by Henderson (1969). Mineral analyses were made on the ARL microprobe at Lamont-Doherty Geological Observatory at Palisades, New York.

2) Petrography, Modal Mineralogy, and Mineral Chemistry

The samples from the Boqueron lavas show substantial petrographic variation. Cinders, glasses, and porphyritic lava flows are represented. The majority are grey to black porphyritic flows with phenocrysts of zoned plagioclase, olivine, clinopyroxene, and occasionally Titanium-rich magnetite. Orthopyroxene is occasionally present. Amphiboles were not observed. The plagioclase is predominantly labradorite and bytownite, and ranges in size from groundmass dimensions to 5 mm. Glomeroporphyritic crystal clusters of pyroxene, olivine, plagioclase, and opaques are observed in some samples, particularly B-12 and B-13. The clusters are interpreted as nucleation and cooling phenomena. Stewart (1975) interprets clots containing all four minerals as breakdown products of high-temperature amphiboles, but the wide range of mineral associations make this interpretation unlikely for the Boqueron samples. Reaction rims of clinopyroxene on olivine are seen in some samples. Groundmass consists of plagioclase, clinopyroxene, magnetite, and glass in varying proportions. Most samples are moderately to highly vesicular. Modal mineralogy is given in Appendix A.

Plagioclase

Plagioclase occurs in sizes ranging from phenocrysts (5 mm. to less than or equal to 1 mm.) to groundmass. It predominates in both the phenocrysts and groundmass. Modal phenocryst plagioclase ranges from

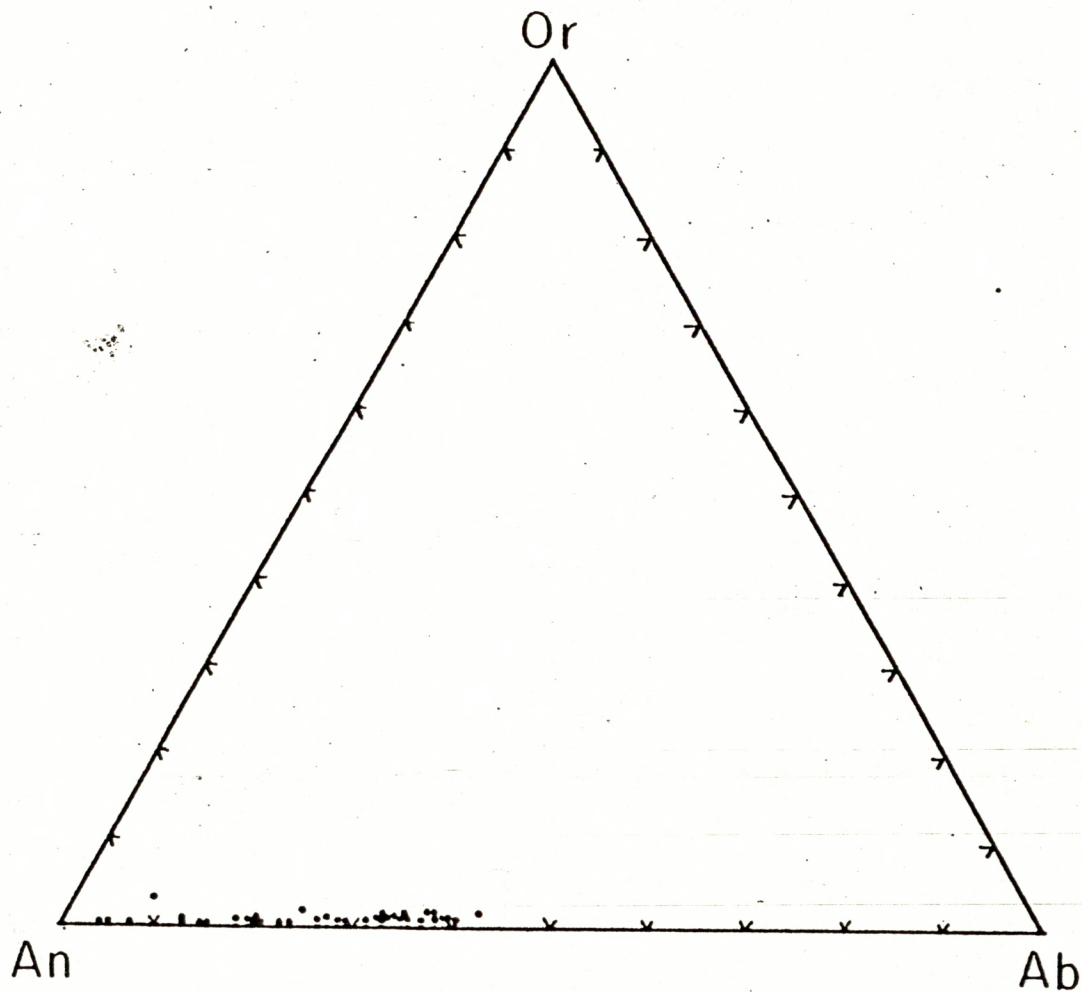


Figure 4 - Phenocryst plagioclase compositions in lava samples B-3, B-22, B-11, and B-6.

0.0 to 35.6% and groundmass plagioclase from 0.0 to 55.9% of the total count. Microprobe analyses show anorthite contents ranging from 95.5 to 57.8 (see Figure 4). Zoning is common in the phenocrysts. Occasionally plagioclase occurs in glomeroporphyritic clusters with Titanium-rich magnetite and, less frequently, with pyroxene or olivine also. Microprobe analyses of selected grains are given in Appendix A.

Olivine

Olivine ($\text{Fo}_{46.1}$ to $\text{Fo}_{65.4}$) occurs in some samples as phenocrysts or microphenocrysts, but it is never common, and is never found in the groundmass. Modal phenocryst counts range from 0.0 to 5.5% of the total count. Olivine is occasionally found in glomeroporphyritic clusters with Titanium-rich magnetite, and less frequently with plagioclase and/or pyroxene. Reaction rims of augite on olivine occur mainly in the samples from the middle of the sequence. Weathering of olivine is common in the older samples and has progressed almost to completion in the samples from the bottom of the section. Representative analyses are given in Appendix A.

Pyroxenes

Phenocrysts, microphenocrysts, and groundmass clinopyroxenes occur in all the samples except the glasses. Microprobe analyses (see Appendix A) give augite compositions with Wo values between 35.4 and 39.4, and En values varying from 38.9 to 43.8 mole % (see Figure 5). Orthopyroxene is absent in most samples and is present in trace amounts in the others. After glass and plagioclase, pyroxene is usually the most common groundmass constituent. Modal phenocryst counts range from 0.0 to 40.0% of the total count. Pyroxene occurs with Titanium-

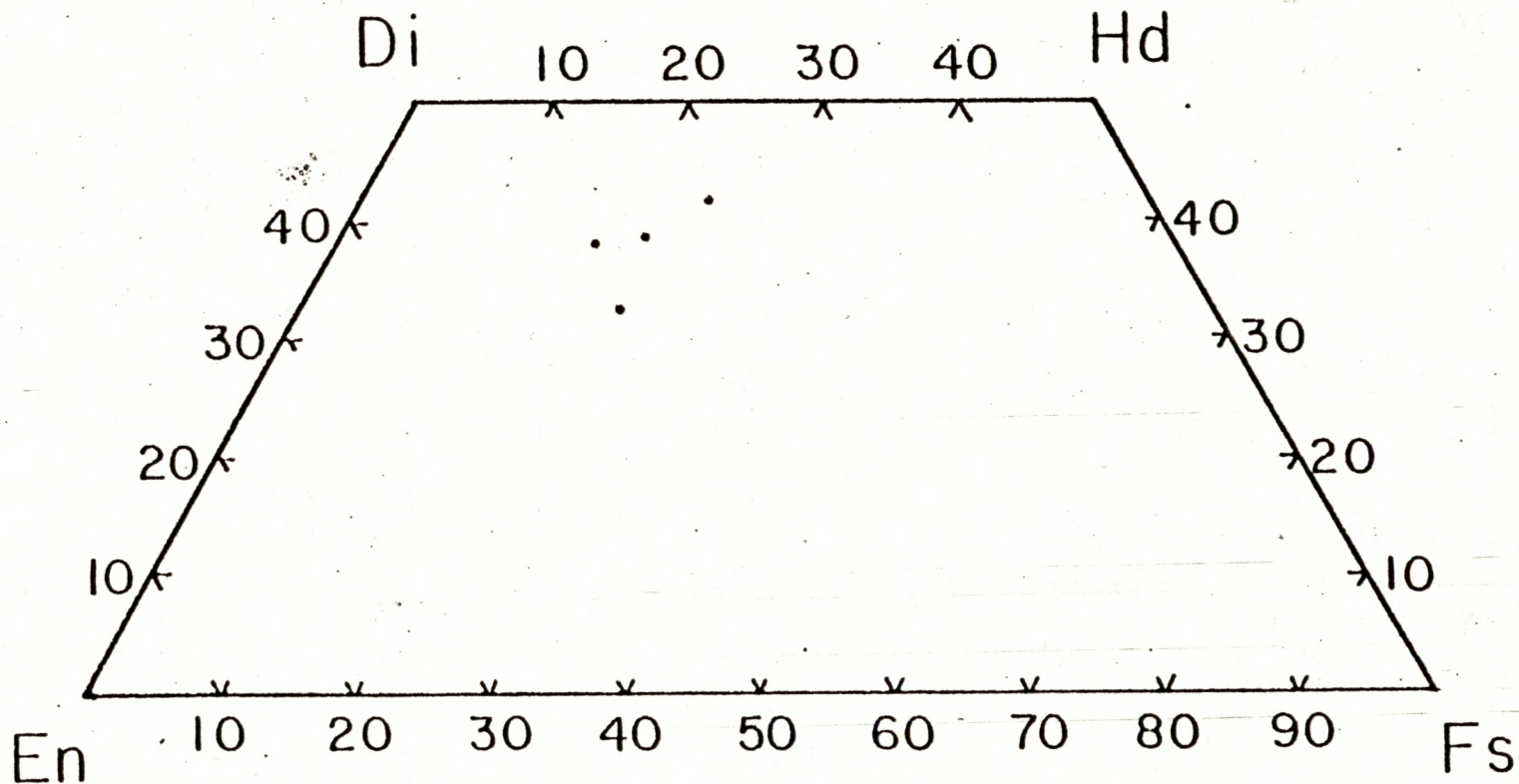


Figure 5 - Phenocryst augite compositions in lava samples B-3, B-22, B-11, and B-6.

rich magnetite in crystal clots, either independently or together with plagioclase and/or olivine. Inclusions of pyroxene in plagioclase or vice versa do not occur. Rims of augite on olivine are seen in some samples.

Opaques

Opaque minerals occur as phenocrysts and groundmass grains, with modal phenocrysts ranging from 0.0 to 1.1% and groundmass from 0.0 to 10.4% in modal abundance. The large opaques most commonly occur with plagioclase, pyroxene, and/or olivine. Opaques of groundmass dimensions occasionally occur as inclusions in pyroxene or plagioclase. Microprobe analyses (see Appendix A) show the opaques to be of High-Titanium magnetite composition ($Mt_{85.9} Uv_{14.1}$ to $Mt_{88.5} Uv_{11.5}$), and reflected-light analysis shows exsolution of magnetite and ilmenite in one of the older rocks.

Glass

Glass is normally the most common constituent of the Boqueron samples, with modal counts seldom falling below 12%; B-11 has the least glass, with 2% of the total count. Glass color ranges from light-brown to black, and alteration is common in many of the older samples. Silica contents may range as high as 70% (B-3) and potassium as high as 5.6%, as determined by microprobe analysis.

Using the chemical data and the volcanic rock classification scheme of Irvine and Baragar (1971), the rocks were classified as tholeiitic and calc-alkaline basalts and andesites (see Appendix A). Data points cluster near the tholeiitic/calc-alkaline and andesite/basalt boundaries. Medium- and long-term trends can be seen across both.

3) Bulk Chemical Data

Normative mineralogy is listed in Appendix A and summarized in Figure 6. All values are in the CIPW norm and are expressed in weight percent. All samples but B-11 are quartz-normative, and none have nepheline in the norm.

Major element compositions of the Boqueron lavas are presented in Figures 7, 8, and Appendix A. In Figure 7, the same scale is used for weight percent on the horizontal axis, as a means of comparing the range of variability among the oxides. In Figure 8 the scale of weight percent on the horizontal axis is adjusted so that range of variation is the same in each plot. This is done to compare the details of the variation. In all figures in which parameters are plotted against sample number, the vertical sample number scale represents relative ordinal position in time, not elevation. No attempt has been made to quantify the absolute time between the samples. Short-, medium, and long-term variations can be seen in the modal, and normative mineralogy, and most clearly of all in the bulk chemical data (see Figures 6, 7, and 8).

The range of chemical compositions varies among the oxides, but is generally much larger than the error due to analytical uncertainty (see Appendix A) or sampling techniques. Recalculated SiO_2 weight per cent values range from 51.9 to 61.1. Large variations are also seen in Fe, Mg, Ca, and Al (Figures 7 and 8). K also shows small variations which correlate with larger variations in other oxides (Figure 8). Only Na and Ti show no consistent pattern over time. $\text{Fe}/(\text{Fe} + \text{Mg})$ varies between 0.68 (B-6) and 0.83 (B-3), with a trend toward magnesium depletion over time (see Figure 9). Total alkalis (Figure 10) vary between 4.67 (B-6) and

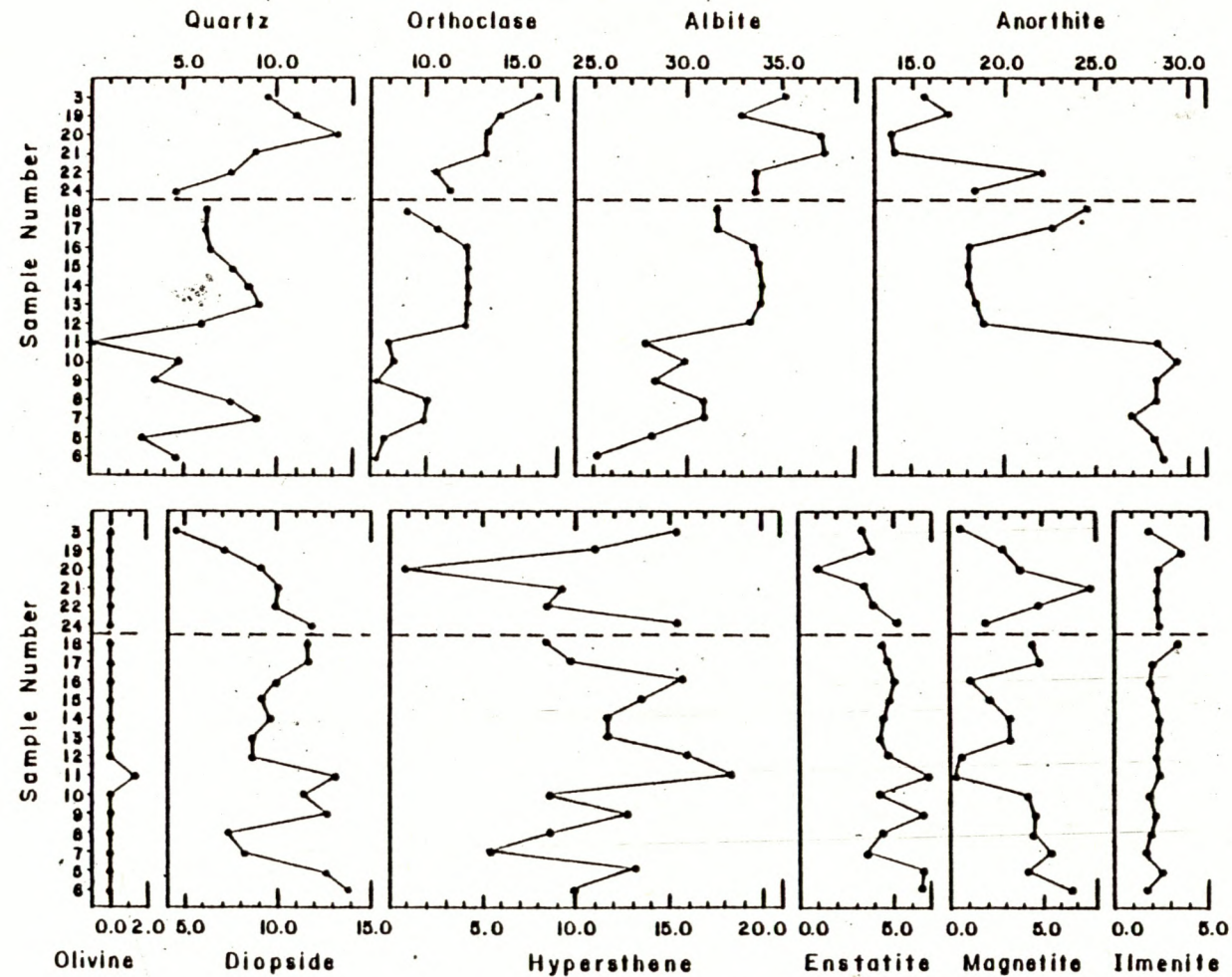


Figure 6 - Normative mineralogy vs. time (sample number).
Dotted line as in figure 7.

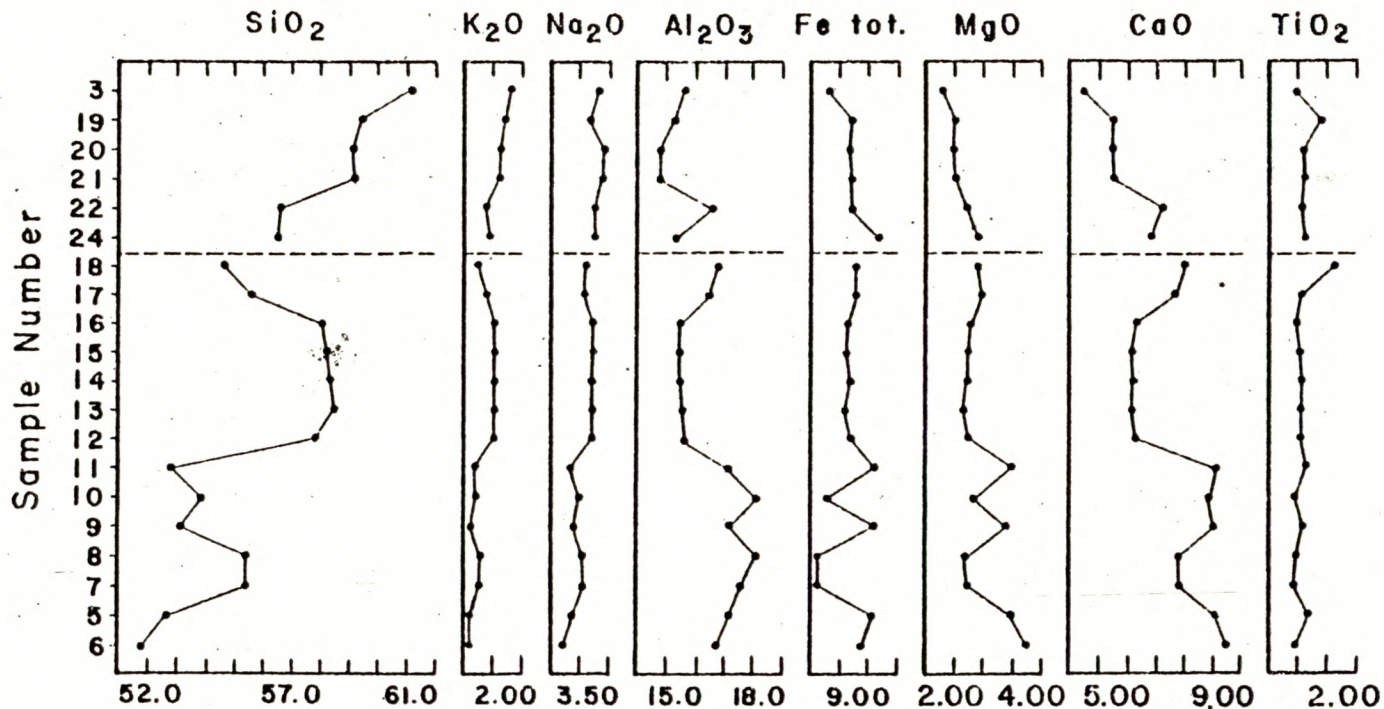


Figure 7 - Weight percent of the major oxides vs. time (sample number), with weight percent plotted in the same abscissa units for all oxides. Dotted line separates the flows in the crater wall from the flank flows.

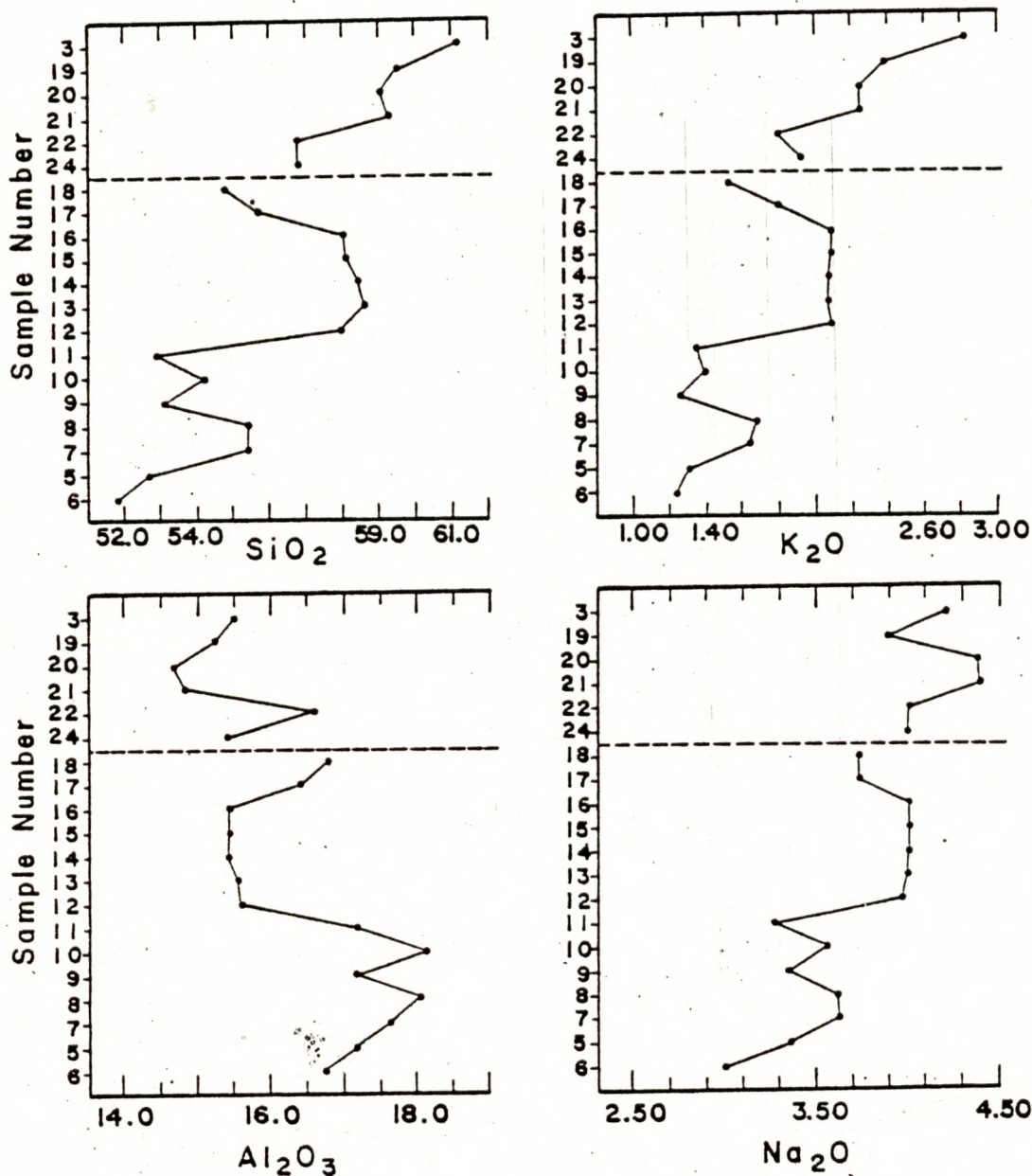


Figure 8 - Weight percent of the major oxides vs. time (sample number), with variation range plotted in the same abscissa units. Dotted line as in figure 7.

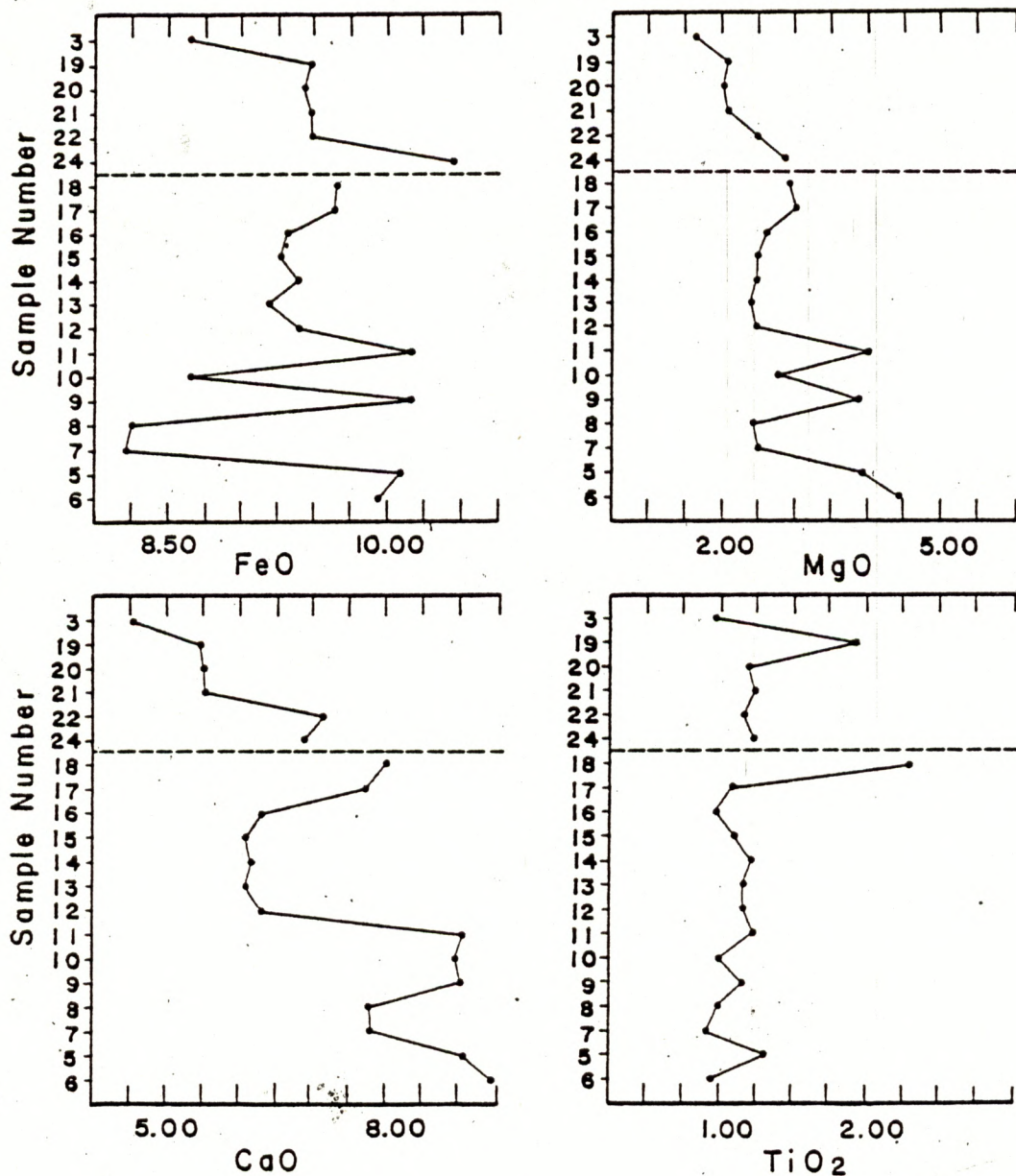


Figure 8 (cont'd.)

6.92 (B-3), and they also show a long-term enrichment. $K/K + Na$ values (Figure 11) show a pattern similar to $Fe/Fe + Mg$ and are consistent with a trend toward higher potassium content with time.

Complementary patterns are exhibited in the time plots between the oxides concentrated in the early crystallizing phases (CaO , MgO , FeO , TiO_2) and those which tend to concentrate in the residuum (SiO_2 , K_2O , Na_2O) (see Figure 8). The complementary character of the oxides in the Boqueron rocks suggests that magma differentiation has occurred, probably involving olivine, pyroxene, Ca-plagioclase and high-Ti magnetite or ilmenite. This proposal is examined in more detail in later sections. If differentiation is occurring, an indication of the extent of differentiation can be obtained in the ratio of the two groups of oxides - specifically, $(Fe\text{-total} + MgO + CaO + TiO_2/SiO_2 + K_2O + Na_2O)$. Plotting this index along the section (Figure 12) summarizes the variations and trends in the chemical data.

4) Temporal Magmatic Variations

Several scales of chemical variation have been observed in lava sequences. These can be divided into four categories—A) Variations in composition, mainly vertical, within a single flow (short-term), B) Variations between different stages of the same eruption (also short-term), C) Variations between eruptions, often cyclic, which recur over a period of years to centuries (medium-term, cyclic), and D) Variations which develop over the life of the volcano (long-term). The Boqueron samples show significant trends in each of the last three categories.

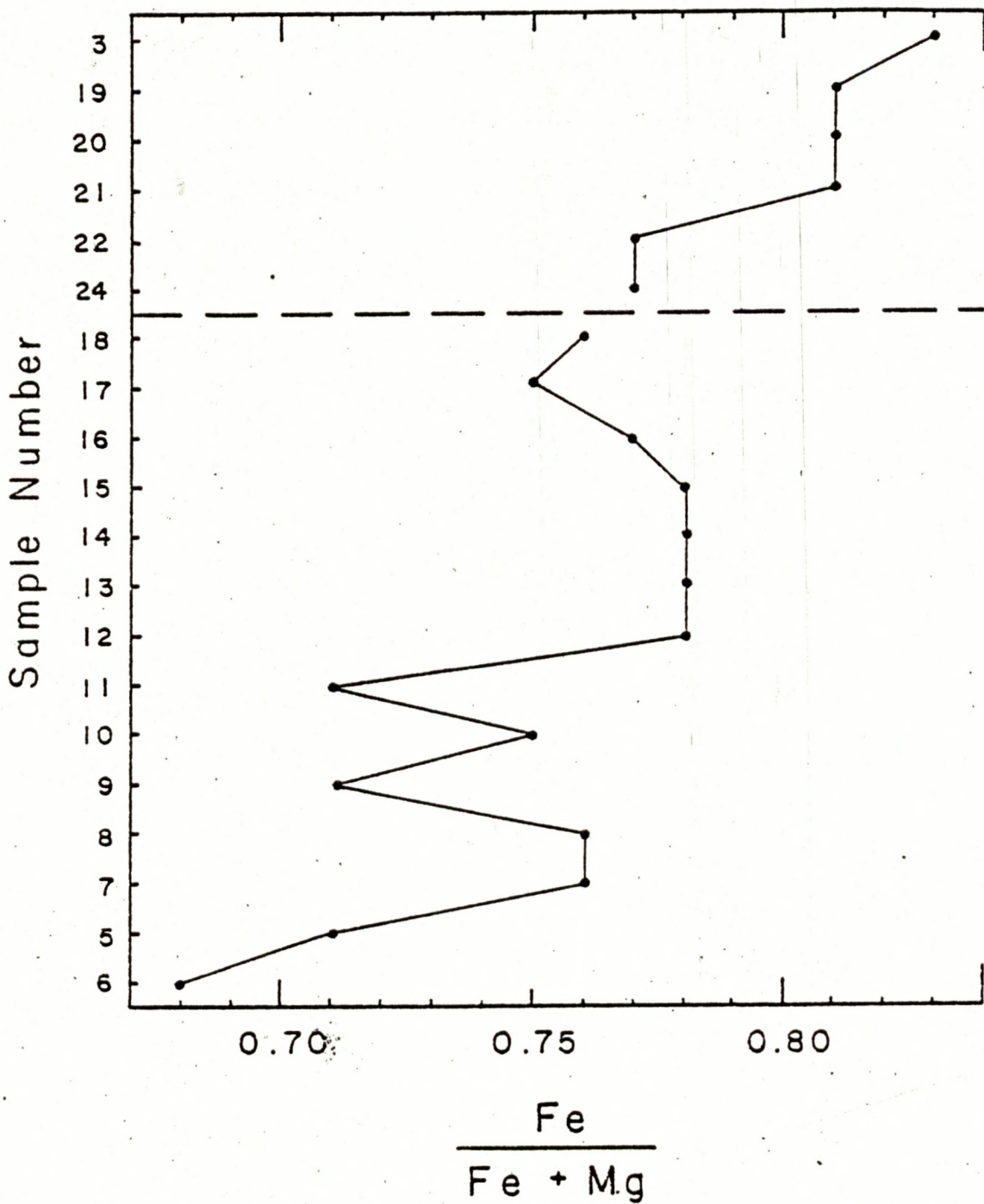


Figure 9 - Fe/Fe+Mg vs. time (sample number). Dotted line as in figure 7.

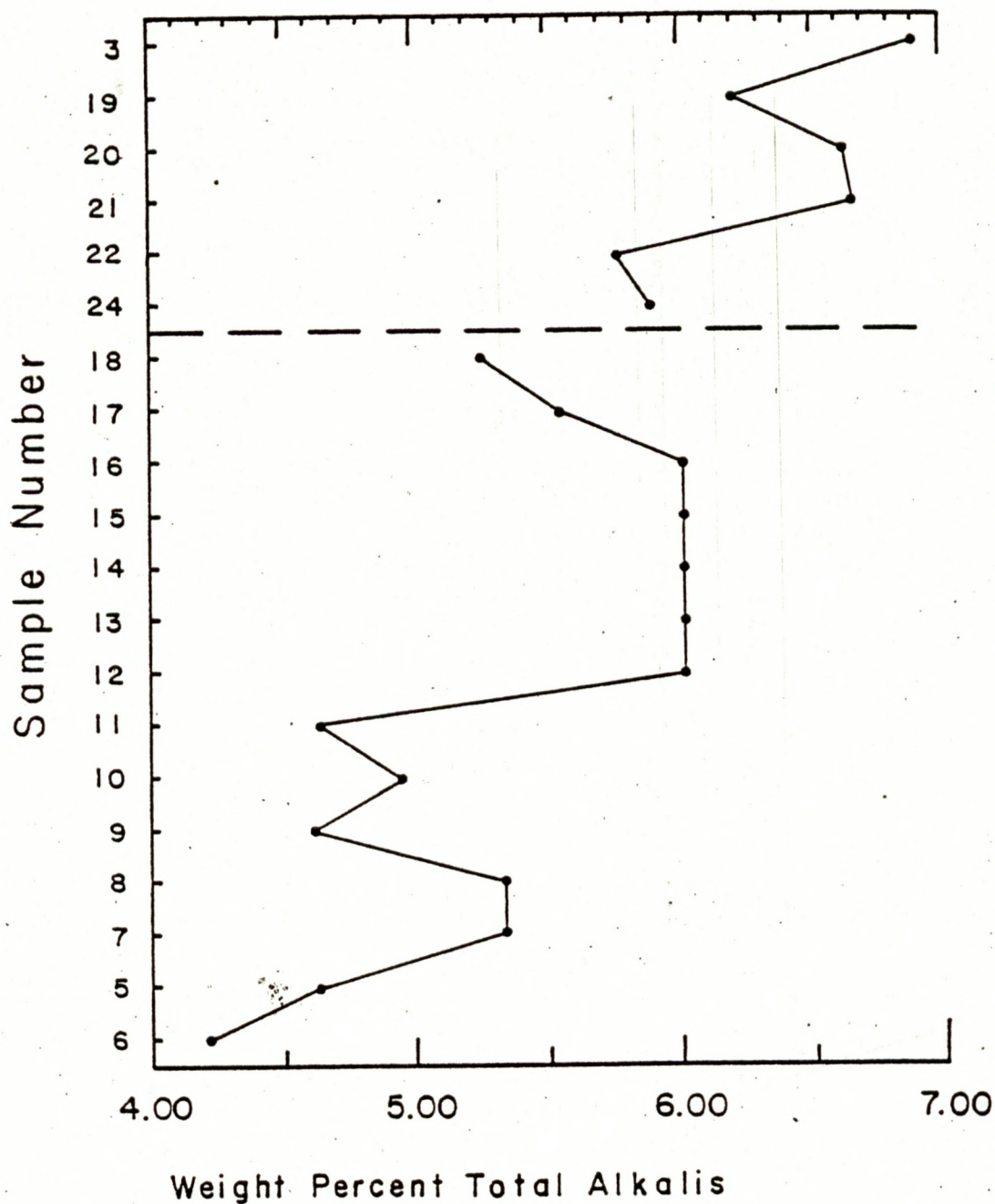


Figure 10 - Total alkalies vs. time (sample number).
Dotted line as in figure 7.

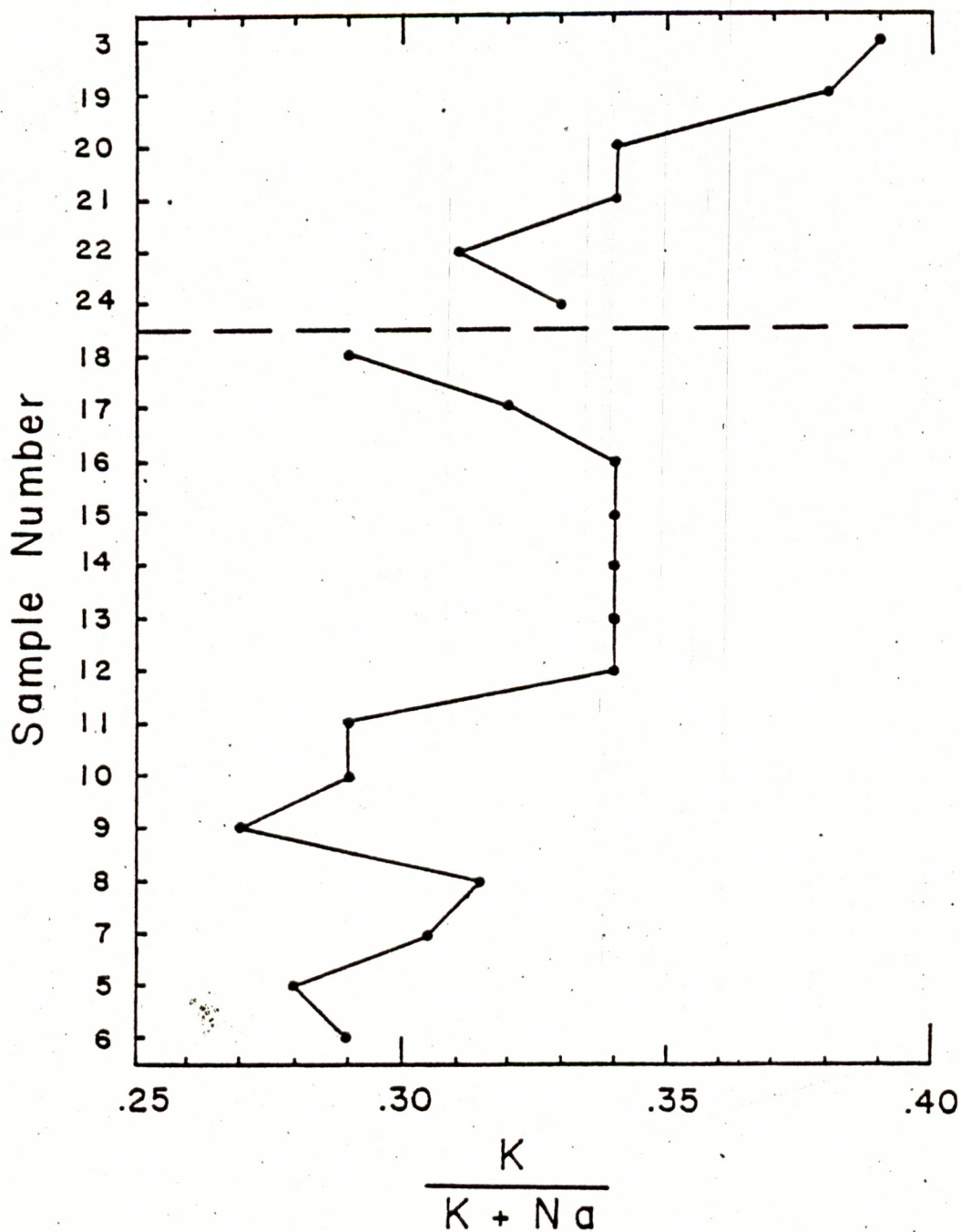


Figure 11 - $K/K+Na$ vs. time (sample number).
Dotted line as in figure 7.

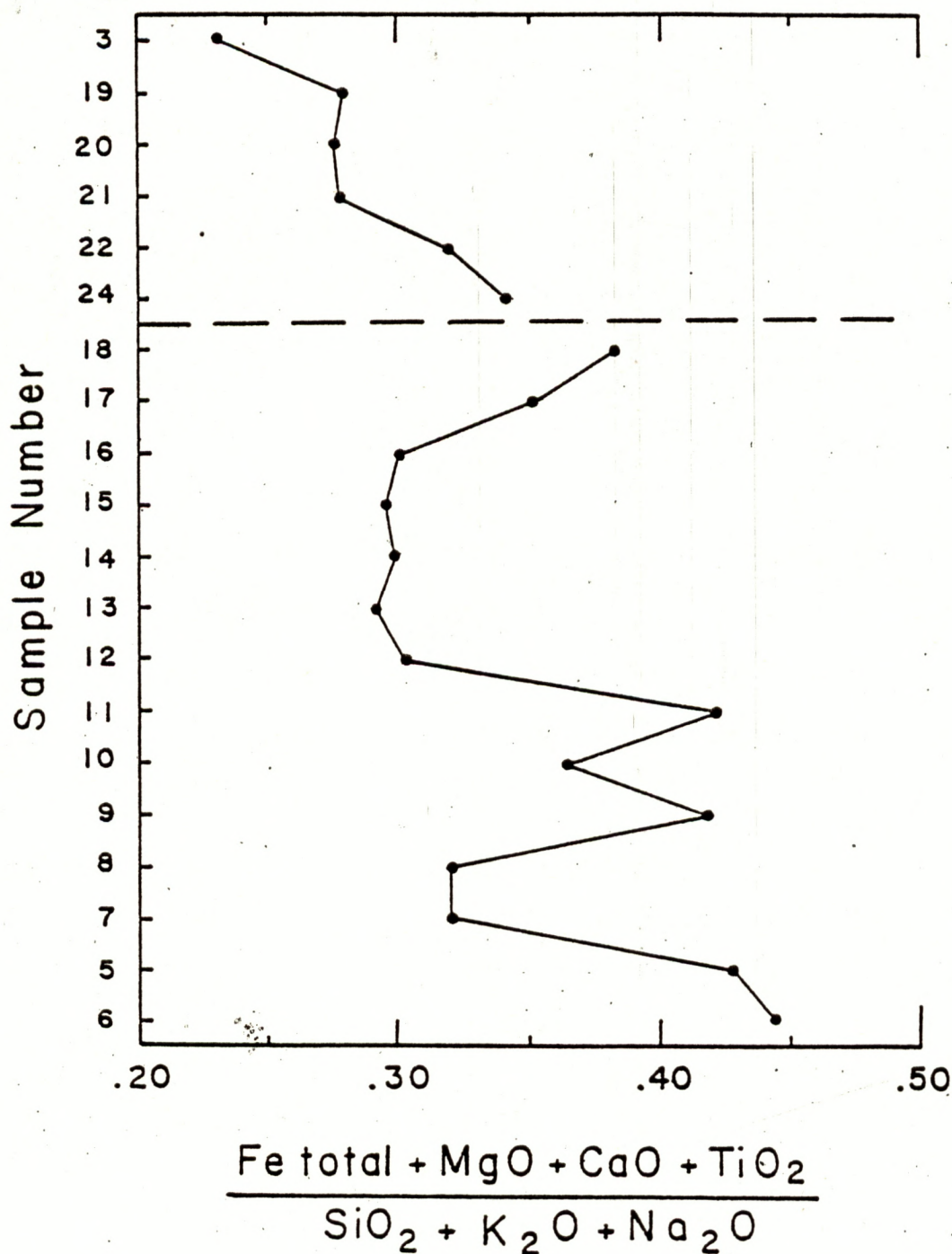


Figure 12 - $(\text{Fe total} + \text{MgO} + \text{CaO} + \text{TiO}_2) / (\text{SiO}_2 + \text{K}_2\text{O} + \text{Na}_2\text{O})$ vs. time (sample number).
Dotted line as in figure 7.

A) Variations within a lava flow

Fuller (1939) examined late Tertiary basalt flows and found a surface depletion and basal concentration of olivine which presumably developed during the later stages of cooling. Watkins, Gunn and Coy-yll (1970) and Hart, Gunn and Watkins (1971) examined vertical sections in a 10 m. thick Icelandic lava flow for significant variations in major and trace element concentrations. They found large vertical variations in the late crystallizing components (especially K and Rb), which they explain by a variation in the pyroxene-plagioclase ratio, uneven distribution of K-Feldspar and olivine, and by migrations of residual liquids during the final stages of cooling.

Variation of the major oxides, however, was limited to a maximum range of 1.0 to 2.0 weight percent (SiO_2), with much of this occurring in the top and bottom edges of the flow. The authors recommend crushing and homogenizing several samples from various levels of lava flows, but outcrop exposures in the Boqueron crater limited the applicability of this procedure. However, data from the 1917 flank flows (B-19, B-20, B-21) suggest that intraflow variation at Boqueron is negligible or absent (see below).

The scale of intraflow effects can also be evaluated by comparing the time-profile plots for the major oxides. Figure 8 shows that some of the major oxides—especially SiO_2 and CaO —show interflow variation ranges that far exceed those found by Watkins, et. al. Watkins' intraflow processes cannot explain the fact that most of the oxides show patterns parallel to trends in SiO_2 and CaO . Since the SiO_2 - K_2O - Na_2O and CaO - MgO - FeO trends are each internally parallel, and at least one oxide

in each group has a variation range larger than that found for intraflow processes. It is reasonable to conclude that these variation patterns reflect other processes. Patterns of Al_2O_3 and TiO_2 in Figure 8 show few consistent correlations with the others. Also, their variation ranges are only slightly larger than those given by Watkins, et. al. (1970). It is therefore possible that these two oxides—especially Al_2O_3 —show patterns which are essentially obscured by flow-cooling effects. Al_2O_3 was therefore neglected in the analyses of temporal variation.

B) Variations between different stages of the same eruption

The distinction between this category and the previous one is the introduction of processes causing chemical variation among materials extruded at different times during the same eruption. Different phases of the same eruption may exhibit sharply different compositions due to fractionation processes operating in the interior of the volcano before or during the eruption.

MacDonald (1944) found that lavas from vents at different altitudes during the 1840 eruption of Kilauea showed compositional differences that were largely the result of fractionation caused by olivine settling in the magma column. Murata and Richter (1966) found compositional variations in the 1959 Kilauea eruption which they could relate to fractional crystallization of a tholeiitic magma. Tilley (1950), Powers (1955), Wager (1956), Muir and Tilley (1957), and Tilley (1960) have also considered the variation trends in the Kilauea eruptions as a function of fractional crystallization.

At Boqueron samples from the 1917 eruption were taken from the lip of the cinder cone in the main crater, Boqueroncito (1380 m., B-3), from two locations in the main flow on the north flank of the volcano (vent at 1340 m., B-21, B-21), and from a secondary flow, also on the north flank (vent at 1380 m., B-19). According to historical accounts, eruption of the flank flows preceded the birth of the cinder cone by at least three weeks, and the eruption of the cinder cone ended almost five months after the formation of the lava flows. Since sample B-3 was taken at the crater rim, it must have erupted at least several months after the flank flow samples. The relationship between the samples can be summarized as follows:

B-20 and B-21 flowed from the lowest vent on the north flank and were the first to be erupted. They were collected from sites over 3 km. apart.

B-19 was erupted at approximately the same time as B-20 and B-21, but from a vent 40 m. higher up.

B-3 was erupted much later than the others from a central vent at approximately the same elevation as B-19.

Figure 7 shows little difference between B-19, B-20, and B-21. B-3, however, is definitely more fractionated than the earlier lavas. The samples fall on a differentiation trend which includes all the recent flank eruption lavas collected. B-3 is the most differentiated of all the Boqueron lava samples. Analysis by least-squares mixing indicates that, within limits of analytical error and possibly wall-rock contamination, the trend in the 1917 lavas can be explained by fractional crystallization involving plagioclase ($An_{81.2}$ to $An_{60.0}$),

olivine ($\text{Fo}_{64.5}$), augite, and High-Titanium magnetite (see Appendix A and Table 1 for mineral analyses). Samples B-20 and B-21, which were taken from locations over 3 km. apart and 240 m. apart in elevation, but from the same flow, were almost identical in chemical compositions—well within the smallest range of uncertainty. Here, intra-flow variation appears to have been negligible; the collection site of the sample had no measurable effect on the chemical characterization of the flow.

On the basis of the data it appears that differentiation was occurring in the interior of Boqueron before and during the 1917 eruption. The slightly more acidic character of B-19, compared to B-20 and B-21, is sufficiently small that it is probably due to analytical error. The differentiation model predicts that B-19 will be more highly fractionated than B-20 and B-21 since it was erupted from a higher elevation in the magma feeding channels (MacDonald, 1944). The observed differences in the B-19 and B-20/B-21 analyses, however, are too small to be considered significant. The highly acidic character of B-3 compared with the others is significant, and it is reasonable to consider B-3 as the result of a differentiation process occurring in the interior of the volcano during the five months of the 1917 eruption.

C) Medium-term, cyclic variation

Over a period of years to centuries the chemical compositions of magmas vary in distinct, often cyclical patterns. Rittmann (1933) noted a long-term trend at Vesuvius toward more iron-, magnesium-, and alkali-rich compositions. Within this long-term trend he distinguished gradual

trends from acidic to basic compositions, with abrupt returns to acidic composition. Tilley and Schoon (1961) found compositional changes at Mauna Loa and Kilauea which occurred over time periods on the order of 20-50 years. Wise (1969) has found variational trends suggestive of a series of magma batches at Mount Hood. Higgins (1973) found medium- and long-term trends associated with extreme differentiation at Newberry Volcano, Oregon. Rose (1977) has found medium-term variation in the lavas of Santa Maria Volcano, Guatemala. Newhall (1977) has done an extensive study of cyclic, medium-term variation of Mayon Volcano in the Philippines.

Most authors conclude that magma fractionation in one form or another is responsible for the cyclic, medium-term variations. Acidic-basic cycles are seen within long-term trends from basic to acidic compositions. In most cases long-term trends are recognized mainly by the trend of the endpoints of the medium-term cycles to more acidic compositions; the most acidic and basic points in each cycle become more acidic compared with those of the previous cycle.

Figure 12 gives a summary of the cyclic, medium-term variation at Boqueron. There are at least three clear trends from basaltic to andesitic compositions (B-6 to B-8, B-11 to B-16, B-18 to B-3, and possibly B-9 to B-10.) Each is terminated by an abrupt jump back to more basaltic compositions. The time required to go from basic to acidic and from acidic to basic compositions is not known, and could be different for each cycle. Within these cycles it is almost certain that many flows were never sampled, but appeared in other walls of the crater. The latest trend, of B-18 to B-3 is probably the most complete. Petrologic mixing calculations were carried out to evaluate

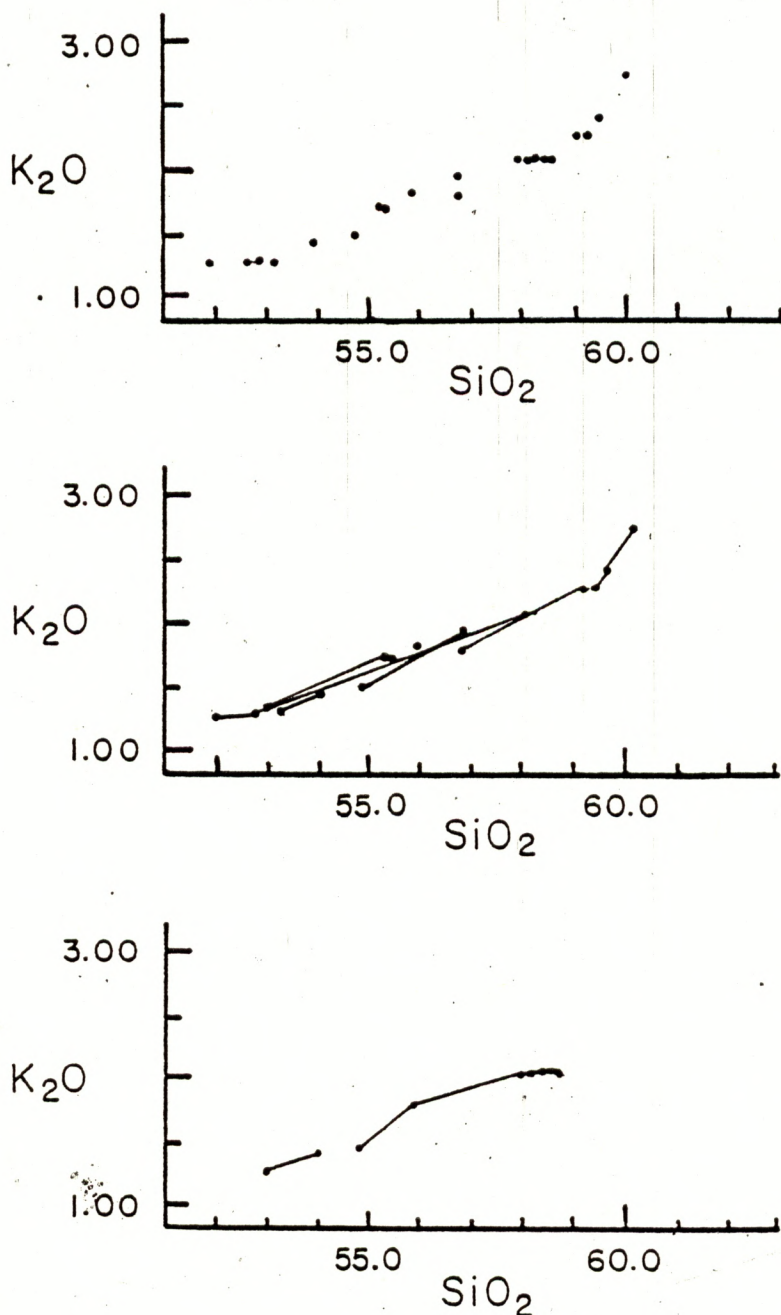


Figure 13 - Harker plot of the Boqueron lavas, K_2O vs. SiO_2 . Top diagram plots all points. Middle diagram plots only those lava pairs which trend toward increasing K_2O - SiO_2 over time. Bottom diagram plots only lava pairs which trend toward decreasing K_2O - SiO_2 over time.

the possibility of magma differentiation causing these trends (see below.

The relationship between cyclic, medium-term variation and long-term variation is demonstrated in Figure 13, which is a Harker Plot of K_2O vs. SiO_2 , with directional lines. The time progression of the data points clearly shows the long-term enrichment trends are not uniform in the acidic direction, as is often proposed for lava suites uncontrolled along the time dimension.

D) Long-term variation

Long-term trends in volcanic products are well established for volcanoes in a wide variety of tectonic settings (Rittmann, 1933; Wilcox, 1954; Wise, 1969; Savelli, 1969; Higgins, 1974; Rose, 1977). Generally these trends are toward increasing silica, alkalis, iron, or some combination of these. In many cases these long-term trends have superimposed over them a series of medium-term cycles.

The long-term trends in the Boqueron lavas (see Figures 7, 8, 9, 10, 11, 12, and 14) are identifiable in all the major oxides but Fe total. A strong enrichment trend is seen in SiO_2 and K_2O . MgO , CaO , and Al_2O_3 are depleted over time (see figure 7). Pronounced chemical trends relative to SiO_2 are shown in Figure 14, which is a Harker Plot for the major oxides. Only TiO_2 shows no identifiable trend. Both the long-term and medium-term trends are consistent with a differentiation process involving olivine, augite, Ca-rich plagioclase, and Titanium-rich magnetite (see below).

5) Mixing Analysis of Magma Differentiation

Fractional crystallization, assimilation, and mixing of magmas may

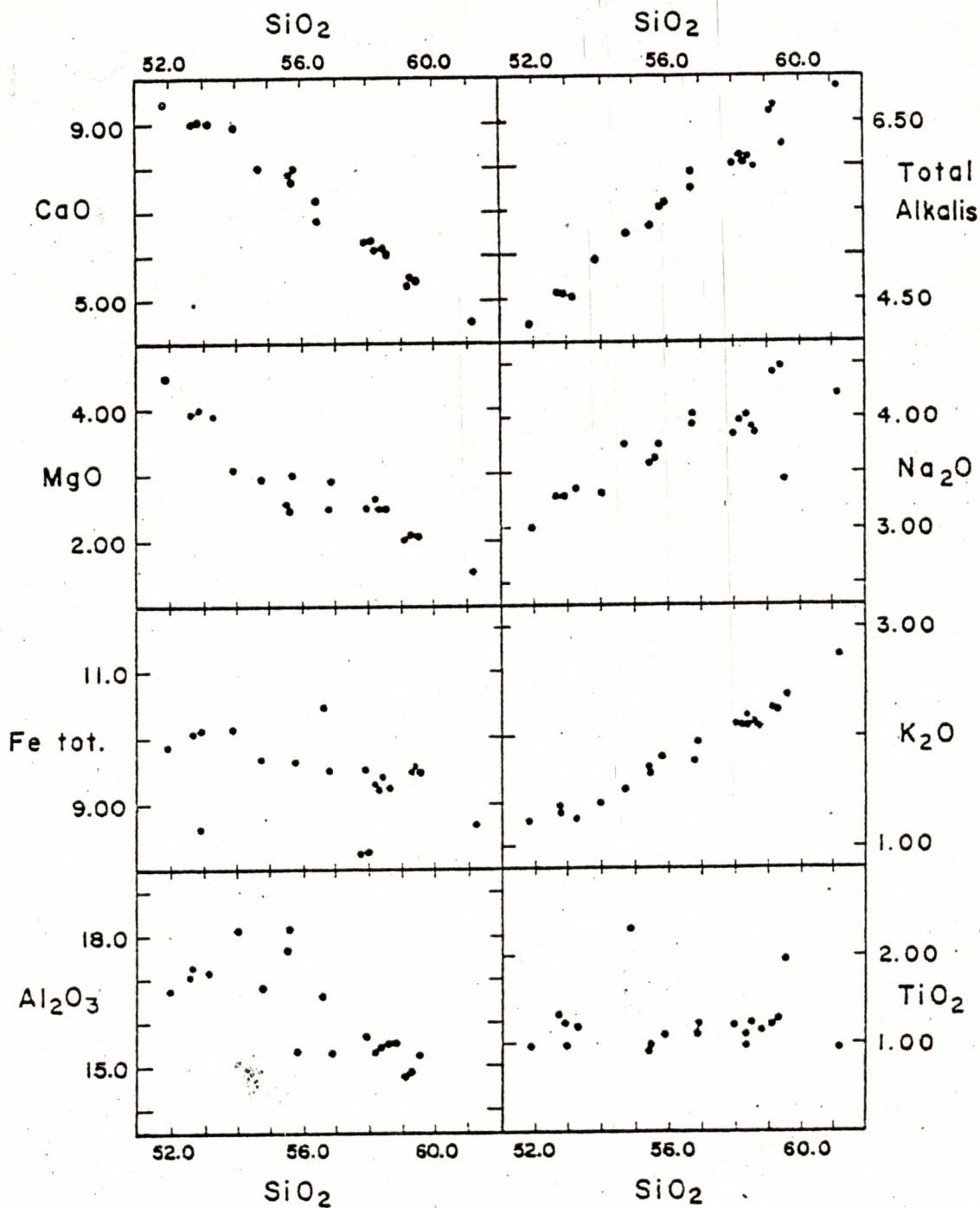


Figure 14 - Harker plots for the Boqueron lavas.

be expressed and tested as problems in least-squares approximation (Bryan, et. al., 1968). The method is superior to the graphical or trial-and-error methods (Wilcox, 1955; Murata and Richter, 1966) in that all the bulk chemical data is used and a unique solution is derived for each model. The analysis is used to determine whether an assumed residual liquid may be derived by addition or subtraction of mineral phases of known composition from an assumed parent liquid, or by mixing of two or more liquids to yield a third of intermediate composition. The method can be used whenever the number of oxides is greater than the number of components. A computer program (listed in Appendix B) was used to estimate the composition of residual liquids by least-squares approximation. Essential to application of the method is a reasonable approximation of the composition of the components; if mineral phases are to be fractionated, their compositions should be known. Analysis by least-squares approximation has been used successfully by a number of workers (Bryan, 1969; Bryan, et. al., 1969; Wright and Doherty, 1970; Arculus, 1976).

Application of mixing analysis to the Boqueron lava series has yielded results which support magma differentiation involving the fractionation of plagioclase, augite, olivine, and Titanium-rich magnetite. Selection of the mineral fractionates was based on the observed modal mineralogy. The fractionation of Titanium-rich magnetite was supported by its occurrence as phenocrysts, and its inclusion in other fractionating minerals and the glomeroporphyritic crystal clots. Mineral compositions were taken from electron microprobe analyses of mineral phases in selected assumed parent magmas (e.g. B-6, B-11, and B-22),

and one of the differentiated end-products (B-3). Plagioclase compositions were taken from the phenocryst cores only, and analyses with the highest An-content were used on the assumption that these represent the first-crystallizing compositions of the fractionating plagioclase.

The mineral compositions used are given in Table 1. Magma compositions were taken from the nonrecalculated bulk-rock analyses of the Boqueron lavas. The potential differentiation pairs analyzed were B-3 from B-20, B-20 from B-22, B-22 from B-24, B-12 from B-11, B-10 from B-9, B-7 from B-6, B-3 from B-6, B-18 from B-6, B-12 from B-6, and B-20 from B-6 (see Figure 15).

The results of the analysis are given in Table 2. The 'observed' and 'calculated' columns are the compositions of the parent magma, the former being the known composition and the latter being the composition calculated by adding the fractionate minerals to the assumed residual magma. The 'residual' column contains the differences between the observed and calculated parent magma compositions. The 'sum of squares' is a sum of the squares of the residuals. The residuals were not weighted. The sum of the squares of the differences in composition between the assumed parent and assumed residual magmas is also given as a measure of the original disparity of the two liquids before fractionation is taken into account.

Except for the pairs B-22 from B-24 and B-3 from B-20, the origin of the andesites by crystal fractionation is supported by the least squares analysis. These two exceptions may also be fractionates; the possibility cannot be excluded on the basis of least-squares analysis alone. The negative plagioclase value in the B-22/B-24 pair can be

TABLE 1

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	53.09	51.05	48.72	44.96	51.87	51.31	52.34	34.39	36.52	0.33	2.20
Al ₂ O ₃	26.61	30.49	29.81	33.74	1.79	2.40	2.23	0.32	0.35	4.82	4.98
Fe tot.	1.24	0.82	1.89	1.81	13.92	11.62	12.57	42.72	30.77	80.82	80.32
MgO	0.04	0.07	0.05	0.06	13.24	14.63	---	20.63	31.43	3.42	2.33
CaO	10.66	12.63	14.56	18.66	18.10	19.11	16.64	0.50	0.27	---	---
Na ₂ O	7.66	3.13	4.84	0.97	---	---	0.30	---	---	---	---
K ₂ O	0.28	0.16	0.13	---	---	---	0.09	---	---	---	---
TiO ₂	---	0.03	0.02	---	0.46	0.45	0.48	0.06	0.02	11.09	9.24
MnO	---	---	---	---	0.61	0.45	0.48	1.16	0.61	0.48	0.35

1) B-3 plagioclase

5) B-3 augite

8) B-3 olivine

2) B-22 plagioclase

6) B-22 augite

9) B-11 olivine*

3) B-11 plagioclase

7) B-6 augite

10) B-11 magnetite

4) B-6 plagioclase

11) B-6 magnetite

* B-11 is the
average of 11
analyses.

TABLE 1 - Mineral analyses used in the least-squares calculations. Pyroxene analyses were determined by averaging recalculated values of more than one grain. All other analyses are of individual phenocryst cores, except where noted.

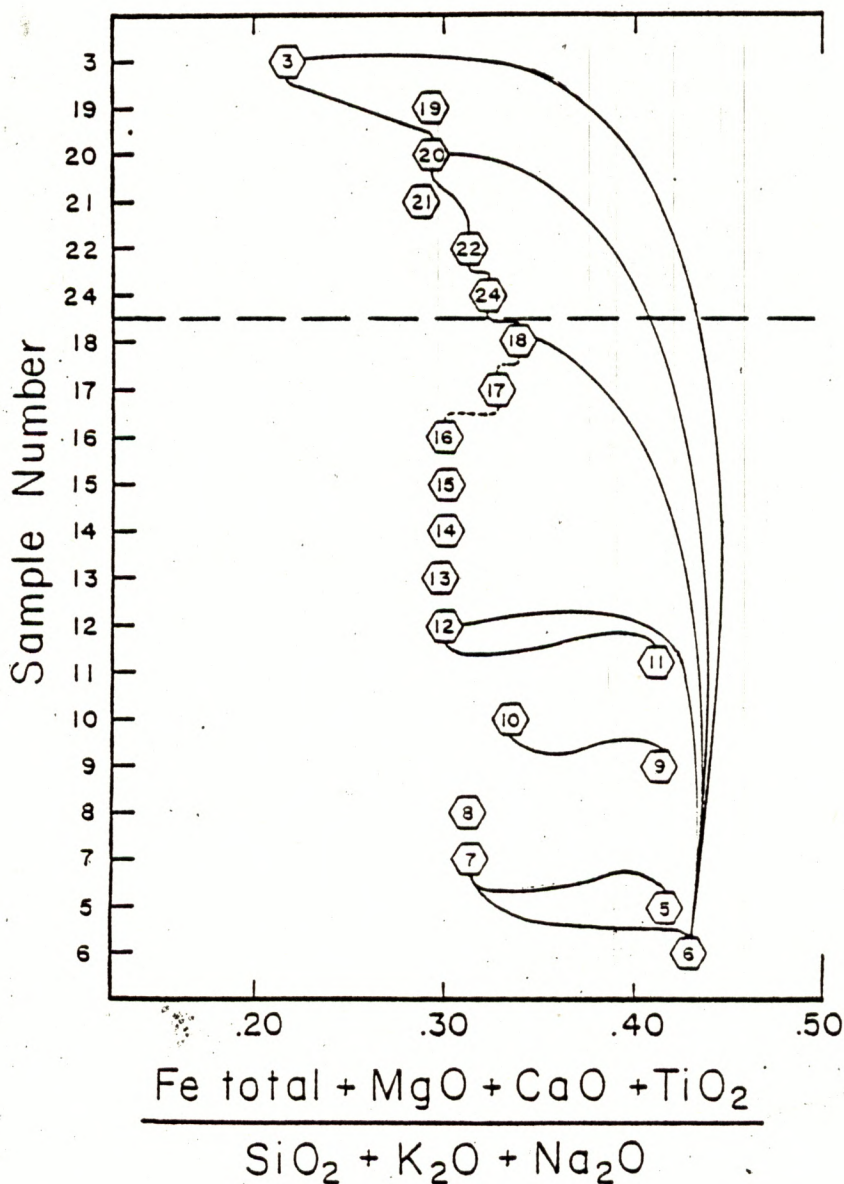


Figure 15 - Mixing pairs used in the least-squares analysis, plotted on the $(\text{Fe total} + \text{MgO} + \text{CaO} + \text{TiO}_2) / (\text{SiO}_2 + \text{K}_2\text{O} + \text{Na}_2\text{O})$ vs. time diagram to show lava relationships. Solid lines indicate fractionation pairs. Dotted Line indicates trio in magma mixing analysis.

TABLE 2

Parent = B-20

<u>SAMPLE</u>	<u>%</u>
B-3	89.4
B-11 magnetite	1.1
B-3 plagioclase	3.2
B-3 augite	5.6

Parent = B-22

<u>SAMPLE</u>	<u>%</u>
B-20	77.8
B-11 magnetite	1.3
B-22 plagioclase	16.1
B-22 augite	4.6
B-11 olivine	0.6

Parent = B-24

<u>SAMPLE</u>	<u>%</u>
B-22	105.8
B-11 magnetite	0.6
B-22 plagioclase	-7.5
B-22 augite	0.9
B-11 olivine	0.4

<u>OXIDE</u>	<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
SiO ₂	58.90	58.87	0.03
Al ₂ O ₃	14.70	14.89	-0.19
Fe tot.	9.38	9.39	-0.01
MgO	2.00	2.17	-0.17
CaO	5.44	5.37	0.07
Na ₂ O	4.40	3.97	0.43
K ₂ O	2.23	2.43	-0.20
TiO ₂	1.20	0.99	0.21
P ₂ O ₅	0.23	0.20	0.03
MnO	0.22	0.19	0.03

$$\text{Sum of squares} = \frac{0.34}{5.95}$$

<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
56.70	56.70	-0.00
16.60	16.60	0.00
9.21	9.22	-0.01
2.47	2.46	0.01
7.18	7.17	0.01
3.98	3.93	0.05
1.78	1.76	0.02
1.15	1.11	0.04
0.25	0.18	0.07
0.21	0.20	0.01

$$\text{Sum of squares} = \frac{0.01}{12.11}$$

<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
56.70	56.70	-0.00
15.30	15.30	0.00
10.40	10.39	0.01
2.87	2.88	-0.01
6.81	6.80	0.01
3.97	3.97	-0.00
1.92	1.87	0.05
1.22	1.29	-0.07
0.23	0.26	-0.03
0.23	0.23	-0.00

$$\text{Sum of squares} = \frac{0.01}{12.43}$$

TABLE 2 - Results of least-squares mixing for the Boqueron lavas.

TABLE 2 (cont'd.)

Parent = B-11

<u>SAMPLE</u>	<u>%</u>
B-12	59.5
B-11 magnetite	2.5
B-11 plagioclase	25.2
B-6 augite	10.2
B-11 olivine	2.9

Parent = B-9

<u>SAMPLE</u>	<u>%</u>
B-10	93.3
B-6 magnetite	1.2
B-6 plagioclase	0.4
B-6 augite	3.8
B-11 olivine	2.4

Parent = B-6

<u>SAMPLE</u>	<u>%</u>
B-7	72.5
B-6 magnetite	1.8
B-6 plagioclase	10.4
B-6 augite	11.1
B-11 olivine	2.8

<u>OXIDE</u>	<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
SiO ₂	53.00	52.99	0.01
Al ₂ O ₃	17.20	17.15	0.05
Fe tot.	10.20	10.23	-0.03
MgO	4.00	3.98	0.02
CaO	9.09	9.12	-0.03
Na ₂ O	3.29	3.59	-0.30
K ₂ O	1.34	1.27	0.07
TiO ₂	1.22	1.01	0.21
P ₂ O ₅	0.20	0.11	0.09
MnO	0.20	0.20	0.00

Sum of squares = $\frac{0.15}{36.39}$

<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
53.30	53.30	-0.00
17.20	17.20	0.00
10.20	10.21	-0.01
3.93	3.91	0.02
9.06	9.06	-0.00
3.35	3.31	0.04
1.25	1.32	-0.07
1.15	1.04	0.11
0.20	0.20	0.00
0.20	0.19	0.01

Sum of squares = $\frac{0.02}{5.08}$

<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
51.80	51.82	-0.02
16.70	16.70	0.00
9.90	9.91	-0.01
4.41	4.38	0.03
9.47	9.43	0.04
2.98	2.78	0.20
1.23	1.21	0.02
0.95	0.89	0.06
0.20	0.18	0.02
0.19	0.21	-0.02

Sum of squares = $\frac{0.05}{24.46}$

TABLE 2 (cont'd.)

Parent = B-6

<u>SAMPLE</u>	<u>%</u>
B-3	51.3
B-6 magnetite	2.5
B-6 plagioclase	25.5
B-6 augite	15.9
B-11 olivine	3.6

<u>OXIDE</u>	<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
SiO ₂	51.80	51.84	-0.04
Al ₂ O ₃	16.70	16.70	0.00
Fe tot.	9.90	9.92	-0.02
MgO	4.41	4.35	0.06
CaO	9.47	9.41	0.06
Na ₂ O	2.98	2.42	0.56
K ₂ O	1.23	1.40	-0.17
TiO ₂	0.95	0.78	0.17
P ₂ O ₅	0.20	0.11	0.09
MnO	0.19	0.21	-0.21

Sum of squares = $\frac{0.39}{118.93}$

Parent = B-6

<u>SAMPLE</u>	<u>%</u>
B-18	74.4
B-6 magnetite	0.3
B-6 plagioclase	11.9
B-6 augite	8.0
B-11 olivine	3.7

<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
51.80	51.77	0.03
16.70	16.73	-0.03
9.90	9.80	0.10
4.41	4.54	-0.13
9.47	9.50	-0.03
2.98	2.92	0.06
1.23	1.14	0.09
0.95	1.78	-0.83
0.20	0.16	0.04
0.19	0.22	-0.03

Sum of squares = $\frac{0.74}{16.41}$

Parent = B-6

<u>SAMPLE</u>	<u>%</u>
B-12	61.6
B-6 magnetite	1.5
B-6 plagioclase	20.0
B-6 augite	11.4
B-11 olivine	3.5

<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
51.80	51.83	-0.03
16.70	16.70	0.00
9.90	9.91	-0.01
4.41	4.37	0.04
9.47	9.42	0.05
2.98	2.66	0.32
1.23	1.29	-0.06
0.95	0.90	0.05
0.20	0.12	0.08
0.19	0.20	-0.01

Sum of squares = $\frac{0.12}{51.76}$

TABLE 2 (cont'd.)

Parent = B-6

<u>SAMPLE</u>	<u>%</u>
B-20	56.1
B-6 magnetite	1.6
B-6 plagioclase	24.0
B-6 augite	12.1
B-11 olivine	4.5

<u>OXIDE</u>	<u>OBS</u>	<u>CALC</u>	<u>RESID</u>
SiO ₂	51.80	51.82	-0.02
Al ₂ O ₃	16.70	16.70	0.00
Fe tot.	9.90	9.91	-0.01
MgO	4.41	4.38	0.03
CaO	9.47	9.43	0.04
Na ₂ O	2.98	2.74	0.24
K ₂ O	1.23	1.26	-0.03
TiO ₂	0.95	0.88	0.07
P ₂ O ₅	0.20	0.13	0.07
MnO	0.19	0.21	-0.02

Sum of squares = $\frac{0.07}{79.81}$

interpreted as requiring that plagioclase be added to the fractionated magma, rather than subtracted. Considering that plagioclase floatation has been demonstrated by Walker (1977), this is not an unreasonable possibility. Addition of plagioclase during eruption could have occurred when the upper parts of the fractionating magma chamber became involved in the eruptive process. The fact that plagioclase is not negative in the other series, however, requires that the eruptive mechanism be different for the B-22/B-24 pair. No other data in the Boqueron lavas support this change in the eruptive mechanism, which leaves the validity of the model for this pair in doubt. The derivation of B-3 from B-20 originally required negative olivine. When olivine was removed from the suite of fractionating minerals, however, the analysis gave a reasonable result, suggesting that olivine was not a stable crystallizing phase during the fractionation of B-3 magma.

Mixing calculations were also carried out to determine if magma mixing could be occurring beneath Boqueron. The composition of B-17 was approximated by mixing B-16 and B-18. Table 3 gives the results, which are supportive of magma mixing.

TABLE 3

	<u>SAMPLE</u>	<u>%</u>		
	B-16	33.6		
	B-18	65.9		
<u>OXIDE</u>	<u>OBS</u>	<u>CALC</u>	<u>RESID</u>	
SiO ₂	55.60	55.69	-0.09	
Al ₂ O ₃	16.40	16.25	0.15	
Fe tot.	9.63	9.47	0.16	
MgO	3.01	2.81	0.20	
CaO	7.68	7.41	0.27	
Na ₂ O	3.74	3.80	-0.06	
K ₂ O	1.80	1.70	0.10	
TiO ₂	1.07	1.84	-0.77	
P ₂ O ₅	0.22	0.21	0.01	
MnO	0.20	0.21	-0.01	

Sum of squares = 0.77

TABLE 3 - Results of mixing calculation which mixes B-16 and B-18 to produce B-17.

Models to Explain the Chemical Trends

The best assumption that can be made concerning the source of the Boqueron magmas is that they originate at depth by some process of partial melting. If this assumption is correct, the medium-term, cyclic variation at Boqueron is most easily explained by some mechanism involving injections of basaltic magma of deep origin into a near-surface magma reservoir, in which fractionation involving Ca-rich plagioclase, augite, olivine, and Titanium-rich magnetite occurs. Eruptions periodically occur during all phases of this sequence, possibly controlled by tectonic events. There are alternative models which cannot be excluded by the data (see Figure 16). Among these are:

- 1) Continuous supply of magma directly from the source region, with the extent of lava differentiation determined by the length of time between magma generation and eruption (Rose, 1977).

- 2) Formation of a layered magma reservoir by fractional crystallization (phenocryst-depleted and phenocryst-enriched liquids), followed by variation in the level from which magma is derived. Proposed mechanisms which accomplish this include changes in the location of the chamber tap and motion within the magma body (e.g. convective overturn) which would bring magmas of different compositions to the same tap.

- 3) Mixing of magmas from different source regions or, alternatively, of magmas from the same source

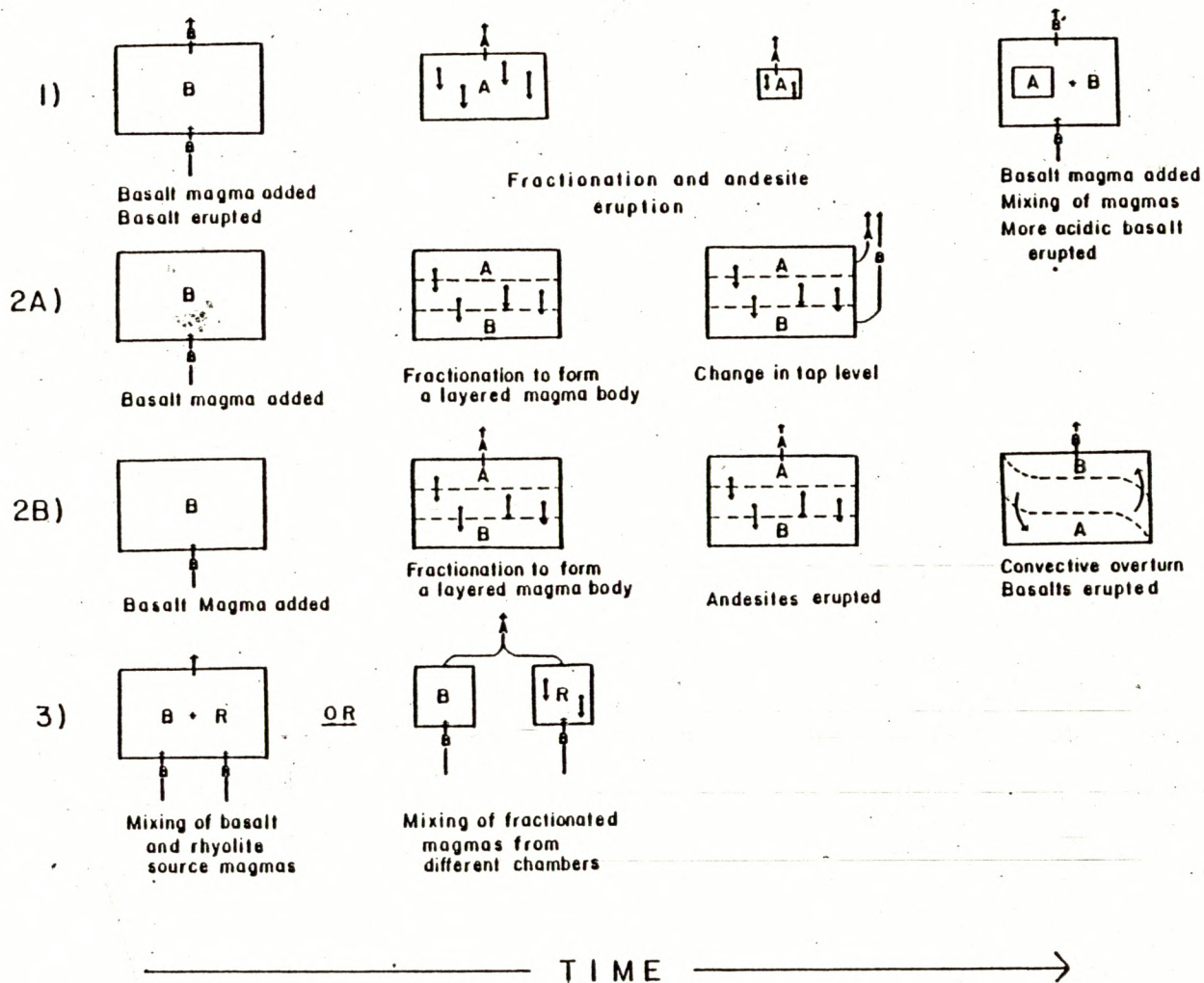


Figure 16 - Models proposed to explain chemical variation patterns in lavas over one or more time scales.

regions but from different reservoirs in which differentiation has proceeded to varying degrees. Variation in erupted lava compositions is produced by changes in the mixing ratios.

None of these possibilities can be categorically rejected, but some are more plausible. Lavas erupted from a layered magma body should be rich in cumulate crystal clots and should show evidence of equilibrium crystallization. Crystal clots are not widely observed and plagioclase phenocrysts are intensely zoned, which is evidence of undercooling and crystal growth rates exceeding diffusion rates (Lofgren, 1972, 1974). Of the three models, only the first requires the observed pattern in medium-term variation, in which cycles begin and end with basaltic eruptions and are separated by greater numbers of andesitic flows. Although the latter two mechanisms may be used to explain this pattern of medium-term variation, the patterns are not a necessary consequence of them and there is no reason to expect development of such patterns to be either likely or persistent. Data supporting the mixing and layered magma chamber models is lacking. Only the first model of periodic injections of magma into a shallow, fractionating chamber is supported by the observed trends and would necessarily produce cyclic variations of the kind observed. For this reason it is the favored explanation.

Conclusions based on the Boqueron data are relevant to several aspects of the andesite problem. These can be summarized as follows:

- 1) At Boqueron there is an intimate association of basaltic and andesitic lavas, and there is a cyclic variation between basalts and andesites. Cawthorn and O'Hara (1976) have noted such relationships

between basalts and andesites in support of their model of amphibole + olivine + clinopyroxene (and possibly orthopyroxene + plagioclase) fractionation. They note, however, that their model does not apply to fractionates beyond andesite. The dacite pumice found in the vicinity of the volcano complicates the application of their model, but does not necessarily preclude it. There is no evidence of interbedding of lava flows with dacitic pumice, and the absence of other pumice units in the Boqueron history, leaves open the possibility that the pumice eruptions were a special event occurring on a larger geographic scale (McBirney, 1976), and were not directly related to the other Boqueron lavas. It is also possible that the interpretations of field data (Williams and Meyer-Abich, 1955; Weyl, 1954, 1955, 1961) are incorrect, and that dacites never erupted from Boqueron at all.

2) The presence of dacites in close proximity to andesites and basalts also raises the possibility of magma mixing (Ewart and Bryan, 1973; Eichelberger, 1974, 1975a, 1975b) as a mechanism capable of producing the observed andesites. No evidence of mixing can be found in the Boqueron lavas.

3) Using the bulk-rock analyses and analyses of observed mineral phases, least-squares mixing analysis suggests that fractionation of Ca-rich plagioclase, augite, olivine, and Titanium-rich magnetite is alone capable of producing the andesites from the basalts. The most acidic lava, B-3 (60.7% SiO_2), can be produced from the most basaltic lava, B-6 (51.8% SiO_2), by fractionation of 24.5% plagioclase, 15.9% augite, 3.6% olivine, and 2.5% Ti-rich magnetite.

4) Glomeroporphyritic crystal clots of plagioclase, augite, olivine, and Titanium-rich magnetite are observed in varying abundance in most of the Boqueron lavas. 3) and 4) together can be interpreted as supporting the fractionation models of Bowen (1928), Cawthorn and O'Hara (1976), and/or Osborn (1959, 1962, 1969). Amphibole fractionation may be supported by the crystal clots, if Stewart's interpretation of similar clots in andesites from Crater Lake (1975) as breakdown products of high-Al, paragenetic hornblendes is correct. The fact that the clots vary widely in mineral composition, however, is evidence that the clots are not breakdown products of any one high-temperature and/or high-pressure mineral. Fractionation is almost surely one of the main mechanisms, if not the only one, producing the medium-term cycles observed. Similar fractionation has also been shown to occur during the 1917 eruption.

5) There is a superimposition at Boqueron of medium-term cycles and long-term chemical trends. This seems to indicate that two mechanisms of $\text{SiO}_2\text{-K}_2\text{O-(Fe total)}$ enrichment are operating simultaneously, and presumably separately. Two models are proposed here to explain the long-term, enrichment in $\text{SiO}_2\text{-K}_2\text{O-(Fe total)}$, the depletion in $\text{MgO-CaO-Al}_2\text{O}_3$, and the existence of the medium-term cycles within the long-term trend. Both involve periodic injections of basaltic magma into a differentiating magma chamber, which produces the medium-term cycles.

One reasonable supposition is that two processes are operating separately and independently of one another at different depths beneath the volcano. Fractionation of the observed minerals, as

delineated in the least-squares analysis, is one of these, occurring at shallow depth. The other is presumably occurring in the source region of the magma, which is at greater depths, possibly as deep as the quiet area in the inclined seismic zone beneath the line of active volcanoes (Carr and Stoiber, 1973). Although partial melting is the most plausible mechanism for magma production, it is difficult to envisage a scheme of partial melting which would deplete the refractory components, or conversely, enrich the residual, low melting-point components over time. If fractionation at these depths is producing the long-term trends, it is certainly not the same one which produces the medium-term trends.

A second model supposes that, as differentiation proceeds in the shallow magma chamber between periodic influtions of uniform basaltic magma, all the residual liquids are not erupted. That is, differentiated, andesitic liquids are still in the chamber when new batches of basaltic magma are added in. Assuming the volumes of basalt do not increase over time, the andesite/basalt ratio will gradually increase with each new influx of basaltic magma, accounting for an enrichment in the residual components. Under this model, the first basaltic magmas to be erupted after each andesitic period should show a gradual trend toward increasing SiO_2 - K_2O -Fe total. As Figures 7, 8, and 12 show, this is consistently observed.

On the basis of the information obtained from the Boqueron lavas, a clear choice between the two models cannot be made. However, the latter is preferred because of its simplicity (it requires no second differentiation process), and because it requires the observed superimposition of variation trends; in all the other models such super-

imposition is coincidental to the mechanisms involved, and is only a chance occurrence.

APPENDIX A

Analyses of the Boqueron Rocks

	<u>B-1</u>	<u>B-2</u>	<u>B-3</u>	<u>B-5</u>	<u>B-6</u>	<u>B-7</u>
SiO ₂	56.8	53.1	60.7	52.7	51.8	55.5
Al ₂ O ₃	18.0	18.3	15.5	17.2	16.7	17.7
Fe ₂ O ₃	2.96	2.85	0.34	2.91	4.57	4.38
FeO	5.06	6.80	8.29	7.46	5.75	4.26
MgO	2.04	3.59	1.55	3.95	4.41	2.48
CaO	7.60	9.62	4.49	9.10	9.47	7.83
Na ₂ O	4.08	3.21	4.17	3.33	2.98	3.65
K ₂ O	1.81	1.33	2.71	1.30	1.23	1.65
H ₂ O	0.43	0.59	0.30	0.37	1.54	1.44
TiO ₂	0.99	1.14	0.93	1.30	0.95	0.92
P ₂ O ₅	0.22	0.22	0.22	0.28	0.20	0.25
MnO	<u>0.18</u>	<u>0.19</u>	<u>0.21</u>	<u>0.20</u>	<u>0.19</u>	<u>0.18</u>
Total	100.17	100.94	99.41	100.10	99.79	100.24
Q	7.2	3.2	9.6	2.7	4.6	9.0
Or	10.7	7.9	16.0	7.7	7.3	9.8
Ab	34.5	27.2	35.3	28.2	25.2	30.9
An	25.5	31.6	15.6	28.1	28.6	27.0
Di	9.0	12.1	4.5	12.5	13.9	8.2
Hy	6.2	12.1	15.3	13.2	9.8	5.2
Ol	0.0	0.0	0.0	0.0	0.0	0.0
Mt	4.3	4.1	0.5	4.2	6.6	6.4
Il	1.9	2.2	1.8	2.5	1.8	1.7
Hm	0.0	0.0	0.0	0.0	0.0	0.0
Ap	0.5	0.5	0.5	0.6	0.5	0.6

	<u>B-8</u>	<u>B-9</u>	<u>B-10</u>	<u>B-11</u>	<u>B-12</u>	<u>B-13</u>
SiO ₂	55.7	53.3	53.1	53.0	57.7	58.7
Al ₂ O ₃	18.2	17.2	18.1	17.2	15.6	15.6
Fe ₂ O ₃	3.12	3.16	2.85	0.12	0.38	2.06
FeO	5.47	7.33	6.02	10.10	9.04	7.33
MgO	2.41	3.93	2.75	4.00	2.47	2.38
CaO	7.82	9.06	8.94	9.09	6.30	6.12
Na ₂ O	3.64	3.35	3.53	3.29	3.94	3.99
K ₂ O	1.69	1.25	1.41	1.34	2.07	2.06
H ₂ O	1.08	0.23	0.99	0.41	0.64	0.42
TiO ₂	0.98	1.15	0.98	1.22	1.14	1.16
P ₂ O ₅	0.25	0.20	0.21	0.20	0.19	0.22
MnO	<u>0.18</u>	<u>0.20</u>	<u>0.16</u>	<u>0.20</u>	<u>0.20</u>	<u>0.20</u>
Total	100.54	100.36	99.74	100.17	99.67	100.24
Q	7.5	3.4	4.8	0.0	5.9	9.1
Or	10.0	7.4	8.3	7.9	12.2	12.2
Ab	30.8	28.3	29.9	27.8	33.3	33.8
An	28.3	28.2	29.4	28.2	18.8	18.6
Di	7.3	12.8	11.3	13.1	9.6	8.7
Hy	8.6	12.8	8.6	18.5	16.0	11.7
Ol	0.0	0.0	0.0	1.3	0.0	0.0
Mt	4.5	4.6	4.1	0.2	0.6	3.0
Il	1.9	2.2	1.9	2.3	2.2	2.2
Hm	0.0	0.0	0.0	0.0	0.0	0.0
Ap	0.6	0.5	0.5	0.5	0.4	0.5

	<u>B-14</u>	<u>B-15</u>	<u>B-16</u>	<u>B-17</u>	<u>B-18</u>	<u>B-19</u>
SiO ₂	58.6	58.0	58.0	55.6	54.9	59.0
Al ₂ O ₃	15.5	15.4	15.4	16.4	16.8	15.1
Fe ₂ O ₃	2.12	1.44	0.69	3.38	2.98	2.00
FeO	7.47	7.91	8.65	6.55	6.86	7.57
MgO	2.49	2.47	2.64	3.01	2.92	2.03
CaO	6.21	6.11	6.27	7.68	8.05	5.40
Na ₂ O	4.02	3.99	3.97	3.74	3.74	3.86
K ₂ O	2.08	2.07	2.07	1.80	1.52	2.35
H ₂ O	0.20	0.65	0.69	0.21	0.23	0.14
TiO ₂	1.19	1.13	0.97	1.07	2.30	1.90
P ₂ O ₅	0.19	0.24	0.20	0.22	0.21	0.22
MnO	<u>0.20</u>	<u>0.20</u>	<u>0.20</u>	<u>0.20</u>	<u>0.21</u>	<u>0.23</u>
Total	100.27	99.61	99.75	99.86	100.38	99.09
Q	8.5	7.7	6.3	6.1	6.2	11.0
Or	12.3	12.2	12.2	10.6	9.0	13.9
Ab	34.0	33.8	33.6	31.6	31.6	32.7
An	18.1	18.0	18.1	22.6	24.6	16.9
Di	9.6	9.1	9.9	11.6	11.6	7.1
Hy	11.7	13.4	15.6	9.6	8.4	11.0
Ol	0.0	0.0	0.0	0.0	0.0	0.0
Mt	3.1	2.1	1.0	4.9	4.3	2.9
Il	2.3	2.1	1.8	2.0	4.4	3.6
Hm	0.0	0.0	0.0	0.0	0.0	0.0
Ap	0.4	0.6	0.5	0.5	0.5	0.5

	<u>B-20</u>	<u>B-21</u>	<u>B-22</u>	<u>B-23</u>	<u>B-24</u>	Precision*
SiO ₂	58.9	59.0	56.7	51.7	56.7	0.5
Al ₂ O ₃	14.7	14.8	16.6	18.3	15.3	0.2
Fe ₂ O ₃	6.74	2.59	3.32	3.46	1.31	0.07
FeO	3.25	7.09	6.19	5.71	9.21	
MgO	2.00	2.05	2.47	4.79	2.87	0.05
CaO	5.44	5.54	7.18	9.16	6.81	0.04
Na ₂ O	4.40	4.42	3.98	3.28	3.97	0.04
K ₂ O	2.23	2.23	1.78	0.92	1.92	0.01
H ₂ O	0.30	0.15	0.22	0.84	0.20	
TiO ₂	1.20	1.23	1.15	1.11	1.22	
P ₂ O ₅	0.23	0.25	0.25	0.23	0.23	
MnO	<u>0.22</u>	<u>0.22</u>	<u>0.21</u>	<u>0.17</u>	<u>0.23</u>	0.003
Total	99.61	99.57	100.05	99.67	99.97	
Q	13.3	8.9	7.7	2.7	4.6	
Or	13.2	13.2	10.5	5.4	11.3	
Ab	37.2	37.4	33.7	27.8	33.6	
An	13.8	14.0	22.2	32.5	18.3	
Di	9.1	10.0	9.8	9.3	11.9	
Hy	0.8	9.3	8.4	13.5	15.4	
Ol	0.0	0.0	0.0	0.0	0.0	
Mt	7.7	3.8	4.8	5.0	1.9	
Il	2.3	2.3	2.2	2.1	2.3	
Hm	1.4	0.0	0.0	0.0	0.0	
Ap	0.5	0.6	0.6	0.5	0.5	

* Precision is the average of 23 standard deviations calculated for each of the Boqueron samples. Each standard deviation is based on at least three replicate analyses.

MINERAL ANALYSES: B-3

Plagioclases

Si	53.83	53.99	54.30	53.09	53.60	55.10
Al	25.89	27.09	27.00	27.61	25.71	25.65
Fe	1.24	1.27	1.33	1.24	1.26	1.53
Mg	0.02	0.02	0.01	0.04	0.01	0.03
Ca	10.08	10.05	9.89	10.66	10.08	9.98
Na	7.77	7.68	7.45	7.66	8.24	7.62
K	0.29	0.29	0.30	0.28	0.33	0.23
Ti	<u>0.00</u>	<u>0.02</u>	<u>0.00</u>	<u>0.00</u>	<u>0.00</u>	<u>0.05</u>
Total	99.14	100.40	100.29	100.57	99.23	100.20
An	58.32	58.53	58.84	60.03	53.84	58.67
Ab	40.68	40.47	40.10	39.03	40.10	40.53
Or	1.00	1.01	1.06	0.94	1.06	0.80

Augites

Si	52.26	52.21
Al	1.90	1.70
Fe	13.56	14.48
Mg	13.30	13.36
Ca	18.69	17.77
Ti	0.48	0.45
Mn	0.57	0.65
Ni	<u>0.01</u>	<u>0.00</u>
	100.77	100.62

En	29.41	38.77
Wo	41.03	38.37
Fs	29.77	22.87

Olivines

Si	35.48	34.59
Al	0.34	0.32
Fe	43.60	43.43
Mg	21.22	20.81
Ca	0.41	0.61
Ti	0.06	0.07
Mn	1.20	1.16
Ni	0.08	0.09
Cr	<u>0.02</u>	<u>0.04</u>
	102.41	101.13
Fo	46.5	46.1
Fa	53.5	53.9

MINERAL ANALYSES: B-22

Plagioclase

Augite

Si	51.05	Si	51.89
Al	30.49	Al	2.43
Fe	0.82	Fe	11.75
Mg	0.07	Mg	14.80
Ca	12.63	Ca	19.33
Na	3.13	Ti	0.46
K	0.16	Mn	<u>0.46</u>
Ti	0.03	Total	101.13
Mn	<u>0.00</u>		
Total	98.38	En	32.3
		Wo	42.1
An	81.2	Fs	25.6
Ab	18.2		
Or	0.6		

MINERAL ANALYSES: B-11

Plagioclases

Si	53.18	51.94	52.17	53.64	51.93	51.77
Al	26.54	27.43	27.35	25.71	26.38	27.10
Fe	1.75	2.07	2.18	2.09	2.47	2.20
Mg	0.07	0.07	0.08	0.08	0.05	0.08
Ca	10.11	11.88	11.83	10.43	10.84	11.89
Na	8.81	6.70	6.88	7.67	7.32	6.68
K	0.53	0.32	0.37	0.49	0.56	0.30
Ti	<u>0.00</u>	<u>0.00</u>	<u>0.04</u>	<u>0.04</u>	<u>0.03</u>	<u>0.01</u>
Total	100.99	100.40	100.90	100.15	99.59	100.04
An	54.95	65.52	64.73	59.05	60.91	65.64
Ab	43.33	33.43	34.06	39.29	37.22	33.37
Or	1.72	1.05	1.21	1.65	1.87	0.99

Magnetites

Si	0.33	0.38
Al	4.82	5.14
Fe	80.82	79.70
Mg	3.42	2.77
Ti	11.09	9.82
Mn	<u>0.48</u>	<u>0.43</u>
Total	100.95	98.23

Olivines

Si	37.83	38.06	37.80
Al	0.32	0.38	0.38
Fe	32.80	32.27	31.73
Mg	32.69	32.77	33.66
Ca	0.19	0.19	0.16
Ti	0.02	0.00	0.02
Mn	<u>0.68</u>	<u>0.61</u>	<u>0.61</u>
Total	104.62	104.26	104.36

Po	64.0	64.4	65.4
Fa	36.0	35.6	34.6

MINERAL ANALYSES: B-6

Plagioclases

Zoning track

Si	44.67	44.96	45.41	47.93	51.34	51.41
Al	33.21	33.74	33.05	31.93	28.12	27.87
Fe	1.91	1.81	1.98	1.78	2.20	2.10
Mg	0.05	0.06	0.02	0.09	0.08	0.08
Ca	18.62	18.66	18.18	16.50	12.27	11.79
Na	1.18	0.97	1.72	3.29	6.47	6.67
K	0.00	0.00	0.03	0.05	0.23	0.22
Ti	<u>0.00</u>	<u>0.00</u>	<u>0.00</u>	<u>0.04</u>	<u>0.03</u>	<u>0.03</u>
Total	99.65	100.20	100.39	101.61	100.73	100.16
An	94.58	95.51	92.03	84.59	67.19	65.66
Ab	5.42	4.49	7.88	15.26	32.06	33.61
Or	0.00	0.00	0.09	0.15	0.75	0.73

Augites

Magnetites

Si	51.61	52.08	Si	0.23	0.29
Al	2.15	2.26	Al	4.82	4.42
Fe	13.77	11.12	Fe	80.41	81.18
Mg	14.66	14.75	Mg	2.52	1.48
Ca	15.13	17.84	Ti	9.70	10.71
Na	0.32	0.27	Mn	<u>0.36</u>	<u>0.39</u>
K	0.09	0.09	Total	98.05	98.48
Ti	0.51	0.45			
Mn	0.48	0.48			
Cr	0.03	0.03			
Ni	<u>0.01</u>	<u>0.03</u>			
Total	98.74	99.38			
En	44.08	43.62			
Wo	32.69	37.93			
Fs	23.24	18.45			

MODAL ANALYSES

	<u>B-1</u>	<u>B-2</u>	<u>B-3</u>	<u>B-5</u>	<u>B-6</u>	<u>B-7</u>	<u>B-8</u>	<u>B-9</u>	<u>B-10</u>
<u>Phenocrysts</u>									
Plagioclase	28.0	30.5	6.7	34.4	28.4	25.9	24.4	35.6	31.0
Augite	0.7	0.1	1.7	0.1	7.6	0.9	1.3	0.1	0.0
Opagues	0.1	0.5	0.7	0.3	1.1	0.2	0.6	0.1	0.3
Olivine	0.1	2.0	1.6	4.8	3.8	0.6	0.5	5.5	2.7
<u>Groundmass</u>									
Plagioclase	19.9	26.5	55.8	10.4	28.0	39.9	38.1	30.4	18.9
Augite	18.4	12.9	23.0	3.8	10.8	10.0	14.0	9.3	23.9
Opagues	8.1	9.0	6.7	8.3	8.1	7.4	4.7	7.6	6.6
Glass	24.7	18.5	3.8	37.8	12.3	15.1	16.4	11.4	16.6

MODAL ANALYSES (cont'd.)

	<u>B-11</u>	<u>B-12</u>	<u>B-13</u>	<u>B-14</u>	<u>B-15</u>	<u>B-16</u>	<u>B-17</u>	<u>B-20</u>	<u>B-21</u>
<u>Phenocrysts</u>									
Plagioclase	32.2	9.0	9.3	6.9	11.9	8.8	12.6	1.1	0.8
Augite	2.0	0.5	1.2	0.8	0.5	2.1	0.3	0.4	0.3
Opakes	0.2	0.1	1.0	0.4	0.2	0.2	0.2	0.0	0.1
Olivine	3.7	0.8	1.3	0.3	0.4	0.2	0.1	0.1	0.0
<u>Groundmass</u>									
Plagioclase	10.0	29.7	29.3	55.9	46.9	45.8	23.5	5.6	7.1
Augite	40.0	18.5	21.1	21.1	17.9	14.5	2.0	3.0	2.7
Opakes	9.8	3.9	3.9	3.4	3.3	1.7	3.6	3.2	10.4
Glass	2.1	37.5	32.9	11.3	18.8	26.7	57.6	86.6	78.6

MODAL ANALYSES (cont'd.)

	<u>B-22</u>	<u>B-23</u>
<u>Phenocrysts</u>		
Plagioclase	10.0	0.6
Augite	0.2	0.0
Opagues	0.0	0.0
Olivine	0.1	5.7

B-18, B-19, and B-24 are 100% glass.

<u>Groundmass</u>		
Plagioclase	21.6	21.5
Augite	1.5	3.4
Opagues	7.5	2.8
Glass	59.1	66.0

ROCK CLASSIFICATION*

- B-1 Tholeiitic andesite
- B-2 Tholeiitic andesite
- B-3 Tholeiitic andesite
- B-5 Calc-alkaline basalt
- B-6 Calc-alkaline basalt
- B-7 Calc-alkaline andesite
- B-8 Calc-alkaline andesite
- B-9 Calc-alkaline basalt
- B-10 Calc-alkaline basalt
- B-11 Calc-alkaline basalt
- B-12 Tholeiitic andesite
- B-13 Tholeiitic andesite
- B-14 Tholeiitic andesite
- B-15 Tholeiitic andesite
- B-16 Tholeiitic andesite
- B-17 Tholeiitic basalt
- B-18 Calc-alkaline basalt
- B-19 Tholeiitic andesite
- B-20 Tholeiitic andesite
- B-21 Tholeiitic andesite
- B-22 Tholeiitic andesite
- B-24 Tholeiitic andesite

*under the Irvine and Baragar system, 1971

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