

Multi-stage magma mixing in the pre-caldera series of Fuego de Colima volcano

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RESUMEN

Datos geoquímicos y petrográficos acerca de las lavas anteriores a la formación de la caldera del Volcán Fuego de Colima indican dos procesos magmáticos: cristalización fraccionada y mezcla de magma. Estos procesos pudieron suceder juntos, de tal manera que sus efectos se adicionan. Se distinguen tres tipos de mezcla: (i): mezcla entre nuevas inyecciones de magma profundo y minerales máficos acumulados en la parte inferior de la cámara magmática somera. (ii): Mezcla, en la cámara, entre este magma juvenil (anteriormente diferenciado o no en una cámara más profunda, contaminado por olivino y clinopiroxeno o no) y un magma diferenciado de composición andesítica o dacítica. (iii): Mezcla por convección entre magmas ya diferenciados, por separación de minerales, o mezcla, o por ambos procesos, a diferentes niveles en la cámara somera.

PALABRAS CLAVE: Cámara magmática, mezcla, cristalización fraccionada, andesitas, Volcán Fuego de Colima, México.

ABSTRACT

Mineralogical and geochemical data from pre-caldera lavas of Volcan Fuego de Colima indicate that both fractional crystallization and mixing processes occurred together. Three types of mixing are evidenced: (i): Mixing between fresh input of mafic magma and olivine-clinopyroxene cumulates in the lower part of the magma chamber. (ii): Mixing, within the shallow chamber, between this deep juvenile magma (previously differentiated by crystal fractionation or not, ol-cpx enriched or not in a deeper magma chamber) and a differentiated magma, andesitic or dacitic in composition. (iii): mixing by convection between magmas previously differentiated by mixing and/or crystal fractionation at different levels in the magma chamber.

KEY WORDS: Magma chamber, mixing, crystal fractionation, andesites, Volcan Fuego de Colima, Mexico.

INTRODUCTION

Fuego de Colima volcano (19° 30' 40"N; 103°37'W) is considered one of the most active volcanoes in the North American continent. The present summit cone is located in the avalanche caldera of a former edifice built on the southern side of Nevado de Colima volcano (Figure 1). Substantial petrologic studies have been carried out on the post-caldera lavas and eruptive styles of activity (Luhr, 1981; Medina, 1983; Robin *et al.*, 1987), the petrology of recent volcanic products (Luhr and Carmichael, 1980; 1990, Robin *et al.*, 1987; 1991), as well as the gigantic Mount St Helens (MSH)-type event which marks the transition between the ancient edifice and the recent cone (Vincent *et al.*, 1983; Robin *et al.*, 1987; 1990; Luhr and Prestegard, 1988). Since the first observations in the 16th century, the summit cone has displayed a pattern of eruptive cyclicity with alternate explosive and effusive episodes, clearly related to periodic supplies of deep mafic magma to the shallow reservoir (Robin *et al.*, 1991).

OBJECTIVES

Volcanological and petrological information on the basal edifice called Paleo-Fuego by Robin *et al.* (1984) is scarce. The lavas from the upper part of the caldera wall, which precede directly the MSH event, are dacites ($\approx 65\%$ SiO₂) whereas post-caldera volcanics consist of andesites. Interaction of "mafic" magma ($\approx 56\%$ SiO₂) with silicic andesite or dacitic magma just before or dur-

ing the MSH-type eruption has been demonstrated (Robin *et al.*, 1990). Since the MSH event represents a major stage in the structural and petrological development, and since no magma mixing is shown in heterogeneous pyroclastic deposits of the stratigraphic sequence of Paleo-Fuego (contrary to the summit cone) a question arises: are the mafic magma supplies a characteristic of the terminal cone stage only? In other words, did this phenomenon occur for the first time during the MSH event, or were such magma injections also repeated during the development of Paleo-Fuego?

This paper presents new petrographic and geochemical data which indicate that the dominant mechanism in the evolution of Paleo-Fuego lavas was mixing during a multi-stage process in the shallow reservoir and/or at deeper levels in the crust. Some of the magmas involved in the mixing (generally the mafic member) may have previously experienced contamination by mafic crystal-enriched zones prior to their injection in the magma chamber. Fractional crystallization, prior and subsequent to mixing events, also occurs and complicates the problem of the origin of the series.

SAMPLING

Twenty-four samples were studied. Field location is given in Robin *et al.*, 1984. Although these samples result from different magmatic processes (see discussion and conclusion) and thus belong to various magmatic series, they are considered here in two parts: eight from

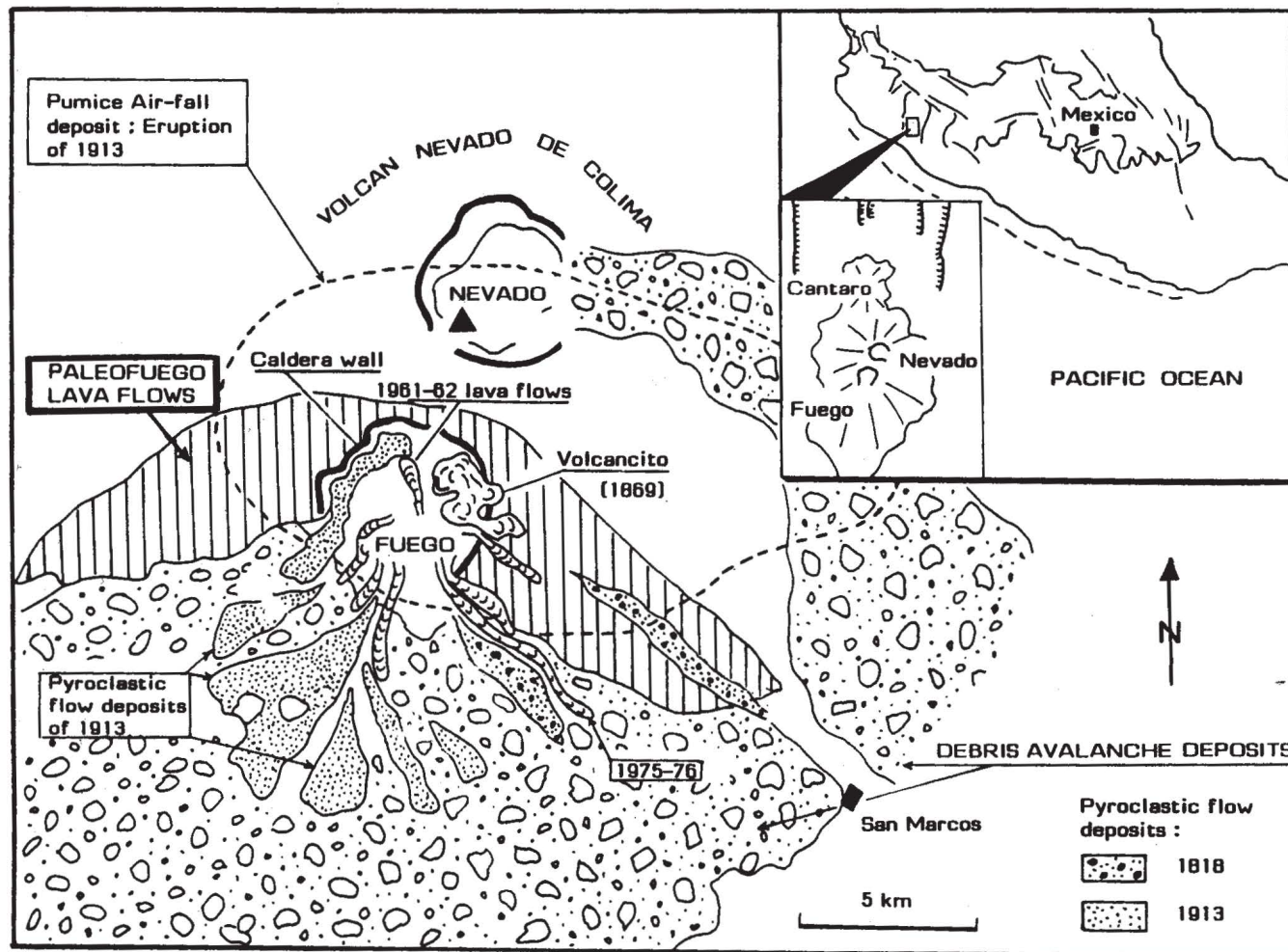


Fig. 1. Simplified map of Fuego de Colima volcano showing the extent of Paleo-Fuego lava flows, the avalanche caldera and recent products from the cone. From Robin *et al.*, 1991, modified.

the caldera wall, above 3100 meters elevation, in such a way that their relative chronology is well established; and nearly all other samples from volcanic sequences of the lower slopes of the volcano. Since these sequences are strongly dissected by erosion and filled by recent products, they are considered older than the caldera sequence which topped the summit cone before the avalanche. They come from lava flows or pyroclastic flows from sporadic domes in the summit area.

Only one sample (Co 11), collected from a thick pumice flow deposit on the southeast flank, appears to be related to a major pyroclastic event, large enough to produce a major crater or collapse not visible at present.

The oldest dated lava in the collection (Co 35) is about 80,000 years old (Robin *et al.*, 1987). Excluding the parasitic scoria cones located north of Nevado de Colima, this lava is the most mafic found in the entire volcanic complex of Colima. It will be considered the mafic member from which the magmatic series differentiated. For comparison, this study also presents the characteristics of the Tezontal basalt (Co 103), from one of the ex-

ternal scoria cones described in detail by Luhr and Carmichael (1981). The mafic juvenile magma (Co152) collected in pyroclastic-surge deposits associated with the MSH event (Robin *et al.*, 1990) is also discussed.

PETROGRAPHY AND MINERAL CHEMISTRY

Modal analyses are presented in Table 1. Except for Co35, a poorly porphyritic basaltic andesite, lavas collected from Paleo-Fuego are andesites, acid andesites and dacites that exhibit porphyritic textures (20 to 40% phenocrysts), sometimes with glomeroporphyritic tendencies. Plagioclase (13.3 to 35% in volume) is the most abundant phase. Clinopyroxene ranges from 0.7 to 6%; it is more abundant than orthopyroxene (0 to 2.2%). Clinopyroxene is found as individual grains, as glomerocrysts, and in glomeroporphyritic clots with plagioclase and/or orthopyroxene. When present, amphibole does not exceed 1% in andesites but is more abundant in dacites (up to 3%). Olivine occurs in a few samples.

Plagioclase phenocrysts are up to 1.5 mm long, optically zoned and have inclusions of Fe-Ti oxides, brown

Table 1

Modal analyses of lavas from the Paleo-Fuego series.

	CO35	CO36	CO13	CO41	CO11B	PF13	F6	F19	F17	F13	F10
Plagioclase	3.5	17.3	20.5	28.9	13.3	23.4	21.5	20.8	17.1	18.2	15.6
Clinopyroxene	3	2.7	4.5	2.2	0.7	3	5.5	3.3	5.9	2.8	2.7
Orthopyroxene	-	0.4	1.7	1.2	0.6	0.6	1.1	0.8	2.2	2.1	0.8
Amphibole	-	0.8	0.9	0.7	3.1	2.6	-	0.2	-	1.7	3
Olivine	0.4	-	0.6	0.2	-	0.5	-	2.2	-	0.2	-
Fe-Ti oxides	1.4	2	2.3	1.6	1.8	2.1	1.4	3.9	2.2	2	1.8

glass, apatite, and sometimes clinopyroxene. The composition of phenocrysts ranges from An 35 to An 70, regardless of petrographic type (Figure 2). Histogram frequencies show a unimodal or bimodal distribution; the latter (for example in F13, Figure 3) is classically interpreted as evidence of mixing. Thirteen samples were analysed by microprobe and the results do not show any correlation of plagioclase composition with either SiO₂ content (Figure 2A) or with stratigraphic position (for the samples from the caldera wall, Figure 2B). Compositional zoning in plagioclases is either normal and gradual, or reverse and sharp. The plagioclases with sharp variations of composition show dark (or cloudy) zones consisting of skeletal feldspar and a channel-like network of tiny glass inclusions, commonly overgrown by a rim of clear plagioclase. These destabilized zones are An-enriched. Differences of 18-20% of anorthite have been noticed between these zones and their surrounding clear zones. Note that the rims of plagioclase phenocrysts have a broad range of composition and, considering all plagioclases from one sample, no progressive normal evolution (towards sodic plagioclase) or reverse evolution is obvious (Figure 2 and 3).

Clinopyroxenes and orthopyroxenes are mostly diopsidic augite (Wo 40-43, En 42-45.5, Fs 13-16) and hypersthene (En 65-75), respectively. In a few cases, the orthopyroxene is Mg-rich bronzite (up to En 84).

The compositional evolution from the core to the rim of clinopyroxene crystals is generally normal except in F13 and F6, but no major evolution has been noticed for this mineral over the series. Sample F13 is also notable because of the coexistence in this rock of different clinopyroxene core compositions.

Following Leake's classification (1978), two types of calcic **amphibole** are present in the Paleo-Fuego lavas: (i) amphiboles along the tschermakite to magnesio-hornblende trend, and (ii) a group of magnesio-hastingsites and magnesio hastingsitic hornblendes, in the most differentiated samples.

Most **Fe-Ti oxides** are titanomagnetites with 5-15 wt% TiO₂. In four samples the coexistence of titanomagnetite and ilmenite (with TiO₂ up to 45%) was recorded.

Olivine. Most grains exhibit reaction rims. Microprobe analyses indicate compositions ranging from Fo 66

to 77 for the basaltic-andesite to dacite suite of Paleo-Fuego. Common inclusions are spinels. Olivines from the basaltic andesite Co152 and basalt Co103 (Volcán Tezontal) have Fo 73-85 and Fo 79-80, respectively. It is worth noting that this phase is more abundant in F19 (57.2% SiO₂) than in Co 35 (55.9% SiO₂) and that it is well represented in some acidic andesites and dacites, e.g. in F13, 64.5% SiO₂.

GEOCHEMISTRY: ANALYTICAL RESULTS

Table 2 and Figures 4 and 5 present the analytical results for major and minor elements measured at the Centre de Mesures Physiques, University of Clermont-Ferrand.

On the K₂O-SiO₂ diagram of Peccerillo and Taylor (1976) (Figure 4), the Paleo-Fuego samples plot in the medium-K calcalkaline series. SiO₂-variation diagrams show roughly linear trends for FeO, CaO, TiO₂ whereas MgO, Cr, Ni and Co exhibit pronounced scatter with anomalous enrichment in some rocks. The enriched samples are those for which mineralogical anomalies such as presence of olivine or reverse zoning in pyroxene were found.

Relationships between SiO₂ and Al₂O₃, Na₂O, K₂O, Ba and Sr, elements that are strongly controlled by plagioclase behaviour also show a large dispersion.

INTERPRETATION OF PETROLOGICAL DATA

Using the diopside-enstatite geothermometer of Wells (1977), temperatures of crystallization of acidic andesites appear homogeneous between 918° and 982°C (Table 3). The calculated temperature for the andesite Co16 by the same method is 1040° C or 1120°C using the ilmenite-magnetite thermometer (Buddington and Lindsley, 1964; Ghiorso and Carmichael, 1981). These results suggest a thermally zoned magma chamber with different magma compositions. Based on the olivine-spinel thermometer, the temperature of olivine crystallization in the basalt Co 103 is even higher: 1280°C.

1. Role of crystal fractionation.

Mineralogical data and evolutionary trends between strongly incompatible elements and compatible ones indicate that crystal fractionation participated in the differentiation. Crystal fractionation calculations using the

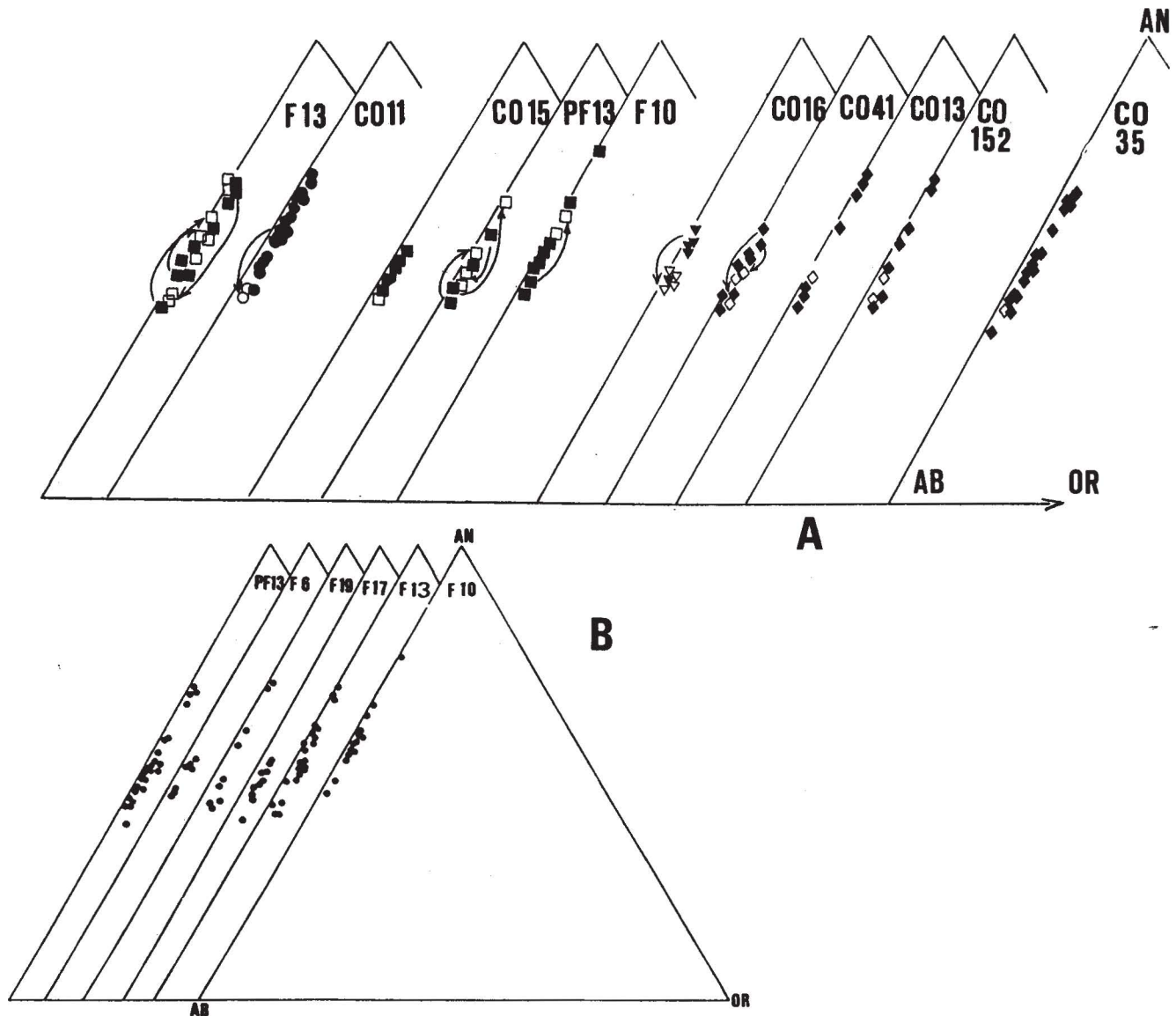


Fig. 2. Ab-An-Or diagram for plagioclases. A: Samples from lower lava sequences (Co 11, Co 15, Co 16, Co 41, Co 13, Co 35) and remarkable zonings from core (solid symbols) to rims (empty symbols) in plagioclase within samples from the caldera sequence (F13, PF13, and F10). Samples ordered from left to right by decreasing SiO₂ content (note that no evolution is marked). B: Core compositions in the caldera wall sequence; samples ordered by stratigraphy (note that no evolution is marked).

least squares method (Wright and Doherty, 1970) are successful for a few lavas. For example, the chemical composition of F17 (acid andesite, 62.4% SiO₂) may be obtained after separation of 34% plagioclase, 1.8% clinopyroxene, 7.4% orthopyroxene and 3.2% Fe-Ti oxides, using the andesite F19 as starting material (Table 4). As these two lavas from the caldera wall were erupted successively; they probably represent different degrees of magma differentiation during a single magmatic cycle. Nevertheless, such successful tests are rare and other complementary magmatic processes must be taken into account in order to explain the whole series.

2. Magma mixing

Two important points are revealed by the modal compositions: First, except for a slight enrichment in ortho-

pyroxene and/or amphibole in the most differentiated lavas, there is no clear relation between whole rock SiO₂ content and mineralogy. Second, some lavas as evolved andesites and dacites (e.g. Co 13, Co 41, PF 13 and F 13) contain olivine. The presence of olivine in such differentiated lavas is commonly interpreted as a result from mixing between a differentiated silicic magma and an olivine-bearing mafic magma (Anderson, 1976; Sakuyama, 1979).

A mixing calculation test was applied to the dacite F13 and the basalt Co 103, in order to produce the composition of F10, an acidic andesite flow that lies on top of F13 in the caldera wall. Plagioclase in F10 is characterized by strong reverse zoning and the rock has an anomalous MgO content (4% for SiO₂-61.1%). This rock

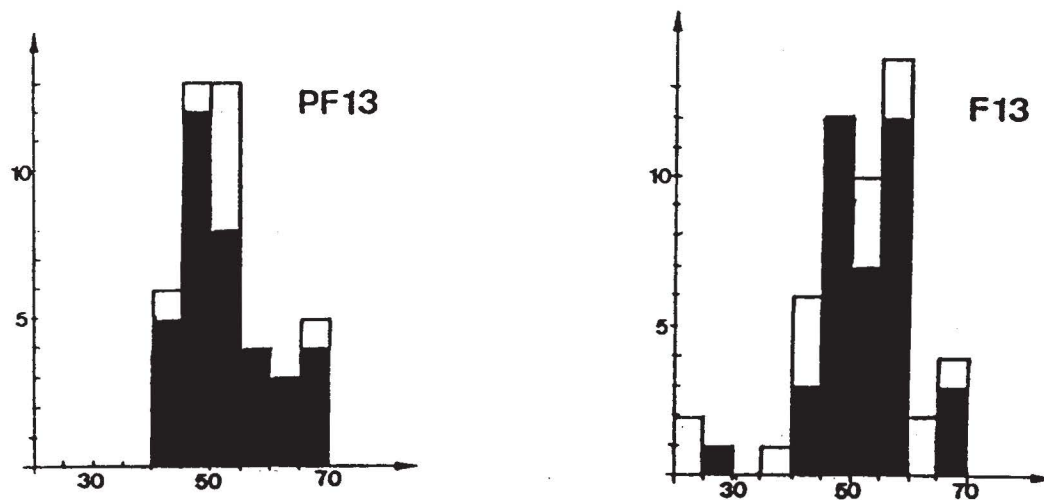


Fig. 3. Histogram for anorthite content in plagioclase phenocrysts. Solid: cores of phenocrysts; empty: rims of phenocrysts.

may result from the mixing of 74% F13 and 26% Co 103 (Table 5). An important fact is that F13 also shows unambiguous evidence of mixing, as discussed above. Thus, to explain the mineralogy of the caldera wall sequence, a multi-stage mixing model is required.

Such a model, with two or more steps, is emphasized by three arguments that suggest long differentiation path controlled by crystal fractionation, and rapid successive incorporation of plagioclase from various levels of the magmatic column during the mixing events:

- (i) large compositional range of the core phenocrysts.
- (ii) the composition of glass in minerals: for example, glass inclusions in plagioclase from sample F13 have 76-78% SiO₂ (0.5% CaO and 12% Al₂O₃) whereas glass from pyroxene has 69-70% SiO₂ (2% CaO, 17% Al₂O₃). These compositions would correspond to a normal process of differentiation by fractional crystallization.
- (iii) The dispersion of rim compositions in plagioclase (F13, PF 13, Co 35, Figure 3).

3. Crystal assimilation

Since Co152 (SiO₂=57%, MgO=8.2%) is one of the most mafic magmas in the PaleoFuego series, it may be a good candidate to represent the mafic component of the first mixing at deep levels in the reservoir when new magma input occurs. Based on major elements, a crystal fractionation test shows that Co152 may result from a basalt similar to that of Volcan Tezontal after separating out 6.7% olivine, 9.7% pyroxene, 36% plagioclase and 4.4% Fe-Ti oxides (Table 6). However, this result is not in agreement with the high Ni and Cr concentrations observed in the rock. Using the determined Ni concentration in olivine of Co103 (3900 ppm), $D=3.89$ (global partition coefficient calculated from the data of Luhr and Carmichael, 1980) and $F=43\%$, percentage of

liquid given by the calculation, the Ni concentration in the liquid after separation of 7% olivine would be 13 ppm. Since the concentration in Co 152 is 170 ppm, a contamination process by olivine must be considered. This model requires incorporation of around 3.5% olivine in the ascending fractionated magma, perhaps derived from olivine-cumulates on the walls of the magma conduit or zones deep in the magma chamber. Such a value is compatible with the modal composition. In the same way, incorporation of clinopyroxene (and/or spinel included in the olivine) would explain the high Cr content of the rock.

4. Model of magma chamber

Most crystal fractionation tests and mixing tests attempted were not successful. This is explained by the fact that both processes -crystal fractionation and mixing-occurred together, and it is not possible to obtain one rock composition from another if only one of these differentiation processes is invoked. Moreover, crystal fractionation models assume that whole-rock compositions are representative of liquids, which is not the case in andesitic volcanoes where we are dealing rather with a "crystal mush" (Langmuir, 1989; Sparks, 1989). The scattered relationships in Figure 5 presumably are the result of a combination of crystal fractionation, magma mixing and assimilation of mafic crystals in a vertically zoned magma reservoir. A tentative model would take into account the following processes:

1. Crystal fractionation from a parental magma at different levels in the crust and in a shallow chamber, leading to compositional and temperature zoning in this reservoir.
2. Small scale mixing at the interface between adjoining zones.
3. Eruption of differentiated magmas from the upper part (Co11b), showing no evidence of mixing.

Table 2

Chemical analyses of the studied samples.

	Co35	F19	Co36	Co13	Co 8	Co 41	Co 9	Co7	Co16	Co40	PF 13	F 10
SiO ₂	55,9	57,2	58,2	59,6	59,7	59,8	59,9	60,7	61	61	61,1	61,1
TiO ₂	1	0,7	1	0,8	0,65	0,65	0,55	0,65	0,9	0,9	0,85	0,64
Al ₂ O ₃	18,3	18	18	16,2	18,2	18,4	17,3	16,5	17,2	17,8	17,5	17,16
Fe ₂ O ₃ [*]	6,83	6,65	6,23	5,97	5,64	6,18	5,85	5,11	5,75	5,85	6,06	5,85
MnO	0,11	0,12	0,08	0,09	0,09	0,1	0,1	0,09	0,09	0,08	0,12	0,1
MgO	4	4	3,3	3,8	3,2	3,2	3,4	4,6	2,95	2,1	3,4	3,96
CaO	7,7	6,9	6,2	5,8	6,7	5,7	6	6	5,6	5,4	5,7	6,27
Na ₂ O	4,4	4,25	4,3	4,4	4,4	4,5	4,25	3,85	4,65	4,9	4,05	4,55
K ₂ O	1,1	1,2	1,3	1,45	1,4	1,3	1,45	1,55	1,55	1,35	1,1	1,26
P ₂ O ₅	0,25	0,25	0,22	0,3	0,21	0,21	0,22	0,21	0,23	0,22	0,24	0,15
LOI	0,12	0,01	0,62	1,02	0,02	0,14	0,31	0,06	0,08	0,04	0,47	0,06
	99,61	99,28	99,45	99,43	100,21	100,18	99,33	99,32	100,00	99,64	100,59	101,10
Rb	14			20							15	
Ba	376	510	570	486	540	500	560	498	600	520	550	580
Sr	695	700	822	617	543	615	770	1062	700	640	615	560
Zr	97	138	125	112	120	128	130	112	134	130	130	110
Y	14	23	17	14	19	18	17	15	18	19	15	16
Cr	38	21	12	85	60	5	13	168	26	5	20	130
Co	34	36	26	34	25	25	29	28	23	19	25	28
Ni	29	20	20	36	29	20	20	58	22	10	10	50
Sc	19,5	21	16	18,5	16	12	15	17	13	10	17	19
	F 6	Co 3	Co11	Co 15	F 15	F 17	F 11	F 12	Co 11 B	F 13	Co 103	Co 152
SiO ₂	61,2	61,3	61,5	62	62,4	62,4	62,8	62,9	64,2	64,9	50,1	57
TiO ₂	0,75	0,6	0,7	0,5	0,75	0,65	0,65	0,65	0,6	0,55	0,85	0,8
Al ₂ O ₃	17,3	18,2	17,1	16,8	16,8	16,3	16,9	17,2	16,8	16,4	18,2	15,2
Fe ₂ O ₃ [*]	4,74	5,47	4,74	5,16	4,77	4,69	4,34	4,59	3,95	4,31	9,28	6,9
MnO	0,08	0,09	0,09	0,09	0,09	0,08	0,07	0,08	0,07	0,07	0,16	0,11
MgO	3,05	2	1,9	2,6	2,9	3,25	2,7	2,6	1,55	2,5	8,7	8,2
CaO	5,7	5	4,4	5	5,8	5,6	5,4	5,2	4,55	5,2	9,5	7,1
Na ₂ O	4,2	4,85	4,4	4,25	4,2	4,25	4	4,4	4,3	4,5	2,6	3,6
K ₂ O	1,55	1,2	2,5	1,95	1,35	2	1,4	1,2	2,1	1,25	0,7	1,1
P ₂ O ₅		0,22	0,32	0,25	0,18	0,35	0,12	0,16	0,3	0,25	0,32	0,16
LOI	1,07	0,46	1,76	1,36	0,04	0,09	1,12	0,25	1,77	0,07	0,17	0,74
	99,64	99,39	99,41	99,96	99,28	99,66	99,50	99,23	100,19	100,00	100,58	100,91
Rb	nd					22			20	20	12	
Ba	nd	555	880	630	690	540	635	790	494	642	212	390
Sr	nd	630	1034	656	601	914	585	694	922	622	495	635
Zr	nd	121	120	135	113	125	106	105	119	98	99	130
Y	nd	18	19	18	17	12	13	13	9	9	17	16
Cr	nd	6	8	15	23	35	22	19	17	19	361	400
Co	nd	18	28	25	28	33	22	19	17	34	55	40
Ni	nd	10	10	0	26	37	26	27	6	27	152	170
Sc	nd	10	10	12	16	14	15	15	6,5	12	36	29

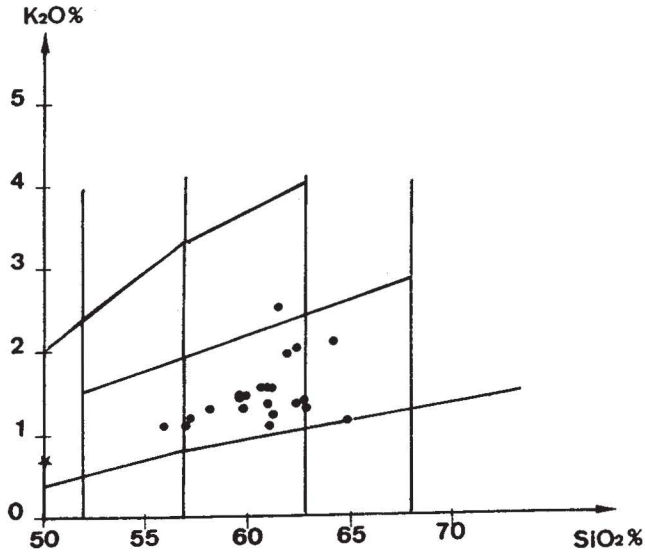


Fig. 4. K₂O-SiO₂ diagram.

Table 3
Calculated temperatures (Opx-Cpx geothermometer; Wells, 1977).

Sample	T°C	R	Number of analyses
F6	977	37	11
F10	982	14	9
F17	971	32	18
PF13	962	14	6
CO16	918	30	13
CO36	1043	42	8

Table 4

Calculation of magmatic differentiation by fractional crystallization from andesite F19 to dacite F17

	Analyzed	Calculated	R	% of phases
SiO ₂	57.2	57.44	-0.25	53.48% dacite F17
Al ₂ O ₃	18.0	18.17	-0.18	1.82% clinopyroxene
Fe*	6.3	6.53	-0.24	7.39% orthopyroxene
MgO	4	4.08	-0.09	34.02% plagioclase
CaO	6.9	7.07	-0.18	3.26% Fe-Ti oxides
Na ₂ O	4.25	4.09	0.15	
K ₂ O	1.2	1.16	0.3	
TiO ₂	0.7	0.73	-0.04	
MnO	0.12	0.12	0	
			ΣR ² =0.214	

Table 5

Results of mixing test by the least squares method between the basalt CO103 and the dacite F13 with the aim to obtain the composition of acidic andesite F10.

	Analyzed	Calculated	R	% of phases
SiO ₂	61.1	61.05	0.04	73.99% F13
Al ₂ O ₃	17.16	16.86	0.29	26% CO103
Fe*	5.85	5.3	0.54	
MgO	3.95	4.11	-0.16	
CaO	6.27	6.31	-0.05	
Na ₂ O	4.55	4	0.54	
K ₂ O	1.26	1.1	0.15	
TiO ₂	0.64	0.62	0.01	
MnO	0.10	0.09	0	
			ΣR ² = 0.71	

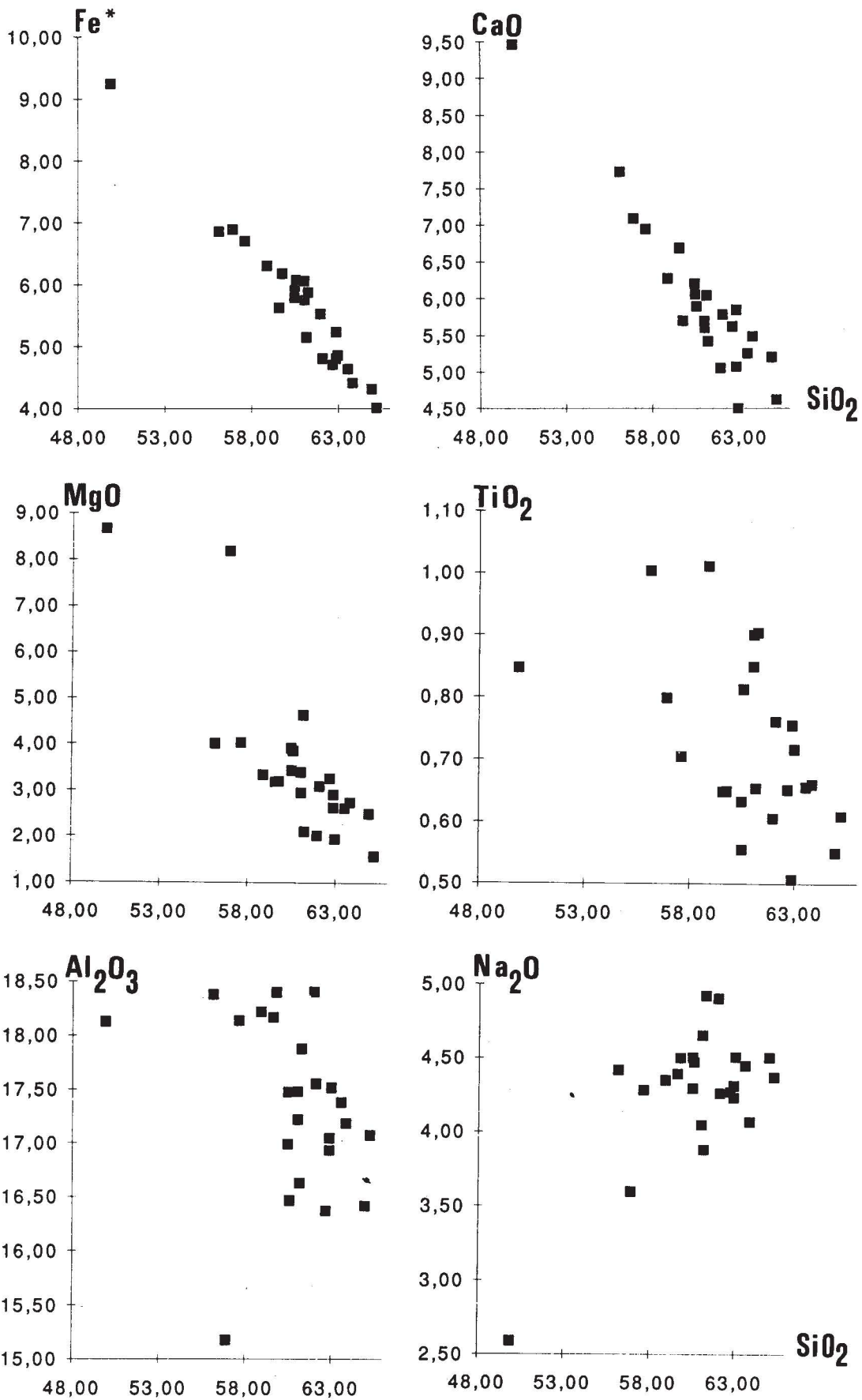


Fig. 5. Major and minor element concentrations correlated to SiO₂.

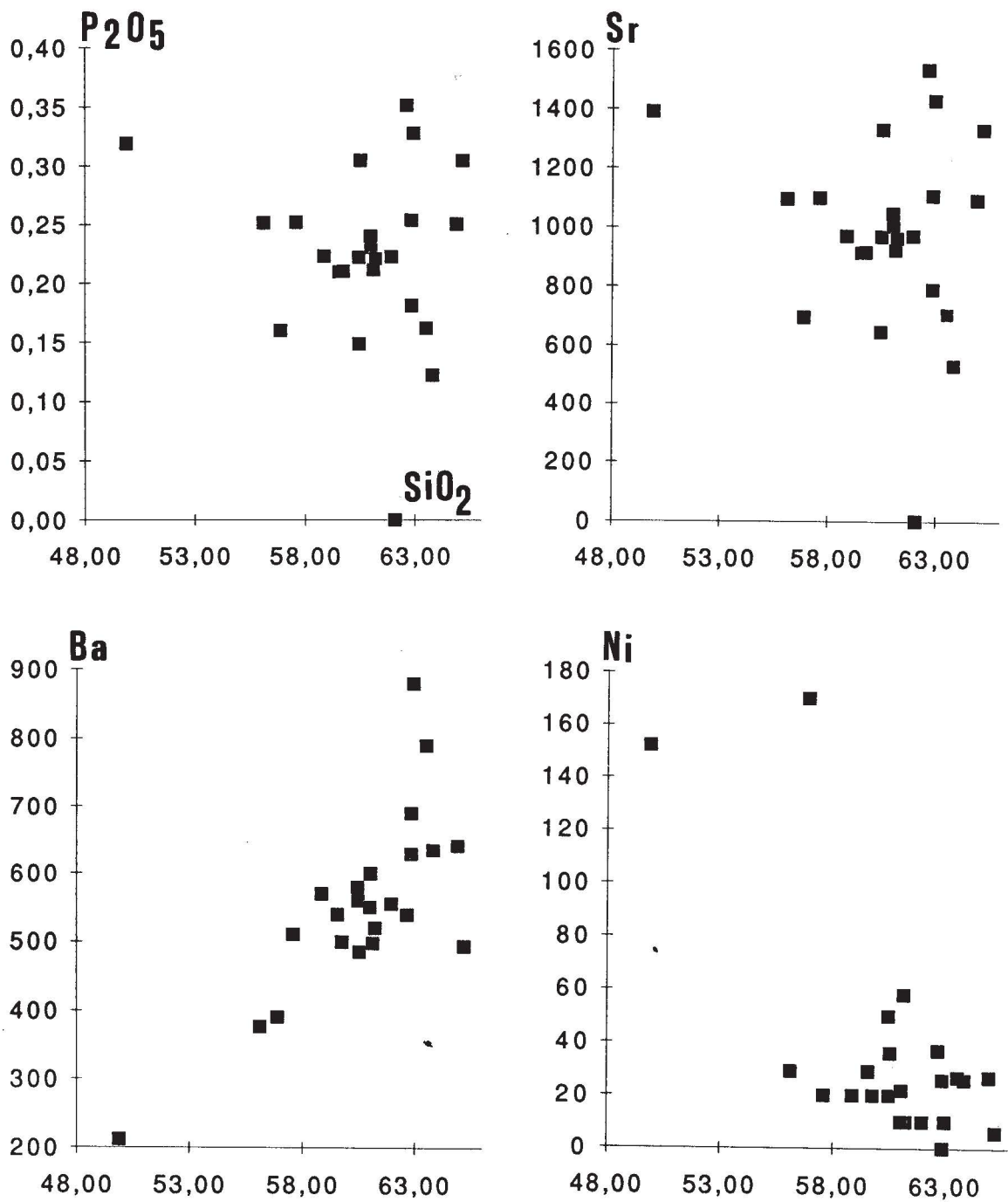


Fig. 5. (Cont.).

Table 6

Calculation of magmatic differentiation by fractional crystallization from basalt Co103 to basaltic andesite Co152.

	Analyzed	Calculated	R	% of phases
SiO ₂	50.1	50.08	0.01	42.74 % andesite CO152
Al ₂ O ₃	18.2	18.17	0.02	4.43 % clinopyroxene
Fe*	9	8.97	0.02	5.32 % orthopyroxene
MgO	8.7	8.68	0.01	36.36 % plagioclase
CaO	9.5	9.47	0.02	4.4 % Fe-Ti oxides
Na ₂ O	2.6	2.65	-0.06	6.72 % olivine
K ₂ O	0.7	0.5	0.19	
TiO ₂	0.85	0.86	-0.02	
MnO	0.16	0.10	0.05	
			ΣR ² =0.048	

4. Periodic injections of deep "mafic" magma, previously differentiated from basalts at greater depth. They intruded at the bottom the magma chamber and assimilated cumulate phases at deeper levels.
5. Elevation of temperature caused by the input of the mafic magma. This may induce convection which destroys the interface and causes true mixing between two successive layers, or at a greater scale if massive reinjection occurs.

Thus, a model implying various degrees of mixing as "simple mixing" between the mafic member and a silicic member from the layered magma chamber (for example, like that which occurred during the 1913 pyroclastic event; Robin *et al.*, 1991) cannot explain the data. Three types of mixing occur:

- (i) Mixing between fresh input mafic magma and cumulates at the bottom of the chamber.
- (ii) "True" mixing between this deep juvenile magma (previously differentiated by crystal fractionation or not, olivine and clinopyroxene-enriched or not in a deeper magma chamber) and a differentiated magma in the shallow chamber.
- (iii) Mixing by convection within the shallow chamber, between magmas previously differentiated (by mixing and/or crystal fractionation) at different zones.

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