

Temporal Magmatic Variation at Boqueron Volcano, El Salvador

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Abstract. The relative ages of 21 lavas from Boqueron volcano in El Salvador were determined by superposition. The lavas are grey to black, porphyritic basalts, basaltic andesites and andesites with phenocrysts of plagioclase, augite, olivine, and magnetite. The andesitic lavas appear to have evolved from basaltic magma by fractionation of the observed phenocryst phases.

The temporal variation in the chemical composition of the lavas at Boqueron is composed of three components. First, there is a crudely cyclical alternation of basalts and andesites. Second, these cycles are progressively shifted toward higher SiO_2 contents. Third, approximately in the middle of the stratigraphic section sampled, there is an abrupt change in chemical variation trends from an Al-rich and Fe-poor trend to an Fe-rich and Al-poor trend. This change is interpreted to have been caused by an increased proportion of plagioclase fractionation and a decreased proportion of augite fractionation. The crudely cyclical change in SiO_2 content with time is interpreted as a combination of crystal fractionation that increases SiO_2 content, followed by influxes of basaltic magma that mix with residual magma to decrease SiO_2 content. Successive cycles are shifted toward higher SiO_2 content because there is a significant volume of fractionated magma remaining in the chamber before each influx of basalt.

Introduction

Andesitic volcanic rocks found at convergent plate margins have been explained as products of fractional crystallization of basalt (Osborn, 1959, 1969). Others

have proposed that andesitic liquids are produced by hydrous partial melting of peridotite (Yoder, 1969; Kushiro, 1972) or subducted oceanic crust (Green and Ringwood, 1968). A wide range of views on the origin of andesitic rocks exists (Boettcher, 1973; McBirney, 1976), and it is possible that andesites have been produced by several of the proposed mechanisms.

The origin of andesitic rocks at a particular volcanic center is best understood when the entire volcanic history of the center is defined. If fractional crystallization is the governing process, then a gradual evolution from basalt to andesite should be found. Alternatively, if partial fusion directly produces an andesitic liquid, rather uniform andesitic rocks should be found. Usually, it is not possible to sample the entire magmatic history of composite cones, however, large pyroclastic eruptions that cause deep craters or calderas expose stratigraphic sections of composite cones. Detailed sampling of such sections has allowed Katsui et al. (1975) and Rose et al. (1977) to define the temporal magmatic evolution of composite volcanos in Hokkaido, Japan and western Guatemala, respectively. A common feature of the magmatic histories of these composite volcanos is that the andesitic rocks, which make up the outer part of the cone, have gradually evolved from basaltic rocks that make up much of the interior of the cone. The observed magmatic histories of these volcanos strongly suggest that their andesitic lavas are a product of fractional crystallization of basalt.

Boqueron volcano is one of 41 historically active Central American volcanos. This volcanic chain, which extends over 1100 km from Guatemala to Costa Rica is located above a well-defined inclined seismic zone that marks the convergence of the Caribbean and Cocos plates (Molnar and Sykes, 1969).

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This convergent plate margin is subdivided by transverse structures into segments 100 to 200 km long (Stoiber and Carr, 1973). At the transverse structures there are abrupt offsets of the volcanic chain and corresponding offsets of the underlying inclined seismic zone (Carr, 1976; Aburto, 1976). Boqueron is located towards the western end of the El Salvador segment of the arc. The depth of the inclined seismic zone beneath Boqueron and the other volcanos along the volcanic front of El Salvador is about 160 km (Carr, 1976).

Eruptive History of Boqueron

Boqueron volcano is the youngest part of the San Salvador or Quezaltepeque volcanic center. The base of this volcanic center is an ancestral volcano, San Salvador, whose summit foundered during a caldera collapse (Williams and Meyer-Abich, 1955). Boqueron volcano has grown within this caldera and has filled it almost completely (Mooser et al., 1958). Boqueron is a gently sloping cone with a 500 m deep summit crater (Fig. 1), which has a diameter of 1500 m. A 30 m high cinder cone, Boqueroncito, has grown at the bottom of the crater. The crater floor is approxi-

mately 1345 m above sea level; the rim of the San Salvador caldera is at approximately 1300 m, and the rim of the Boqueron crater at 1860 m (Williams and Meyer-Abich, 1955).

The walls of the Boqueron crater contain an almost complete history of the Boqueron cone subsequent to the filling of the San Salvador caldera. This represents about 1/4 to 1/3 of the estimated volume of the cone (Fig. 1).

Ash and laharcic materials alternate with lavas in the walls of the Boqueron crater. A prominent 100 m thick ash layer divides the section of lavas in the crater wall into an upper and lower series. Seven samples were taken from each series (B-5 to B-11, the lower series; and B-12 to B-18, the upper series). All samples were collected from flow interiors. Relative ages were established by superposition. After the formation of the summit crater, eruptive activity occurred on the north and northeast flanks of the volcano (Williams and Meyer-Abich, 1955). Sample B-24 was taken from the most prominent of these prehistoric lavas (Fig. 1). More recent flank eruptions formed two chains of cinder cones. The youngest cone, Cerro El Playon, formed in 1658 (Fig. 1) during an eruption that began with tephra and ash eruptions accompanied by a strong earthquake (Montessus de Ballore, 1884; Larde y Larin, 1948). Sample B-22 was collected from an andesitic flow (0.01 km^3) that issued from the eastern base of the cone during this eruption.

The most recent activity of Boqueron began on June 6, 1917 with a destructive earthquake (Schultz, 1963). On the same day, northwest-trending fissures opened on the north flank of Boqueron to release a voluminous flow (0.01 km^3) of black, vesicular, tholeiitic andesite. Two samples, B-20 and B-21 were taken from this main flow and one sample, B-19, was taken from a small subsidiary flow (Fig. 1). On June 10, the lake which previously occupied the Boqueron crater began to boil, and by June 28 it had disappeared altogether (Williams and Meyer-Abich, 1955). Ash and cinder eruptions began in the crater and continued until November. The result was the cinder cone, Boqueroncito. Sample B-3 was collected near the lip of this cone, and must therefore have been erupted toward the end of the summit eruption, at least several months after the eruption of the flank flows.

Two samples (B-1 and B-2) collected on the south flank can not be stratigraphically correlated with the other samples but are chemically similar to the lower series of lavas exposed in the crater. One sample (B-23) collected at the base of a nearby cinder cone is geochemically distinct from the Boqueron lavas and is not included in the following discussions.

Petrography

Boqueron lavas are grey to black, porphyritic, pilotaxitic basalts, basaltic andesites, and andesites that have phenocrysts of plagioclase, augite, olivine, and titaniferous magnetite. Orthopyroxene is present in some samples; amphibole is absent. The groundmass consists of plagioclase, augite, magnetite, and glass in varying proportions. Many samples are moderately vesicular. Modal analyses are given in Table 1. The chemical compositions of phenocrysts in samples B-3, B-6, B-11, and B-22 were determined by electron microprobe. Selected analyses are given in Table 2. In the discussion below the estimates of the ranges of mineral composition are based on the microprobe data for these samples.

There are glomeroporphyritic crystal clusters of augite, olivine, magnetite, and plagioclase in some samples, particularly B-12 and B-13. Stewart (1975) interprets crystal clusters containing these four minerals as breakdown products of high-temperature amphiboles. However, in the Boqueron lavas the relative proportions of these phases in the crystal clusters vary over a wide range which suggests that these clusters represent nucleation and cooling phenomena.

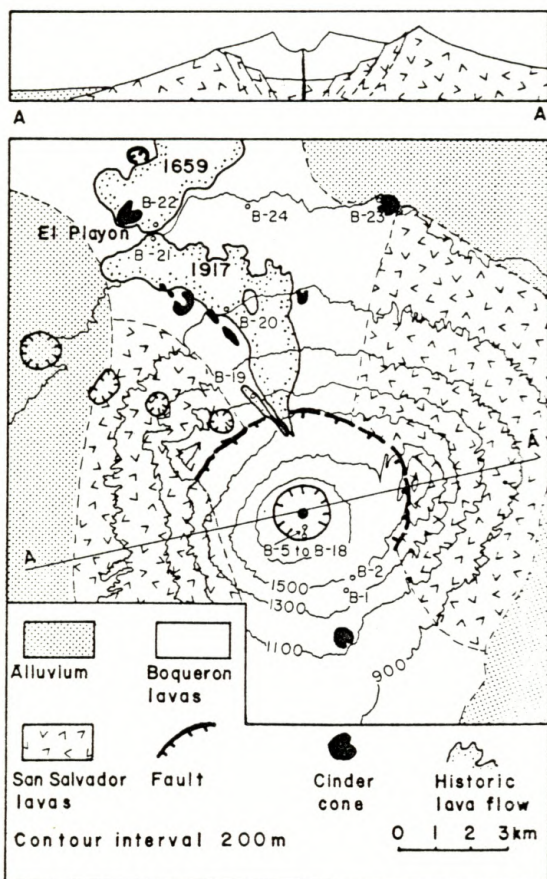


Fig. 1. Generalized geologic map of the San Salvador volcanic center after Williams and Meyer-Abich (1955) and Mooser et al. (1958). Same horizontal and vertical scale in the cross section

Table 1. Chemical and Modal analyses of Boqueron lavas. See Figure 2 for sample location

	B-1	B-2	B-3	B-5	B-6	B-7	B-8	B-9	B-10	B-11	B-12	B-13
<i>Chemical Analyses</i>												
SiO ₂	56.8	53.1	60.7	52.7	51.8	55.5	55.7	53.3	53.1	53.0	57.7	58.7
Al ₂ O ₃	18.0	18.3	15.5	17.2	16.7	17.7	18.2	17.2	18.1	17.2	15.6	15.6
Fe ₂ O ₃	2.96	2.85	0.34	2.91	4.57	4.38	3.12	3.16	2.85	0.12	0.38	2.06
FeO	5.06	6.80	8.29	7.46	5.75	4.26	5.47	7.33	6.02	10.10	9.04	7.33
MgO	2.04	3.59	1.55	3.95	4.41	2.48	2.41	3.93	2.75	4.00	2.47	2.38
CaO	7.60	9.62	4.49	9.10	9.47	7.83	7.82	9.06	8.94	9.09	6.30	6.12
Na ₂ O	4.08	3.21	4.17	3.33	2.98	3.65	3.64	3.35	3.53	3.29	3.94	3.99
K ₂ O	1.81	1.33	2.71	1.30	1.23	1.65	1.69	1.25	1.41	1.34	2.07	2.06
H ₂ O	0.43	0.59	0.30	0.37	1.54	1.44	1.08	0.23	0.99	0.41	0.64	0.42
TiO ₂	0.99	1.14	0.93	1.30	0.95	0.92	0.98	1.15	0.98	1.22	1.14	1.16
P ₂ O ₅	0.22	0.22	0.22	0.28	0.20	0.25	0.25	0.20	0.21	0.20	0.19	0.22
MnO	0.18	0.19	0.21	0.20	0.19	0.18	0.18	0.20	0.16	0.20	0.20	0.20
Total	100.17	100.94	99.41	100.10	99.79	100.24	100.54	100.36	99.74	100.17	99.67	100.24
<i>Modal analyses</i>												
Phenocrysts												
Plagioclase	28.0	30.5	6.7	34.4	28.4	25.9	24.4	35.6	31.0	32.2	9.0	9.3
Augite	0.7	0.1	1.7	0.1	7.6	0.9	1.3	0.1	0.0	2.0	0.5	1.2
Opagues	0.1	0.5	0.7	0.3	1.1	0.2	0.6	0.1	0.3	0.2	0.1	1.0
Olivine	0.1	2.0	1.6	4.8	3.8	0.6	0.5	5.5	2.7	3.7	0.8	1.3
Groundmass												
Plagioclase	19.9	26.5	55.8	10.4	28.0	39.9	38.1	30.4	18.9	10.0	29.7	29.3
Augite	18.4	12.9	23.0	3.8	10.8	10.0	14.0	9.3	23.9	40.0	18.5	21.1
Opagues	8.1	9.0	6.7	8.3	8.1	7.4	4.7	7.6	6.6	9.8	3.9	3.9
Glass	24.7	18.5	3.8	37.8	12.3	15.1	16.4	11.4	16.6	2.1	37.5	32.9
	B-14	B-15	B-16	B-17	B-18	B-19	B-20	B-21	B-22	B-23	B-24	
<i>Chemical analyses</i>												
SiO ₂	58.6	58.0	58.0	55.6	54.9	59.0	58.9	59.0	56.7	51.7	56.7	
Al ₂ O ₃	15.5	15.4	15.4	16.4	16.8	15.1	14.7	14.8	16.6	18.3	15.3	
Fe ₂ O ₃	2.12	1.44	0.69	3.38	2.98	2.00	6.74	2.59	3.32	3.46	1.31	
FeO	7.47	7.91	8.65	6.55	6.86	7.57	3.25	7.09	6.19	5.71	9.21	
MgO	2.49	2.47	2.64	3.01	2.92	2.03	2.00	2.05	2.47	4.79	2.87	
CaO	6.21	6.11	6.27	7.68	8.05	5.40	5.44	5.54	7.18	9.16	6.81	
Na ₂ O	4.02	3.99	3.97	3.74	3.74	3.86	4.40	4.42	3.98	3.28	3.97	
K ₂ O	2.08	2.07	2.07	1.80	1.52	2.35	2.23	2.23	1.78	0.92	1.92	
H ₂ O	0.20	0.65	0.69	0.21	0.23	0.14	0.30	0.15	0.22	0.84	0.20	
TiO ₂	1.19	1.13	0.97	1.07	2.30	1.90	1.20	1.23	1.15	1.11	1.22	
P ₂ O ₅	0.19	0.24	0.20	0.22	0.21	0.22	0.23	0.25	0.25	0.23	0.23	
MnO	0.20	0.20	0.20	0.20	0.21	0.23	0.22	0.22	0.21	0.17	0.23	
Total	100.27	99.61	99.75	99.86	100.38	99.09	99.61	99.57	100.05	99.67	99.97	
<i>Modal analyses</i>												
Phenocrysts												
Plagioclase	6.9	11.9	8.8	12.6	—	—	1.1	0.8	10.0	0.6	—	
Augite	0.8	0.5	2.1	0.3	—	—	0.4	0.3	0.2	—	—	
Opagues	0.4	0.2	0.2	0.2	—	—	—	0.1	—	—	—	
Olivine	0.3	0.4	0.2	0.1	—	—	0.1	—	0.1	5.7	—	
Groundmass												
Plagioclase	55.9	46.9	45.8	23.5	—	—	5.6	7.1	21.6	21.5	—	
Augite	21.1	17.9	14.5	2.0	—	—	3.0	2.7	1.5	3.4	—	
Opagues	3.4	3.3	1.7	3.6	—	—	3.2	10.4	7.5	2.8	—	
Glass	11.3	18.8	26.7	57.6	100.0	100.0	86.6	78.6	59.1	66.0	100.0	

Table 2. Microprobe analyses of phenocrysts from Boqueron lavas

Plagioclase									Olivine				
Lava	B-6	B-6	B-6	B-11	B-11	B-22	B-3	B-3		B-11	B-11	B-3	B-3
SiO ₂	44.67	44.96	45.41	51.77	52.17	51.05	53.09	53.60	SiO ₂	37.80	37.83	35.48	34.59
Al ₂ O ₃	33.21	33.74	33.05	27.10	27.35	30.49	27.61	25.71	Al ₂ O ₃	0.38	0.32	0.34	0.32
FeO	1.91	1.81	1.98	2.20	2.18	0.82	1.24	1.26	FeO	31.73	32.80	43.60	43.43
MgO	0.05	0.06	0.02	0.08	0.08	0.07	0.04	0.01	MgO	33.66	32.69	21.22	20.81
CaO	18.62	18.66	18.18	11.89	11.83	12.63	10.66	10.08	CaO	0.16	0.19	0.41	0.61
Na ₂ O	1.18	0.97	1.72	6.68	6.88	3.13	7.66	8.24	TiO ₂	0.02	0.02	0.06	0.07
K ₂ O	0.00	0.00	0.03	0.30	0.37	0.16	0.28	0.33	MnO	0.51	0.68	1.20	1.16
TiO ₂	0.00	0.00	0.00	0.01	0.04	0.03	0.00	0.00	NiO	—	—	0.08	0.09
									Cr ₂ O ₃	—	—	0.02	0.04
Total	99.65	100.20	100.39	100.04	100.90	98.38	100.57	99.23		104.36	104.62	102.41	101.13
An	94.58	95.51	92.03	65.64	64.73	81.2	60.03	53.84	Fo	65.4	64.0	46.5	46.1
Ab	5.42	4.49	7.88	33.37	34.06	18.2	39.03	40.10	Fa	34.6	36.0	53.5	53.9
Or	0.00	0.00	0.09	0.99	1.21	0.6	9.94	1.06	—				
Augite									Magnetite				
	B-6	B-6	B-22	B-3	B-3								
SiO ₂	51.61	52.08	51.89	52.26	52.21	SiO ₂ 0.23 0.29 0.33 0.38							
Al ₂ O ₃	2.15	2.26	2.43	1.90	1.70	Al ₂ O ₃ 4.82 4.42 4.82 5.14							
FeO	13.77	11.12	11.75	13.56	14.48	FeO 80.41 81.18 80.82 79.70							
MgO	14.66	14.75	14.80	13.30	13.36	MgO 2.52 1.48 3.42 2.77							
CaO	15.13	17.84	19.33	18.69	17.77	TiO ₂ 9.70 10.71 11.09 9.82							
Na ₂ O	0.32	0.27	0.46	0.48	0.45	MnO 0.36 0.39 0.48 0.43							
K ₂ O	0.09	0.09	0.46	0.57	0.65								
TiO ₂	0.51	0.45	—	—	—	Total 98.05 98.48 100.95 98.23							
MnO	0.48	0.48	—	—	—								
Cr ₂ O ₃	0.03	0.03	—	—	—								
NiO	0.01	0.03	—	0.01	0.00								
Total	98.74	99.38	101.13	100.77	100.62								
En	44.08	43.62	32.3	29.41	38.77								
Wo	32.69	37.93	42.1	41.03	38.37								
Fs	23.24	18.45	25.6	29.77	22.87								

Plagioclase (An 96 to An 53), occurs as phenocrysts (5 mm to about 1 mm) and groundmass. The rocks contain 0 to 36% plagioclase phenocrysts which usually are strongly zoned. Augite occurs as phenocrysts and groundmass in most samples. Augite compositions vary from Wo₃₉En₄₄ to Wo₃₅En₃₉. The rocks contain 0 to 8% augite phenocrysts and 0 to 40% groundmass pyroxene. Olivine phenocrysts (Fo₆₅ to Fo₄₆) occur in some samples; but they are never common and olivine was not found in the groundmass. Reaction rims of augite on olivine occur in some samples from the middle of the sequence. Alteration of olivine is common in the samples from the bottom of the Boqueron crater. Representative analyses of fresh olivine are given in Table 2.

Titaniferous magnetite (Mt 86 to Mt 89) occurs as phenocrysts and groundmass, with phenocryst amounts ranging from 0 to 1% and groundmass from 1 to 10% in modal abundance. The magnetite phenocrysts typically occur as inclusions in larger pyroxene or olivine phenocrysts.

Glass is a common constituent of the Boqueron samples, seldom less than 10%. Glass colors range from light-brown to black, and alteration is present in some of the older samples. Microprobe analysis of glass in B-3 showed as much as 70% SiO₂ and up to 4.6% K₂O.

Temporal Variations in Major Element Chemistry

The chemical compositions of Boqueron lavas are given in Table 1. Most major oxides were determined by atomic absorption (Medlin et al., 1969). P₂O₅ was determined by quantitative emission spectroscopy. Total H₂O was measured using the method of Shapiro and Brannock (1955). Two samples, B-18 and B-19, have higher TiO₂ contents than the other lavas. These anomalous titania analyses are not correlated with high modal magnetite; in fact, both samples are completely glassy.

One estimate of the error in sampling and analysis can be made by comparing analyses of B-20 and B-21. These samples were collected from the main 1917 flow at sampling points separated by 3 km. The analyses are identical except for the FeO/Fe₂O₃ ratio.

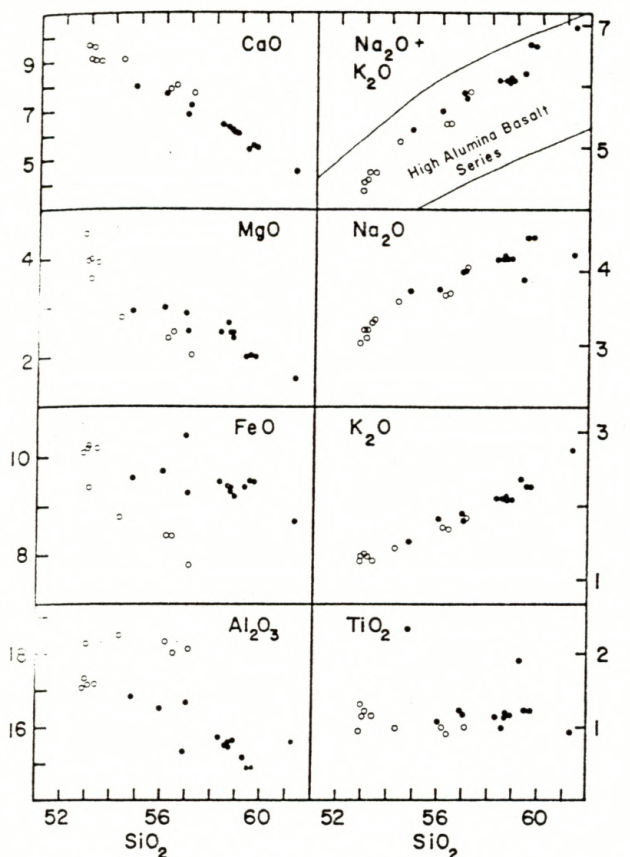


Fig. 2. Harker variation diagrams for Boqueron lavas. Open circles denote Al-rich lava series. The field of the High Alumina Basalt series of Kuno (1966) is shown in the $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 diagram. Analyses recalculated to 100% water-free with total Fe as FeO.

The close similarity of these analyses also suggest that differentiation was negligible within this flow.

Harker variation diagrams, based on analyses recalculated to 100% water-free with total Fe as FeO, are given in Figure 2. The series of lavas from the lower section of the Boqueron crater wall has significantly higher Al_2O_3 and CaO, and lower FeO, MgO, and TiO_2 variation trends than do the later lavas. Since the differences are especially pronounced for Al_2O_3 and FeO (Fig. 3), the lavas from the lower series will subsequently be referred to as the Al-rich series and the later lavas will be referred to as the Fe-rich series. The change from Al-rich to Fe-rich variation trends is an important temporal magmatic variation. This change occurred during or immediately after a voluminous series of pyroclastic eruptions (Fig. 4). The Al-rich lava series has variation trends that are similar to those determined for other calc-alkalic volcanos in Central America by McBirney (1969), Ui (1972), and Pichler and Weyl (1973). The variation trends of the Fe-rich lava series are unusual in comparison with other Central American volcanic rock suites.

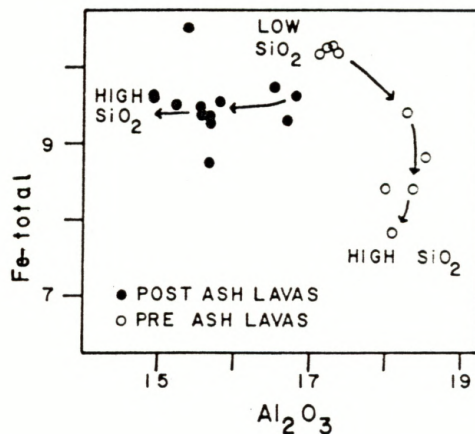


Fig. 3. Fe-total versus Al_2O_3 variation for Boqueron lavas

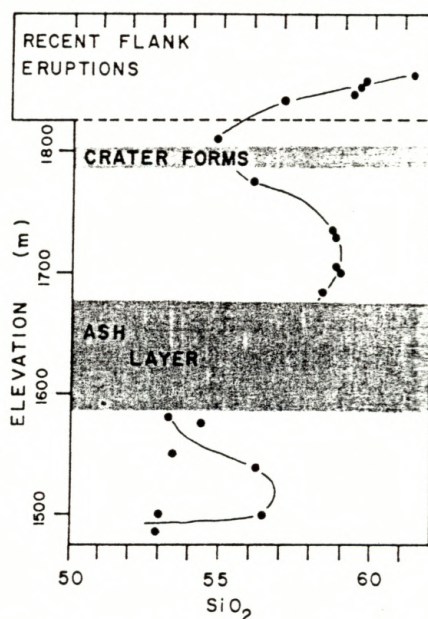


Fig. 4. Change of SiO_2 content with stratigraphic position

The sequential change of chemical composition of lavas can be represented by the changes in SiO_2 content of lavas, since for both the Al-rich and Fe-rich series there are smooth variation trends of major oxides versus SiO_2 . The temporal variation is estimated in Figure 4, in which SiO_2 content, based on analyses recalculated water-free, is plotted against stratigraphic position. The pattern of magmatic evolution appears to be composed of two components; a cyclical component of SiO_2 variation, and a positive linear component which progressively shifts the cycles toward higher SiO_2 contents.

Rock Classification

The Irvine and Baragar (1971) chemical classification scheme for volcanic rocks identifies the Al-rich lava

series as calc-alkaline basalts and andesites. The lavas from the Fe-rich series are tholeiitic andesites. CIPW norms were calculated for each sample, and all samples were quartz normative except for B-11, which was olivine normative. The Peacock alkali-lime index for the Boqueron lavas is 58.5, which is in the calc-alkalic field. On the basis of the $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 plot (Fig. 2) the Boqueron lavas fall within the field of the high-alumina basalt series of Kuno (1966).

Discussion

Fractional Crystallization Model

The Al-rich lava series and the Fe-rich lava series of Boqueron both exhibit well-defined and regular Harker variation trends, which are either simple curves as in the case of MgO, FeO, Al_2O_3 , and Na_2O , or straight lines. This is suggestive of crystal fractionation, and to test this possibility, a series of least squares linear mixing calculations (Bryan et al., 1969) was made for various combinations of lava bulk compositions and analyzed phenocryst compositions. Major element compositions were recalculated water-free with total Fe as FeO. We weighted the major oxides as follows, 0.2 for SiO_2 , 0.5 for Al_2O_3 , and 1.0 for all others. The lowest or earliest lava from the crater wall, B-6, was chosen as a hypothetical parent. We tested the possibility of deriving each subsequent lava from B-6 by using B-6 as a solution vector and calculating a least-squares approximation to it. This approximation is a linear combination of the subsequent lava, and the phenocryst phases (plagioclase, augite, olivine, and magnetite) and apatite. Apatite is not present as separate phenocrysts but was found as inclusions in plagioclase and olivine phenocrysts. After trying many possible combinations of the mineral compositions in Table 2, we found that the most suitable combination was the plagioclase and augite from sample B-22 and the olivine and magnetite from sample B-11. These compositions are intermediate between the more Ca- and Mg-rich minerals of B-6, the lava from near the base of the crater wall, and the relatively Na and Fe-rich minerals of B-3, the last lava erupted.

Representative mixing calculations are shown in Table 3, in which the lava with the highest SiO_2 content, B-3, is derived from B-6 using two different sets of plagioclase and augite compositions. The plagioclase and augite from B-22 (Method 1 on Table 3) give a better fit and require a larger degree of fractionation than do the more calcic plagioclase and

Table 3. Representative mixing calculation

Method 1				Method 2			
B-6 =	B-3	43.3%		B-6 =	B-3	54.0%	
	B-11 Mag.	3.7%			B-11 Mag.	2.3%	
	B-22 Plag.	31.4%			B-6 Plag.	24.3%	
	B-22 Pyrox.	18.0%			B-6 Pyrox.	15.5%	
	B-11 Oliv.	3.2%			B-11 Oliv.	3.9%	
	Avg. Apatite	0.4%			Avg. Apatite	0.3%	
Oxide	Observed	Calculated	Weighted residual	Observed	Calculated	Weighted residual	
SiO_2	52.90	53.33	-0.09	52.90	53.57	-0.13	
Al_2O_3	17.10	17.13	-0.01	17.10	17.10	-0.00	
FeO	10.13	10.14	-0.01	10.13	10.15	-0.02	
MgO	4.51	4.48	0.03	4.51	4.46	0.05	
CaO	9.68	9.65	0.03	9.68	9.64	0.04	
Na_2O	3.05	2.82	0.23	3.05	2.56	0.49	
K_2O	1.26	1.24	0.02	1.26	1.49	-0.23	
TiO_2	0.97	0.91	0.06	0.97	0.84	0.13	
P_2O_5	0.20	0.24	-0.04	0.20	0.26	-0.06	
MnO	0.19	0.21	-0.02	0.19	0.22	-0.03	
Weighted sum of squares			0.07				0.34

more magnesian augite from B-6. Most Boqueron lavas can similarly be derived from B-6 by fractionation of observed phenocryst phases. The fractionation needed to derive subsequent lavas from B-6 is summarized in Table 4. Sample B-2 requires that a small amount of plagioclase be added rather than subtracted and therefore is not included in Table 4.

A possible objection to the fractionation models shown in Table 4 is that the proportions of calculated fractionated phases do not in general agree with the observed proportions of modal phenocryst phases. The phenocryst proportions are dominated by plagioclase, which is the least dense phenocryst phase. Furthermore, the densest phenocryst phase, magnetite, is commonly found attached to or included in less dense phenocryst phases. These relations suggest that the phenocryst proportions reflect the relative buoyancy of the fractionating crystals and not the proportions of fractionated phases.

A major objection to deriving andesite by fractional crystallization of basalt is that it is difficult to produce andesite from basalt without removing magnetite, and experimental studies on andesitic compositions (Eggler, 1971; Eggler and Burnham, 1973) show that oxide phases, especially magnetite, are not liquidus phases and are therefore not likely to be fractionated. This objection cannot apply to the Boqueron lavas because magnetite phenocrysts are found in almost every lava. A further objection to

Table 4. Summary of fractionation needed to produce subsequent lavas from B-6

Final Lava	B1	B5	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B24	B22	B19	B20	B21	B3
% Final Lava	71.0	88.0	68.0	70.0	88.0	86.0	89.0	54.0	52.0	52.0	52.0	53.0	65.0	57.0	70.0	48.0	46.0	47.0	43.0
Plagioclase (B-22)	12.0	6.0	14.0	12.0	6.0	3.0	5.0	26.0	27.0	28.0	27.0	27.0	19.0	26.0	15.0	31.0	31.0	31.0	31.0
Clinopyroxene (B-22)	11.0	5.0	12.0	12.0	5.0	7.0	4.0	14.0	15.0	14.0	15.0	14.0	11.0	13.0	9.0	13.0	16.0	15.0	18.0
Olivine (B-11)	4.4	1.1	2.8	3.0	1.1	3.5	1.0	3.1	3.2	3.3	3.0	2.9	2.8	3.0	4.3	3.2	3.7	3.7	3.2
Magnetite (B-11)	2.2	0.0	2.5	2.1	0.2	0.8	0.1	2.8	3.0	2.9	3.0	3.0	1.9	2.0	1.2	0.1	3.1	3.1	3.7
Apatite (stoichiometric)	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.1	0.2	0.3	0.3	0.4

the fractionation hypothesis is that the amount of fractionation needed may be excessive. Samples B-7, B-8, B-22, and B-24 approximately represent the average lava erupted over the stratigraphic interval sampled. If B-6 is a reasonable parent, then the degree of fractionation needed is approximately 30% to 40%. Considering our ignorance of the dimensions of the magma supply system beneath the volcano, this does not seem excessive.

Field evidence suggests that the section sampled represents 1/3 to 1/4 of the history of the Boqueron cone. Much of the section is basaltic and since there is a progressive decrease in SiO₂ content downward, it is reasonable to infer that most of the buried part of the cone is basaltic. This agrees with McBirney (1976) who has suggested that andesites are not as typical as is commonly thought and, in fact, represent much less volume than do basalts in island arc settings; it is their prominent position as the last lavas erupted in the volcanic cycle that make the andesites appear common. The abundance of basalt, the regular variation trends, and the fact that the Boqueron andesites are readily derived from basalts by removal of observed phenocryst phases indicate that crystal fractionation has been the important process governing the development of andesitic lavas at Boqueron.

Origin of Temporal Magmatic Variation

The temporal magmatic evolution of Boqueron has three components. First, the observed pattern of SiO₂ evolution (Fig. 4) is crudely cyclical. Second, the cycles are gradually shifted to higher SiO₂ contents. Third, there is an abrupt change in Al₂O₃, CaO, FeO, MgO, and TiO₂ variation (Figs. 2 and 3) which is independent of the pattern of SiO₂ evolution.

The abrupt change from Al-rich to Fe-rich variation trends occurred during or immediately after a period of pyroclastic activity. Mixing calculations, summarized in Table 5, suggest that the proportions

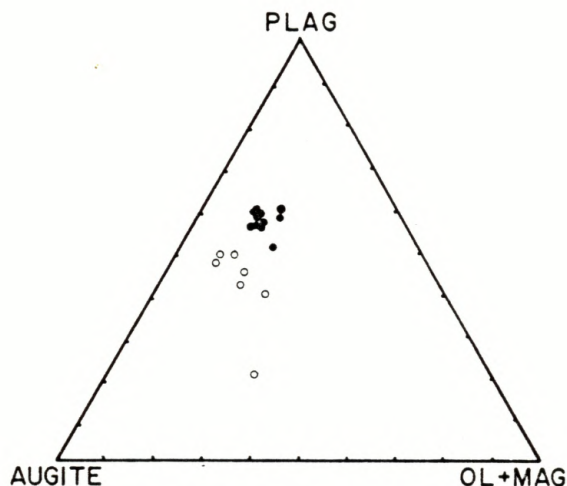


Fig. 5. Estimated proportions of phenocryst phases that need to be subtracted from B-6 in order to produce the Al-rich lava series (open circles) and the Fe-rich lava series (filled circles)

of fractionating phases needed to produce the Al-rich lava series is dominated by augite and plagioclase in roughly equal proportions, or with a predominance of augite (Fig. 5). The fractionation needed to produce the Fe-rich lavas, on the other hand, is dominated by plagioclase (Fig. 5). Experiments on Parícutin andesite (Eggler, 1972) show that decreased pH₂O increases the plagioclase liquidus field, which suggests that decreased pH₂O is responsible for the observed abrupt change in variation trends at Boqueron. The pyroclastic activity which coincided with this abrupt change in variation trends could have lowered pH₂O in two ways. First, the gas-rich pyroclastic eruptions themselves may have devolatilized and degassed the magma chamber. Second, the explosive pyroclastic eruptions may have altered the shape or structure of the chamber-vent system, so that volatiles could more easily escape from the chamber, or so that meteoric water could less easily enter the chamber.

The close association of basalts and andesites, and

the gradual progression from basaltic to andesitic compositions observed in some parts of the stratigraphic record suggest that fractional crystallization is occurring beneath Boqueron. The reappearances of basaltic lavas after periods of andesite eruptions indicate that the magma chamber where fractionation occurs receives fresh influxes of basaltic magma. Such influxes appear to have occurred twice during the recent history of Boqueron; the first just before the thick ash layer, and the second at about the time the present crater formed. The most mafic lava erupted during the first influx of basalt has a slightly higher SiO_2 content than B-6, the lava at the base of the section. The most mafic lava erupted during the second presumed influx of basalt has a considerably higher SiO_2 content than B-6. This suggests that each successive influx of basaltic magma mixes with the fractionated andesitic magma remaining in the chamber. The maximum SiO_2 content reached in each cycle also increases with each successive cycle. We propose that the cyclical trend in SiO_2 content results from a combination of continuous fractionation, periodic addition of basalt, and magma mixing processes. The shifting of the cycle toward higher SiO_2 contents occurs because there is continuous fractionation and because the volume of the liquid remaining in the chamber just prior to a basalt influx is at least 25 to 50% of the volume of the basalt influx.

The magmatic evolution of Santa Maria volcano in western Guatemala described by Rose et al. (1977) is different from that of Boqueron. The variation of SiO_2 content with elevation is more erratic at Santa Maria and Harker variation curves are less coherent. Rose et al. (1977) proposed that there were several batches of basalt magma at Santa Maria, with each succeeding batch fractionating and erupting independently. SiO_2 content of lavas increased with elevation because it became progressively more difficult for succeeding batches to rise through the growing volcano; therefore it took longer and the increased time provided opportunity for increased fractionation. The tentative model for the evolution of Boqueron proposed here differs by having a permanent magma chamber which allows the fractionated remnants of one batch to mix with the next. This mixing allows the SiO_2 content of Boqueron lavas to vary more regularly and makes the Harker variation diagrams more coherent than is the case at Santa Maria.

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