Geof. Int., Vol. 26-1, 1987, pp.85-108.

PETROLOGIC CHARACTERISTICS OF THE 1982 AND PRE-1982 ERUPTIVE PRODUCTS OF EL CHICHON VOLCANO, CHIAPAS, MEXICO

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RESUMEN

Los estudios petrográficos, macroquímicos y por microsonda de una secuencia de rocas del volcán El Chichón, Chiapas, México, indican que los materiales 'juveniles' de las erupciones de 1982 y las anteriores presentan esencialmente la misma química y la misma mineralogía. Nuestros datos analíticos sugieren que los productos magmáticos han permanecido uniformes en composición química durante los aproximadamente 0.3 m.a. representados por las muestras. Modalmente, la plagioclasa es el fenocristo predominante, seguido por la anfibolita, clinopiroxeno y otras varias fases menores, incluyendo anhidrita. La ausencia de anhidrita de todas menos una de las muestras anteriores a 1982 refleja posiblemente el efecto de la lixiviación post-eruptiva de agua meteórica. Los fenocristos de plagioclasa están complejamente zoneados, con agudos picos en los contenidos de Ca en los límites entre las zonas claras y las zonas ricas en inclusiones de plagioclasa. Estas zonas ricas en anortitas en plagioclasa parecen producirse por fluctuationes en la presión de los volátiles sobre el magma y podrían reflejar los cambios en la cámara magmática de El Chichón provocados por la actividad eruptiva explosiva, repetitiva.

ABSTRACT

Petrographic, bulk-chemical, and microprobe studies of a suite of rocks from El Chichón volcano, Chiapas, Mexico, indicate that the juvenile materials of the 1982 and pre-1982 eruptions of the volcano have essentially the same mineralogy and chemistry. Our analytical data suggest that the magmatic products have remained uniform in chemical composition during the approximately 0.3 m.y. represented by the samples. Modally, plagioclase is the dominant phenocryst, followed by amphibole, clinopyroxene, and several minor phases, including anhydrite. The absence of anhydrite from all but one of the pre-1982 samples possibly reflects the effect of post-eruption leaching by meteoric water. Plagioclase phenocrysts are complexly zoned, with pronounced spikes in Ca contents occurring at boundaries between clear and inclusion-rich zones of the plagioclase. These anorthite-rich zones in plagioclase are likely produced by fluctuations in volatile pressure on the magma and may reflect the changes in El Chichón's magma reservoir in response to repetitive, explosive eruptive activity.

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INTRODUCTION

El Chichón volcano is an andesitic dome complex of Quaternary age which has erupted frequently during the Holocene (Duffield *et al.,* 1984). The eruptions of March-April 1982 are part of a recurring cycle - pyroclastic eruptions accompanied or followed by dome emplacement - of approximately 600 (±200) year intervals during the past 2 000 years (Tilling *et al.,* 1984). The 1982 eruptions drew global attention to this previously little known volcano, primarily because of the considerable amount of sulfur-rich debris injected into the atmosphere. Studies of the 1982 eruptive products of El Chichón have revealed several interesting features, perhaps the most notable being the presence of anhydrite that precipitated from magma. The present report is a product of a cooperative reconnaissance study by the Universidad Nacional Autónoma de México (UNAM) and the U. S. Geological Survey (USGS). Samples of 1982 and pre-1982 volcanic rocks were collected at El Chichón during May-June of 1982, and petrologic study of these rocks is underway in order to learn more about the history of this volcano and to relate its petrologic evolution to the broader volcanic history of the region. The results summarized herein represent a progress report. Studies of Sr isotopes and fluid inclusions are underway and results will be incorporated into more comprehensive future reports.

GEOLOGIC AND TECTONIC SETTING

El Chichón volcano, in north-central Chiapas, Mexico, lies on the North American lithospheric plate near its junction with the Caribbean and Cocos plates (Fig. 1). A zone of left-lateral transform faults in the Chiapas area separate the North American and Caribbean Plates. El Chichón is located between the Trans-Mexican Volcanic Belt (TMVB), which has an east-west trend slightly oblique to the Middle American Trench (MAT), and the Central American Volcanic Belt, which begins near the Mexican-Guatemalan border and parallels the Middle American Trench to the southeast. The northwest-trending region in which El Chichón and scattered other volcanos lie has been termed the Chiapanecan Volcanic Arc by Damon and Montesinos (1978).

Before 1982, El Chichón consisted of a complex of volcanic domes and associated pyroclastic flow and air-fall deposits. A 1 200 meter-diameter crater on the southwest flank of the volcano is partly filled by a pre-1982 lava dome, as was the 1 600 meter crater at the summit of the volcano. The summit dome was destroyed during the March and April 1982 eruptions.

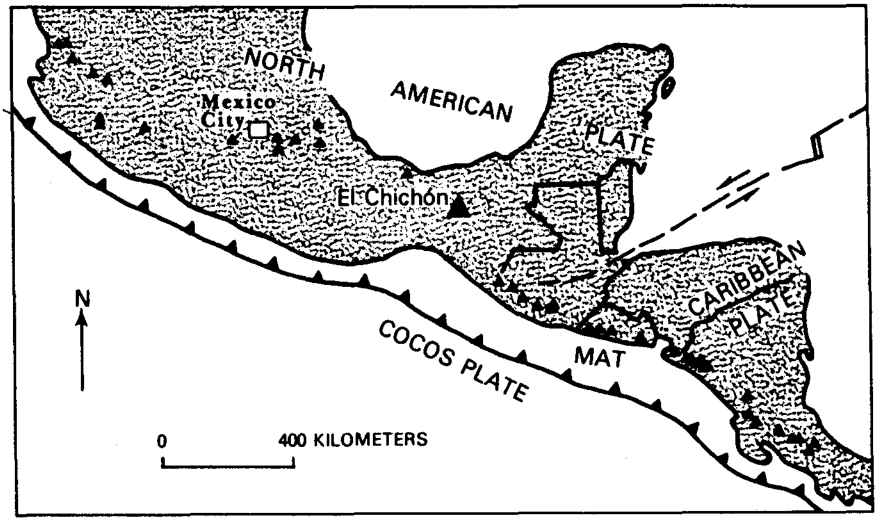


Fig. 1. Location of El Chichón Volcano, Chiapas, Mexico, with respect to the North American, Caribbean and Cocos plates. Triangles trending east-west in Mexico comprise the Trans Mexican Volcanic Belt. Southeast trending triangles are the locations of volcanos of the Central American Volcanic Belt. The Middle American Trench (MAT) separates the Cocos plate from the North American and Caribbean plates. The left-lateral transform fault zone separates the North American and Caribbean plates.

The volcano is situated in a region underlain by Tertiary sandstone/siltstone, Cretaceous limestone, and upper Jurassic-lower Cretaceous evaporite (anhydrite and halite) deposits. The geology of the volcanic complex and of the surrounding area is discussed more completely in Canul and Rocha (1981), Cochemé *et al.* (1982), Peterson (1983) and Duffield *et al.* (1984).

SAMPLE COLLECTION AND ANALYTICAL TECHNIQUES

In May-June, 1982, two of us (R. I. T. and W. A. D.), as part of a cooperative reconnaissance study with the Instituto de Geología of UNAM, collected samples of the 1982 eruption products and of several pre-1982 rocks.

Whole-rock chemistry was determined for the El Chichón samples at the analytical facilities of the U.S.G.S. in Denver using XRF and ICP analytical techniques (Taggart *et al.*, 1981); tens of grams of powdered rock were prepared to provide a representative sample. Chemical compositions of phenocryst and matrix minerals were determined with the electron microprobe. Representative compositions reported here are based on over 1 000 analyses obtained on polished thin sections of seven 1982 and four pre-1982 El Chichón rocks. Microprobe analyses were obtained at the U.S.G.S. in Reston using an ARL-SEMQ 9 channel automated microprobe with Bence and Albee (1968) correction procedures as modified by Albee and Ray (1970). Operating conditions were 15 kV accelerating voltage, 0.1 μA beam current (0.05 μA for glasses), and natural and synthetic silicate and oxide standards. Counting times were 10-20 seconds, depending on the rate of alkali loss in the materials.

Modal data were obtained by point counting 1 000 - 1 500 points per sample, using reflected and transmitted light microscopy. For direct comparison with studies by Luhr *et al.* (1984), phenocrysts were defined as >0.3 mm in size, microphenocrysts between 0.3 mm and 0.03 mm, and matrix as everything smaller than 0.03 mm.

CHEMISTRY AND MINERALOGY

Based on our analytical data, the chemical composition of the eruptive products of the 1982 and pre-1982 eruptions appears to be remarkably uniform during the approximately 0.3 m.y. time span bracketed by our samples (Table 1; Fig. 2). Our analyzed samples are similar in composition to average high-K andesite (Gill, 1981) but are generally enriched in Na_2O, K_2O, and CaO and depleted in MgO compared with high-K andesite (Fig. 2). P_2O_5 and Sr are also enriched in the El Chichón rocks relative to the high-K andesite.

Compositional uniformity of El Chichón eruptive products is also suggested by analytical results obtained in other studies (Cochemé and Silva-Mora, 1983; Hoffer *et al.*, 1982; Luhr *et al.*, 1984; Rose *et al.*, 1984). The overwhelming bulk of the published analyses plot within the solid-line compositional fields shown in Figure 2; however, a few samples plot within the dashed extensions of the compositional fields. The data plotted in Figure 2 are all calculated H_2O-free so that dispersion in the data, especially noticeable in terms of SiO_2 contents, is not an artifact of normalization. Luhr *et al.* (1984) demonstrated that anhydrite is rapidly leached from the 1982 pumices. For samples affected by leaching of SO_3, renormalized oxide values (especially for high concentrations such as SiO_2) may be shifted noticeably, but there is no reason to suspect that samples compared in Figure 2 have undergone differential leaching of sulfur. The SO_3 contents of the 1982 eruptive products are in general agreement among the reported analyses of Rose *et al.* (1984), Luhr *et al.* (1984), and the present study. In fact, two of Rose *et al.*'s older samples have the highest reported SO_3 contents. Even if some inherent differences in the amount of

Table 1 Chemical Analyses of Rocks from El Chichón Volcano

	Pre-1982					1982						
Sample*	1A	3L	3H	9	9**	2A	2B	5	5A	6	7	11L
SiO_2 (wt %)	54.4	55.1	57.3	57.8	57.8	55.5	55.4	55.7	55.7	55.7	54.5	55.1
Al_2O_3	18.5	18.0	18.3	18.2	18.4	17.9	17.9	18.1	18.2	18.1	18.9	17.9
Fe_2O_3 (Tot)	6.81	6.37	6.44	6.23	5.94	6.06	6.43	6.35	6.37	6.16	6.77	6.5
MgO	2.38	2.23	2.17	2.21	2.08	2.12	2.25	2.25	2.21	2.14	2.32	2.33
CaO	7.41	7.94	7.12	7.04	7.07	7.80	7.90	7.99	7.92	7.87	7.37	8.00
Na_2O	3.94	4.03	4.05	4.07	3.99	4.08	4.08	4.11	4.09	4.18	3.85	4.03
K_2O	2.44	2.66	2.69	2.73	2.66	2.77	2.68	2.69	2.72	2.68	2.30	2.63
TiO_2	0.69	0.65	0.66	0.64	0.62	0.64	0.66	0.65	0.65	0.63	0.68	0.67
MnO	0.18	0.18	0.17	0.17	0.16	0.17	0.18	0.17	0.17	0.17	0.18	0.19
P_2O_5	0.37	0.35	0.33	0.32	0.32	0.33	0.34	0.34	0.35	0.33	0.37	0.35
SO_3	0.05	1.12[a]	0.02	0.02	--	1.32	1.15	0.90	0.65	1.20	0.03[a]	1.3
Cl	0.09	0.11	0.03	0.03	--	0.11	0.10	0.07	0.07	0.10	0.07	0.10
F	0.06	0.06	0.06	0.04	--	0.02	0.05	0.05	0.05	0.05	0.05	0.05
Σ	97.32	98.80	99.34	99.50	99.04	98.82	99.12	99.37	99.15	99.31	97.39	99.15
LOI	2.39	1.05	0.08	0.10	0.04	1.06	0.59	0.26	0.41	0.46	2.41	0.98
Sr (ppm)	1000	1100	1100	1200	n	1100	1100	1200	1200	1100	1100	1100
Ba	720	780	820	800	o	770	780	790	800	780	760	770
Co	11	10	10	10	t	10	11	10	11	10	10	12
Cu	34	45	37	27		46	40	40	47	32	14	35
Ni	9	2	5	4		4	5	5	4	4	5	6
Cr	7	6	7	7	d	6	6	6	7	7	9	6
Nb	8	12	10	11	e	10	11	6	7	8	10	8
Sc	9	8	8	8	t	8	7	9	8	7	9	9
Th	6	9	9	<4	e	12	9	11	12	5	17	11
Pb	8	7	10	6	r	14	14	<4	4	<4	10	20
V	190	190	170	140	m	180	190	190	190	180	180	180
Zn	90	100	80	42	i	100	90	80	90	80	80	80
Y	18	18	19	20	n	17	17	18	17	16	19	19
La	29	35	34	29	e	33	33	32	33	32	33	35
Ce	54	52	57	56	d	49	55	55	53	53	64	53
Nd	31	30	33	30		31	30	35	27	33	34	39
Yb	2	2	3	2		2	2	2	2	2	2	3
Dy	10	5	10	4		8	9	9	8	14	11	10
Li	19	23	17	24		26	20	22	24	20	26	22

Major/Minor elements by XRF (U.S.G.S.-Denver, J. Taggart, analyst), except F, Cl, S (Classical chemistry, U.S.G.S.-Reston, F.W. Brown, analyst); Trace elements by ICP method (Taggart et al., 1981)
(Total Fe as Fe_2O_3; total S as SO_3)

* see sample descriptions below
** "blind" duplicate analysis of DT-9, analyzed 2 years after first analysis (trace elements were not re-analyzed)

[a] The SO_3 contents of samples 3L and 7 are anomalous for pre-1982 and 1982 samples, respectively. We are investigating whether or not there was a mixup of sample numbers when the analysis was done.

* *Sample notes* (all Tables) - Sample #'s 1A, 3L, 3H, 9 are pre-1982 rocks. Samples 2A, 2B, 5, 5A, 6, 7, 11L are from the 1982 eruptions. Specific descriptions follow:

Pre-1982 samples consist of: Pumice fragments from air-fall layers beneath the modern soil (#1A). These layers are tentatively assigned unit B of Tilling *et al.* (1984) and have radiocarbon ages of 550-700 years; Boulders and cobbles in a stream terrace deposit below the modern soil, located near Francisco León (#3L, 3H); Lava from a dome (?) exposed in the wall of the summit crater (pre-1982) (#9). This sample has been dated by the K-Ar method and yields a whole-rock age of 0.27 ± 0.006 million years (Duffield *et al.*, 1984).

Samples collected from the 1982 eruption consist of: Pumice fragments from air-fall layers at Francisco León (2A-lower, 2B-upper); Pumice fragments from pyroclastic flow material between these two air-fall layers (7); Hot lithic clasts in pyroclastic flows southwest (#5) and southeast (#6) of the summit; a bread-crust bomb from the same locality as the #5 hot lithic clast (5A); A large block of banded pumice collected just east of the (former) town of Volcán Chichonal.

SO_3 leached did exist, we do not think these differences would account for the discrepancies in the renormalized data.

Dispersion in the data (Fig. 2) are also apparent for CaO and MgO, which are significantly less affected by normalization and/or the SO_3 leaching process. Rose *et al.* (1984, Fig. 3) used a plot of K_2O vs. MgO for their samples to suggest, in part, a time trend for SiO_2, the alkalis, and incompatible elements, with younger rocks having higher levels of these elements. Our data, if plotted comparably, do not show

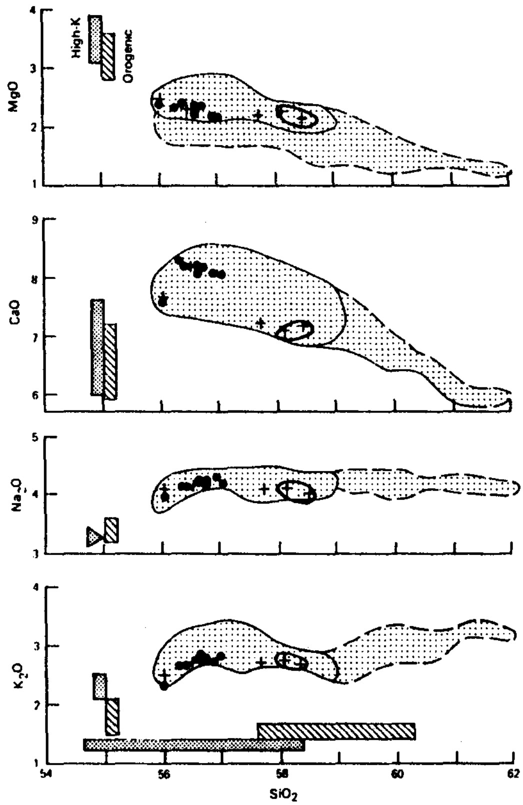


Fig. 2. MgO, CaO, Na_2O and K_2O vs SiO_2 variation diagrams (weight percent, water-free basis) for pumice and dome samples of El Chichón Volcano; Ranges of variation for high-K and orogenic andesite are from Gill (1981). "+" = pre-1982 rocks, "o" = 1982 rocks analyzed in this study. The two circled data points compare the results of the original analysis (October, 1982) of the dated pre-1982 dome rock (Table 1, sample #9) with the results of a "blind" duplicate analysis obtained in June, 1984, indicating excellent reproducibility of our data. The compositional fields are determined from published analyses of El Chichón pumice and dome samples (data sources: Solid lines = Hoffer *et al.* (1982), Cochemé and Silva-Mora (1983), Luhr *et al.* (1984); dashed extension = Rose *et al.* (1984)); no analyses of bulk ash are included.

this time trend. In fact, the 0.27 m.y. dome sample has the highest SiO_2, and its alkali content is virtually identical to those of the 1982 samples. Cooperative studies, including inter-laboratory comparisons of analytical results, are in progress to determine if the extension of the compositional fields beyond 60% SiO_2 reflects analytical bias, or the more extensive sampling by Rose *et al.* (1984), or both.

Petrographic studies revealed considerable variation in both total phenocryst content and relative phenocryst proportions among the El Chichón rocks (Fig. 3, Table 2). Total phenocryst content, as determined by modal analysis of all of the samples, ranges from approximately 20 to 55%, with the remaining proportions consisting of groundmass and vesicles. In all samples, plagioclase is the most abundant phenocryst, followed by hornblende, augite, and minor amounts (≤5%) of magnetite, biotite, sphene, anhydrite, and apatite. Matrix consists of vesicles and variable amounts of glass and minute crystals with dimensions smaller than 30 microns. Using the whole-rock compositions and reconstructed phenocryst bulk compositions based on modes and mineral chemistry, approximate matrix bulk compositions can be calculated.

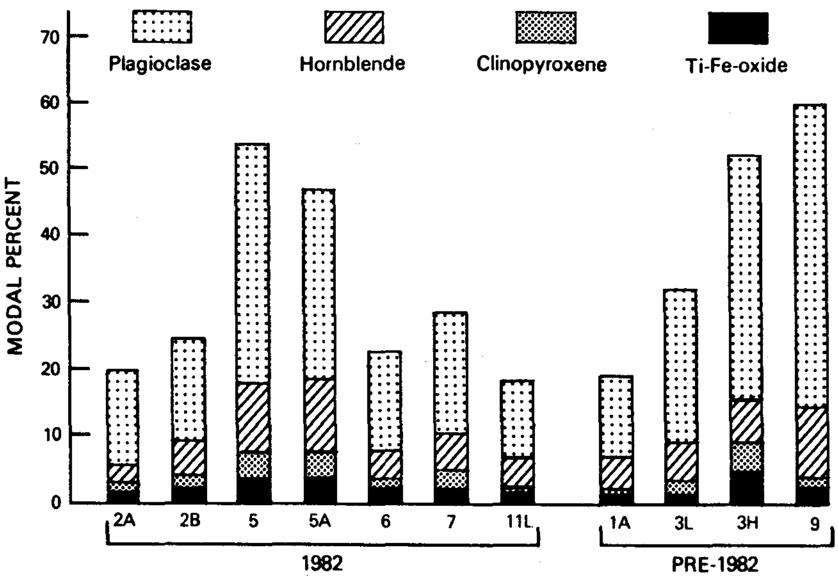


Fig. 3. Histogram displaying modal proportions of phenocrysts and matrix in the 1982 and pre-1982 samples. Total modal proportions range from 20 to 55%. Remainder is combination of glass, groundmass crystals and vesicles classed together as "matrix".

Table 2

El Chichón Modal Data Summary

	Pre-1982				1982						
Sample #	1A	3L	3H	9	2A	2B	5	5A	6	7	11L
Phenocrysts:											
Plag	11.8	22.6	37.2	46.0	14.0	15.6	35.7	28.7	15.0	18.6	11.7
Hbd	5.0	6.1	6.5	11.0	2.9	5.3	10.9	11.0	4.5	5.6	4.1
Cpx	1.1	1.9	3.9	0.3	1.3	1.7	4.1	3.4	1.2	2.5	1.2
Mt	0.5	0.7	1.8	1.6	0.2	0.6	1.6	1.3	1.2	1.3	0.8
Biot			2.1	0.1			0.2		0.2	0.5	
Sph		0.1	0.4	0.3		tr	0.2	0.8	tr	0.1	0.1
Apat			0.3	0.2		0.1	0.1				
Anhy					1.1	1.1	1.3	1.4			
Sulfide	0.2										
Matrix	81.4	68.6	47.8	40.5	80.5	75.6	45.9	53.4	77.9	71.4	82.1
Σ	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
# of points	1247	1390	1420	1485	1312	1306	1277	1510	1305	1291	1119

These reconstructed compositions indicate that the matrix compositions are quite variable. Least squares mixing calculations (Wright and Doherty, 1970) indicate that the modal compositions of the different matrices vary in proportion of glass and minerals, with more matrix-rich samples generally having less glass component. Unaltered subhedral anhydrite (Fig. 4) occurs in both phenocryst and matrix dimensions and also as inclusions in other phenocryst minerals, thus appearing to be a primary magmatic phase. Anhydrite was observed in all but one of the 1982 rocks and in only one of the pre -1982 rocks. If anhydrite was originally present in the other pre-1982 samples (Rose *et al.*, 1984), it may have been leached by meteoric

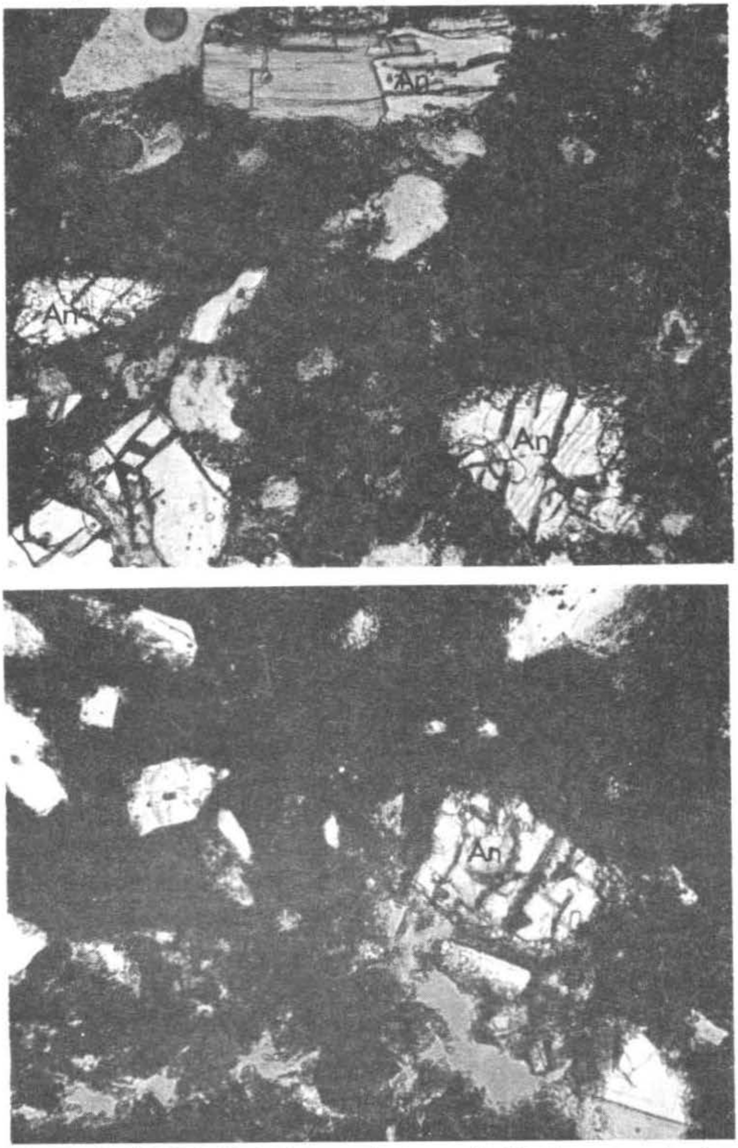


Fig. 4. Photomicrographs of anhydrite (An) phenocrysts, transmitted light, uncrossed polars. Field of view = 1.2 mm. Samples 2A (top) and 5A (bottom).

waters (rainfall in this area is approximately 4 m/y) (Luhr *et al.*, 1984). With the exception of the heterogeneous distribution of anhydrite, the mineralogy and phenocryst proportions in the pre-1982 rocks are similar to those in the 1982 eruptive rocks.

MINERAL AND GLASS CHEMISTRY

Plagioclase

The range in composition (An_{35} to An_{85}) of the 1982 and pre-1982 plagioclase phenocrysts, determined by over 100 analyses in each rock, is essentially the same (Table 3, Fig. 5a). Most compositions fall between An_{40} and An_{55}. Nearly the entire range in anorthite content can be found in some of the individual rocks and a few single plagioclase phenocrysts nearly bracket this entire range of approximately 50 mol% anorthite component. A series of analytical traverses were made across more than 30 plagioclase phenocrysts in order to systematically study the zoning that corresponds to this large compositional range. These traverses revealed that most of the plagioclase phenocrysts are complexly zoned. Many exhibit overall normal zoning (Ca decreasing towards rim) but reversely zoned and unzoned crystals are also present.

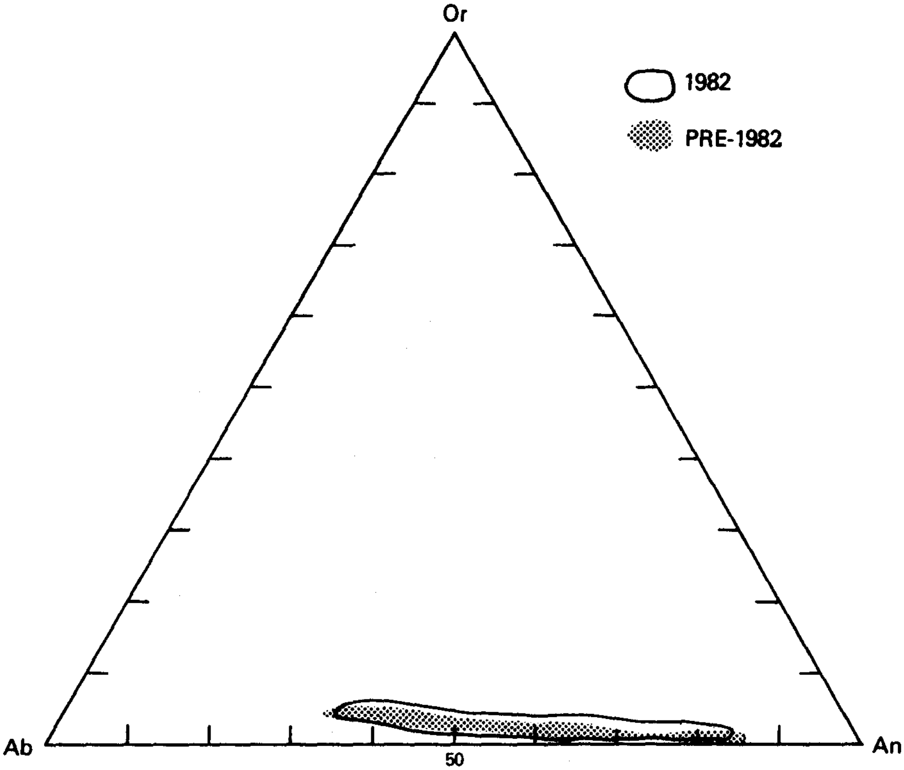
For nearly all crystals that were examined, however, the gross zoning pattern is disrupted by numerous smaller-scale oscillations and sharp discontinuities in composition (Fig. 5b). Small-magnitude compositional oscillations on the order of 2-5 mol% An are common. Larger increases in anorthite content, from 10 to as much as 40 mol% An, are also fairly common, appearing as spikes in Ca on traverses across plagioclase. These spikes in anorthite content are superimposed on the other smaller-amplitude oscillatory zoning and coincide with zones charged with abundant oriented silicate melt and gas inclusions. The proportion of inclusions in these zones, though apparently high based on observation in transmitted light, are estimated to be on the order of 2-3 volume % based on reflected light observation and evidenced by the difficulty of locating surface exposures for microprobe analysis. The calcic, inclusion-rich zones have sharp lateral boundaries; the interface with adjacent plagioclase is generally crossed by one or two 5-micron microprobe traverse steps. Widths of these calcic, inclusion-rich zones vary from as small as 5-10 μm to greater than 100 μm.

Table 3 Chemistry of El Chichón Plagioclase
(Average compositions; standard deviations in parentheses)

Sample #	1A	3L	3H	9
# of points	(42)	(28)	(15)	(115)
SiO_2	56.7 (2.02)	56.2 (1.78)	56.7 (2.44)	55.9 (3.37)
Al_2O_3	27.2 (1.20)	28.1 (1.19)	27.7 (1.59)	28.1 (3.12)
FeO	0.06 (0.05)	0.08 (0.05)	0.08 (0.05)	0.06 (0.09)
MgO	n.d.	n.d.	n.d.	n.d.
CaO	9.16 (1.53)	9.19 (1.32)	9.74 (1.93)	9.67 (2.07)
Na_2O	5.75 (0.73)	5.54 (0.68)	5.47 (0.91)	5.44 (1.08)
K_2O	0.51 (0.14)	0.52 (0.12)	0.44 (0.17)	0.45 (0.45)
BaO	0.02 (0.02)	0.03 (0.03)	0.03 (0.02)	0.03 (0.03)
Σ	99.40	99.66	100.16	99.65
% An	46	46	49	48

Sample #	2A	2B	5	5A	6	7	11L
# of points	(20)	(30)	(35)	(18)	(22)	(20)	(33)
SiO_2	55.5 (2.61)	56.1 (2.15)	57.0 (1.30)	55.4 (2.19)	56.3 (2.52)	56.3 (1.33)	55.6 (2.76)
Al_2O_3	28.1 (1.83)	28.6 (1.38)	27.2 (0.93)	28.0 (1.34)	27.4 (1.63)	27.4 (1.00)	28.5 (2.20)
FeO	0.15 (0.17)	0.09 (0.06)	0.06 (0.07)	0.14 (0.10)	0.07 (0.06)	0.11 (0.06)	0.11 (0.07)
MgO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CaO	10.4 (2.05)	9.88 (1.65)	9.06 (0.87)	10.2 (1.65)	9.49 (2.06)	9.48 (1.12)	10.3 (2.56)
Na_2O	4.96 (1.13)	5.44 (0.82)	5.65 (0.34)	5.10 (0.87)	5.60 (1.03)	5.47 (0.56)	5.24 (1.26)
K_2O	0.46 (0.26)	0.46 (0.11)	0.55 (0.20)	0.46 (0.14)	0.44 (0.17)	0.47 (0.12)	0.47 (0.21)
BaO	0.03 (0.02)	0.03 (0.03)	0.03 (0.02)	0.03 (0.03)	0.04 (0.03)	0.04 (0.03)	0.02 (0.02)
Σ	99.60	100.60	99.55	99.33	99.34	99.27	100.24
% An	52	48	46	51	47	47	51

n.d. = not detected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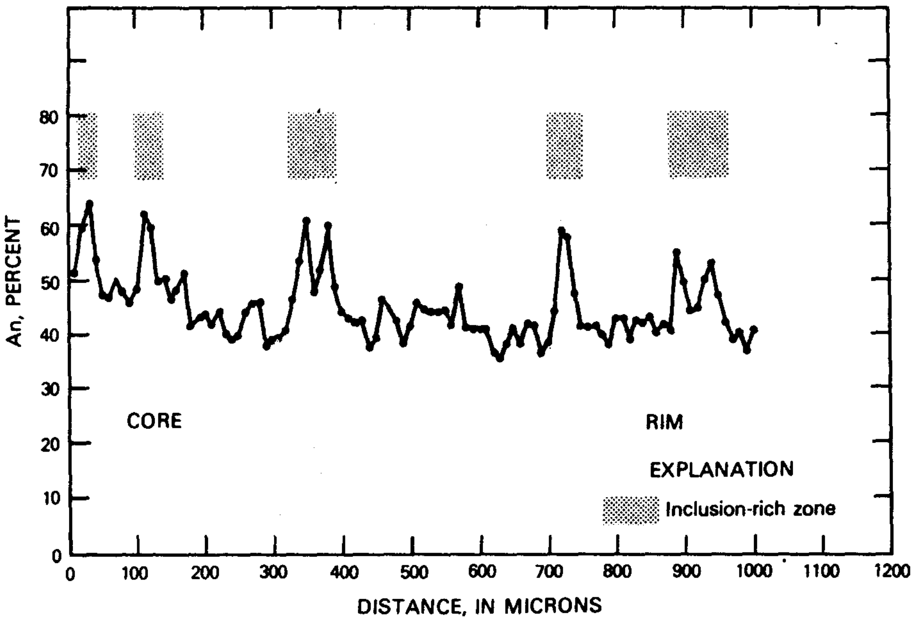
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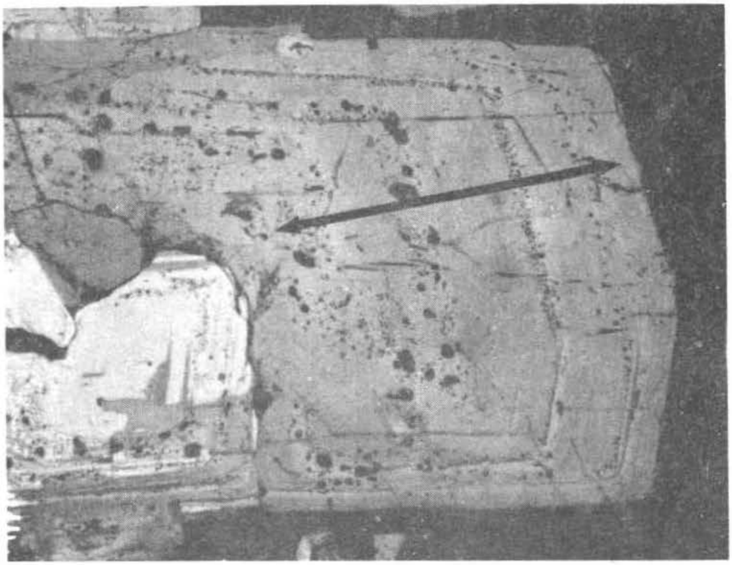
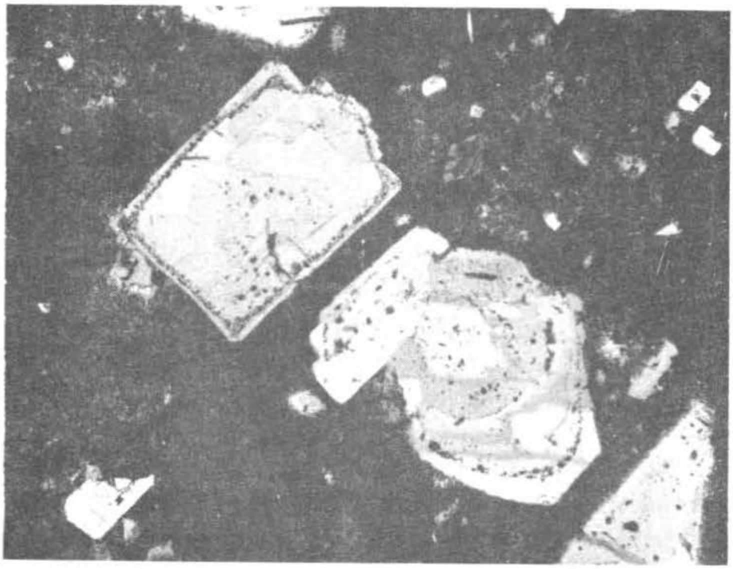
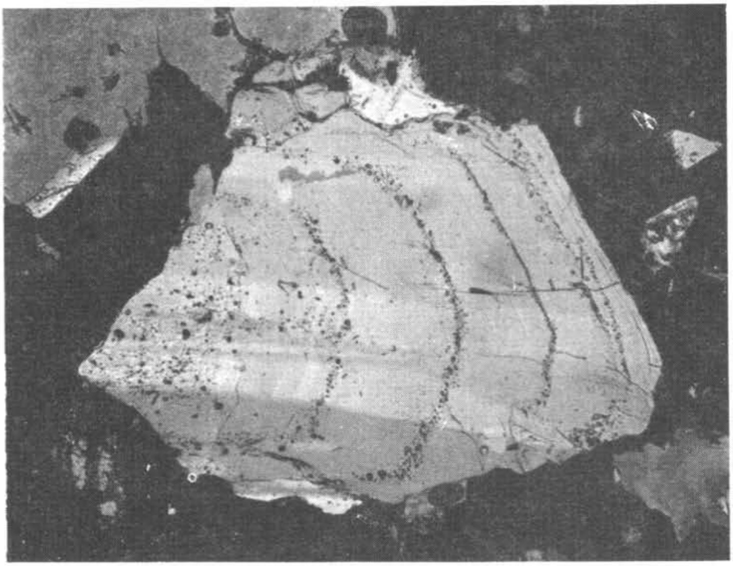


Figure 5b (continued)



c



d

Fig. 5. a) Plagioclase composition fields of 1982 and pre-1982 rocks on the Or-Ab-An ternary; b) Zoning profile (core to rim at 10 μm steps) of a plagioclase phenocryst in sample 9 showing both oscillatory zoning and calcic "spike" zones which correlate with inclusion-rich zones of the crystal. Line in accompanying photomicrograph shows location of traverse (Field of view = 2.5 mm); c, d) Photomicrographs of plagioclase phenocrysts showing variety of distribution of inclusion-rich zones. Transmitted light, uncrossed polars. Field of view= 2 mm. c) sample 9; d) sample 2B.

Patterns of inclusions in plagioclase phenocrysts vary from inclusion-rich cores with clear rims, to clear cores with one or more outer zones of inclusions alternating with clear rims, to other combinations of these types (Figs. 5c, d). Outlines of the inclusion-bearing areas are parallel to the crystal faces, consistent with entrapment of the inclusions during growth of the crystal. Multiple inclusion-rich zones indicate that this growth/entrapment process was cyclical and is recorded in different crystals at different growth stages. The most commonly observed pattern is that of 2 or 3 relatively thin (10-50 μm) inclusion-rich zones surrounding a clear core, with a final clear rim 20-100 μm in width. The observed variations in inclusion patterns may in part reflect variations in the orientation of phenocrysts cut by a thin section. Regardless of the orientation of the inclusion-rich zones, the anorthite-rich zones in the plagioclases correlate systematically with the inclusion-rich zones. These complex zoning and inclusion patterns appear to record systematic and somewhat repetitive fluctuations in the physico-chemical environment of the El Chichón magma reservoir, and are being studied in detail to further quantify their occurrence and significance (McGee and Tilling, 1983; Belkin *et al.*, 1984).

The inclusions in plagioclase and in other phenocryst phases are predominantly glass (silicate melt), some of which contain single or multiple vapor bubbles. Individual glass analyses are highly variable but overall the chemistry is similar whether or not the glass occurs as inclusions in the plagioclase phenocrysts, as rims on the phenocrysts, or as matrix (Table 4). Representative glass analyses are difficult to obtain due to both the scarcity of adequate surface exposure and mobilization of alkalis

Table 4

El Chichón Glass Compositions

	1	2	3	4	5	6	
SiO_2	59.4	68.0	56.8	59.3	70.2 (2.32)	59.9 (4.68)	70.4 (3.11)
Al_2O_3	16.8	15.9	14.5	16.2	16.2 (1.52)	15.5 (2.85)	14.8 (1.63)
FeO (tot)	1.35	1.64	1.52	1.50	1.11 (0.47)	1.10 (0.54)	1.41 (0.46)
MgO	0.18	0.25	0.19	0.18	0.21 (0.19)	0.17 (0.12)	0.19 (0.09)
MnO	0.08	0.10	0.10	0.08	0.05 (0.05)	0.09 (0.06)	0.11 (0.05)
CaO	1.65	2.12	1.77	1.56	1.71 (0.77)	1.43 (0.97)	1.18 (0.62)
Na_2O	4.45	4.56	2.75	3.05	4.19 (0.79)	2.60 (1.11)	2.29 (0.97)
K_2O	5.30	5.05	4.14	5.63	5.83 (1.01)	5.29 (1.61)	5.32 (1.42)
TiO_2	0.28	0.29	0.19	0.28	0.28 (0.10)	0.20 (0.12)	0.24 (0.10)
Cl	0.22	0.25	0.22	na	0.17 (0.16)	0.30 (0.10)	0.30 (0.15)
BaO	0.12	0.10	0.11	na	na	na	na
Σ	99.83	98.26	92.29	97.78	99.96	96.58	96.24

na = not analyzed

1. Bulk ash probe analysis by C.E. Meyer (U.S.G.S.- Menlo Park) - Recalculated to fluid free.
2. Luhr et al., 1984, matrix (rims on phenocrysts).
3. Luhr et al., 1984, inclusions in plagioclase.
4. Cocheme and Silva-Mora, 1983 - Glass from pumice blocks from 1982 deposits.
5. Matrix, this study (average of 11 points; standard deviations in parentheses).
6. Inclusions in plagioclase phenocrysts in inclusion-rich zones, this study (average of 55 points; standard deviations in parentheses; low Na due to mobility during analysis).
7. Random inclusions in plagioclase, this study (average of 31 points; standard deviations in parentheses; low Na due to mobility during analysis).

under the electron beam. The alkali totals (especially Na_2O) are slightly low due to such mobilization, as well as to the contribution due to overlap of the analyzing beam with surrounding phases which are generally lower in total alkalies than the

Table 5 Chemistry of El Chichón Amphibole
(Average compositions; standard deviations in parentheses)

Sample #	1A	3L	3H	9
# of points	(6)	(10)	(5)	(22)
SiO_2	40.0 (0.76)	40.7 (0.96)	41.0 (1.05)	41.3 (1.03)
TiO_2	2.17 (0.43)	1.99 (0.47)	2.07 (0.34)	1.84 (0.23)
Al_2O_3	11.8 (0.55)	11.7 (0.65)	11.9 (0.37)	11.3 (0.93)
FeO	17.5 (0.88)	16.5 (0.95)	17.5 (0.69)	16.9 (1.93)
MgO	9.91 (0.74)	10.4 (0.38)	9.93 (0.37)	10.6 (1.24)
CaO	11.3 (0.17)	11.5 (0.11)	11.7 (0.38)	11.3 (0.34)
Na_2O	2.07 (0.02)	2.04 (0.06)	2.08 (0.06)	2.02 (0.15)
K_2O	1.44 (0.26)	1.41 (0.18)	1.47 (0.08)	1.33 (0.15)
MnO	0.51 (0.05)	0.47 (0.06)	0.54 (0.05)	0.48 (0.13)
Σ	96.70	96.71	98.19	97.07

Sample #	2A	2B	5	5A	6	7	11L
# of points	(19)	(33)	(19)	(44)	(13)	(15)	(9)
SiO_2	40.6 (0.94)	40.5 (1.49)	40.9 (0.96)	41.2 (0.77)	41.3 (1.51)	41.3 (0.64)	41.0 (2.08)
TiO_2	2.16 (0.38)	2.16 (0.33)	2.15 (0.47)	2.07 (0.40)	2.00 (0.22)	2.33 (0.28)	2.14 (0.33)
Al_2O_3	11.6 (0.64)	11.8 (0.85)	11.6 (0.65)	12.1 (0.78)	11.8 (2.29)	11.6 (0.25)	12.8 (4.17)
FeO	16.7 (0.88)	16.7 (0.73)	17.2 (0.56)	15.3 (2.47)	17.1 (0.42)	16.8 (0.48)	16.1 (1.06)
MgO	10.4 (0.56)	10.1 (0.45)	10.1 (0.29)	11.3 (1.58)	9.95 (0.69)	10.3 (0.38)	10.5 (0.84)
CaO	11.4 (0.17)	11.4 (0.34)	11.4 (0.15)	11.7 (0.26)	11.6 (0.29)	11.7 (0.13)	11.5 (0.52)
Na_2O	2.04 (0.08)	2.01 (0.10)	2.03 (0.10)	2.12 (0.11)	1.90 (0.09)	2.01 (0.07)	1.95 (0.19)
K_2O	1.48 (0.17)	1.47 (0.13)	1.43 (0.19)	1.50 (0.16)	1.36 (0.14)	1.53 (0.12)	1.46 (0.13)
MnO	0.47 (0.06)	0.45 (0.07)	0.48 (0.07)	0.42 (0.16)	0.52 (0.05)	0.46 (0.05)	0.47 (0.05)
Σ	96.85	96.59	97.29	97.71	97.53	98.03	97.92

glass. However, the average glass composition is dacitic, with SiO_2 = ~70 %, Al_2O_3 = 15%, FeO = 1.5%, K_2O = 5-7%, Na_2O = 2.5-5.0%, and CaO = 1-2%. The total amounts of analyzed constituents suggest that water contents of the melt are on the order of 1-4%.

Amphibole, Pyroxene, and Minor Phases

Amphibole phenocryst compositions in the 1982 and pre-1982 rocks show little variation (Table 5). The range of compositions, based on more than 50 analyses, expressed in terms of the Ca, Mg, and Fe components is shown in Figure 6a. With

Table 6 Chemistry of El Chichón Pyroxene
(Average Compositions; standard deviations in parentheses)

Sample #	3L	3H	9
# of points	(6)	(17)	(5)
SiO_2	50.8 (1.18)	50.2 (0.93)	51.3 (0.90)
TiO_2	0.32 (0.20)	0.28 (0.11)	n.a.
Al_2O_3	1.90 (0.94)	1.74 (0.46)	1.82 (0.81)
FeO	9.02 (0.80)	9.50 (0.58)	9.31 (0.66)
MgO	12.7 (0.81)	12.7 (0.44)	12.1 (0.61)
CaO	22.5 (0.25)	22.8 (0.26)	23.2 (0.37)
Na_2O	0.50 (0.07)	0.50 (0.07)	0.41 (0.07)
MnO	0.64 (0.08)	0.77 (0.09)	n.a.
Σ	98.38	98.49	98.14
Wo	48	48	48
En	37	36	36
Fs	15	16	16

Sample #	2A	2B	5	5A	7	11L
# of points	(3)	(7)	(5)	(19)	(4)	(4)
SiO_2	51.1 (1.19)	50.7 (0.86)	51.2 (0.76)	51.6 (0.58)	51.3 (0.45)	50.9 (0.35)
TiO_2	0.30 (0.08)	0.40 (0.17)	0.26 (0.07)	0.31 (0.09)	0.31 (0.08)	0.35 (0.08)
Al_2O_3	1.78 (0.75)	2.32 (1.03)	1.50 (0.56)	1.98 (0.57)	1.96 (0.31)	2.19 (0.46)
FeO	9.13 (0.39)	9.36 (0.55)	8.92 (0.65)	9.37 (0.51)	9.61 (0.30)	9.74 (0.74)
MgO	12.7 (0.45)	12.4 (0.73)	13.1 (0.60)	12.6 (0.40)	12.3 (0.28)	12.2 (0.48)
CaO	22.7 (0.17)	22.9 (0.26)	22.9 (0.24)	23.1 (0.26)	23.3 (0.22)	23.0 (0.08)
Na_2O	0.49 (0.11)	0.50 (0.09)	0.47 (0.10)	0.52 (0.06)	0.52 (0.02)	0.55 (0.05)
MnO	0.66 (0.12)	0.64 (0.13)	0.67 (0.07)	0.65 (0.11)	0.67 (0.05)	0.64 (0.06)
Σ	98.86	99.22	99.02	100.13	99.97	99.57
Wo	48	48	48	48	49	48
En	37	36	37	36	35	35
Fs	15	16	15	16	16	17

the exception of two samples (one from each of the 1982 and pre-1982 suites), which have Mg-rich cores, the amphiboles are unzoned. In the nomenclature of Leake (1978), the amphiboles are magnesian hastingsitic hornblendes, with Mg/(Mg + Fe) <0.5, Si <6.25, $(Na + K)_A > 0.5$, Ti < 0.5 and $Fe^{3+} >= Al^{VI}$ (recalculated estimates of Fe^{3+} based on stoichiometric constraints, using the RECAMP program written by Spear and Kimball (1984)). The hornblendes typically have 2 wt.% TiO_2 and Na_2O and 1.5 wt.% K_2O.

Similarly, the pyroxenes in the El Chichón rocks vary little in composition (Table 6). Compositional fields for the 1982 and pre-1982 rocks, represented by approxi-

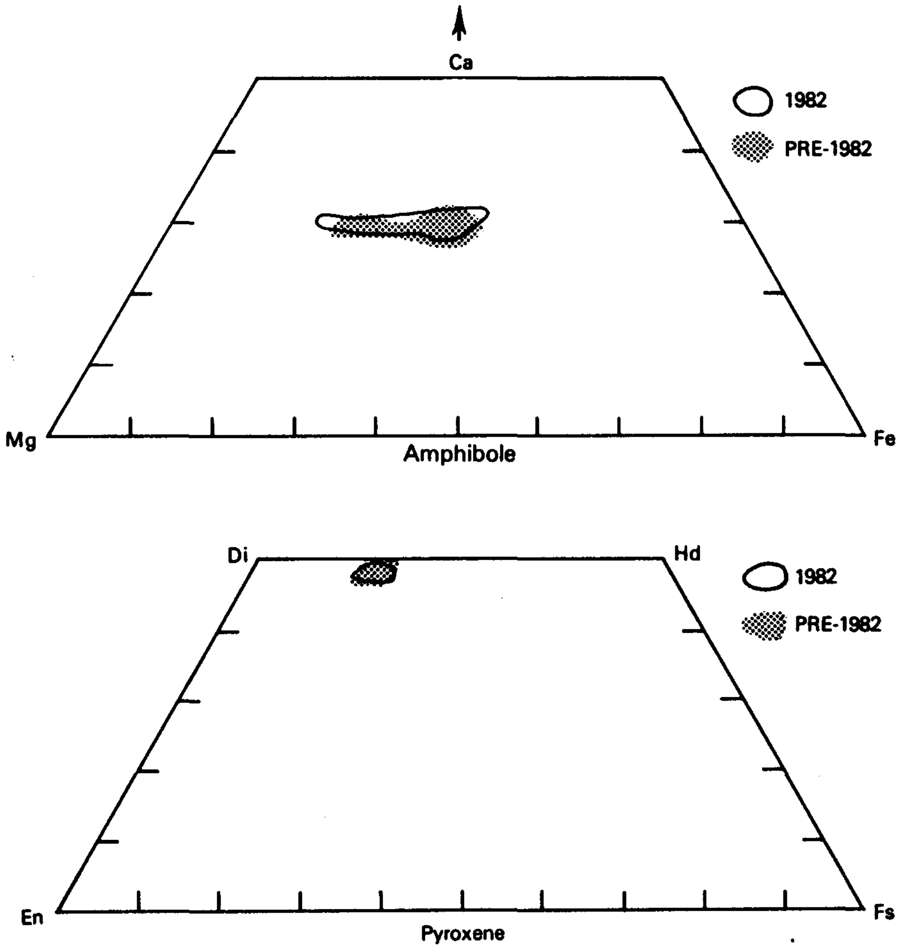


Fig. 6. a) Compositions of amphiboles in terms of Ca, Mg, and Fe proportions; b) Compositions of pyroxenes in terms of the pyroxene quadrilateral components.

mately 35 analyses each, are small and center at about $Wo_{48}En_{36}Fs_{16}$ (Fig. 6b). Minor phases in the El Chichón rocks are compositionally quite uniform amongst the samples (Table 7). Titanomagnetite (5-6% TiO_2) often occurs as inclusions in,

Table 7

Average Compositions of Minor Phases in El Chichón Rocks
(standard deviation in parentheses)

	1	2	3	4	5	6
SiO_2	0.20 (0.05)	0.16 (0.04)	29.2 (0.59)	29.9 (0.28)	35.6 (0.50)	36.1 (0.79)
TiO_2	4.55 (2.60)	5.96 (0.54)	37.0 (0.51)	36.5 (0.41)	4.31 (0.13)	4.47 (0.14)
Al_2O_3	2.12 (1.31)	1.98 (0.16)	1.29 (0.14)	1.15 (0.19)	15.1 (0.56)	14.7 (0.24)
FeO	85.4 (2.63)	84.6 (0.78)	1.13 (0.14)	1.13 (0.18)	16.8 (0.91)	16.3 (0.32)
MgO	0.44 (0.77)	0.43 (0.28)	0.00 (0.00)	0.00 (0.00)	13.6 (0.51)	13.5 (0.14)
CaO	0.09 (0.08)	0.12 (0.08)	27.4 (0.41)	27.7 (0.22)	0.07 (0.02)	0.03 (0.02)
Na_2O	n.a.	n.a.	0.01 (0.02)	0.01 (0.01)	0.49 (0.03)	0.54 (0.07)
K_2O	n.a.	n.a.	0.04 (0.05)	0.02 (0.01)	8.89 (0.19)	8.96 (0.17)
MnO	1.38 (1.42)	1.04 (0.07)	0.13 (0.03)	0.11 (0.02)	0.30 (0.05)	0.28 (0.04)
Σ	94.18	94.29	95.20	96.52	95.16	94.88

n.a.= not analyzed

1. Titanomagnetite, pre-1982 rocks - (23 analyses)
2. Titanomagnetite, 1982 rocks - (32 analyses)
3. Sphene, pre-1982 rocks (19 analyses)
4. Sphene, 1982 rocks (12 analyses)
5. Biotite, pre-1982 rocks (16 analyses)
6. Biotite, 1982 rocks (9 analyses)

or intergrowths with, clinopyroxene. Sphene, biotite, anhydrite and pyrrhotite occur rarely, as phenocrysts as well as inclusions in other phenocrysts phases.

DISCUSSION

The chemical and mineralogical data presented here demonstrate that eruptive products of El Chichón have remained uniform during the past 270 000 years, the period represented by our samples. Our analytical data are generally in good agreement with the data of Luhr *et al.* (1984) and thus their estimations of pre-eruptive intensive variables for the 1982 samples apply to our samples as well. There seems to be no chemical or mineralogical indication that these parameters have changed significantly over the 0.27 m.y. time span represented by our samples. The temperatures estimated by Luhr *et al.* (1984) are within 800° ± 50°C, with fO_2 slightly more oxidizing than the Ni-NiO buffer. We estimate that the water contents of the melt are on the low side of the Luhr *et al.* (1984) estimate of 4 to 10 wt.% H_2O; thus the magmatic water contents are also probably at the lower end of Luhr *et al.*'s 2-4 wt.% estimate.

El Chichón rocks are intermediate in composition between the "orogenic" type andesites of the TMVB to the west-northwest and those of the alkaline provinces (Altiplano and Oriental) which extend northwestward along the coast of the Gulf of Mexico to southern Texas (Robin, 1982). The El Chichón rocks are slightly more alkaline than the rocks of the TMVB. The enrichment of Ca, Na, and Sr in the El Chichón rocks compared with other high-K andesites is consistent with the idea that El Chichón magma may have been contaminated by the local sedimentary rocks during its ascent and storage at shallow level prior to extrusion. Xenoliths of carbonate country rock have been observed in both the pre-1982 and the 1982 deposits (Canul and Rocha, 1981; Sigurdsson *et al.*, 1984). Drilling during oil exploration in the region revealed the presence of evaporite (anhydrite and halite) strata at depths as shallow as 2-3 km (Canul and Rocha, 1981). The Sr isotopic systematics, currently under investigation, will aid in evaluating the extent of possible assimilation of the country rock; however, available sulphur and oxygen isotope data do not uniquely constrain the source region of the El Chichón magmas (Rye *et al.*, 1984).

Alternatively, El Chichón's chemistry may reflect contributions from more alkaline magma sources in a tectonically complex region characterized by the interaction of three active plates. Subduction of the Cocos Plate beneath the North American and Caribbean Plates, along the Middle American Trench, is producing the calc-alkaline andesite suite of the TMVB. Rifting and thinning of the continental crust (Hales,

1971) in the area east of the TMVB, is responsible for the production of the alkaline suites of the Oriental Province, including the Tuxtla volcanic province 250 km northwest of El Chichón (Thorpe, 1977; Robin, 1982).

Radiometric-age data (Tilling *et al.*, 1984) indicate that El Chichón erupted violently during the Holocene at roughly 600 (±200) year intervals.The distinctive, multiple, Ca-rich zones and associated silicate melt and vapor inclusions in the plagioclase phenocrysts may reflect in some complex manner changes in El Chichón's magma reservoir induced by repetitive, explosive eruptive activity. The anorthite and inclusion-rich zones in plagioclase may be produced by changes in volatile pressure in the magma chamber. An increase in volatile content, under otherwise similar conditions, would lower the plagioclase solidus temperature. This has the effect of superheating the plagioclase phenocrysts and stabilizing a more Ca-rich plagioclase composition. Based on available experimental data (Yoder, 1969; Johannes, 1978) it is estimated that increased volatile pressure between 150 bars and 5 kbars (and probably on the order of 1 kbar) would cause precipitation of a significantly more An-rich (15 mol% or greater) plagioclase. Sudden release of volatiles would supercool the plagioclase, effectively decreasing the equilibrium anorthite content of the plagioclase and producing the "down" side of the observed Ca spike and trapping the inclusions in the anorthite-rich zones. A build-up in volatile pressure might occur if the magma reservoir encountered ground water or a sulfur-rich reservoir (e.g., an evaporite horizon or salt dome). The increase in volatile pressure need not be rapid, since the anorthite-rich zones probably reflect only the highest pressure seen by the melt - dissolution has erased the record of zoning during this pressure build-up. However the release of pressure, as recorded by the "down" side of the anorthite spike is probably rapid and presumably is caused by eruption of the magma. Multiple cycles of anorthite- and inclusion-rich zones in the plagioclase, as seen in the El Chichón rocks, could conceivably result from stirring of the magma, multiple cycles of volatile increase and decrease, and random sampling of the phenocryst population. Studies evaluating possible models for this zonation pattern in greater detail are in progress. Regardless of the prevailing conditions when these features formed in the plagioclase, we can conclude that these same conditions prevailed both prior to expulsion of the old rocks and to the eruption of the 1982 rocks. As with the bulk chemistry and phenocryst mineralogy, the plagioclase zoning systematics indicate that the chemical and physical processes in the El Chichón magma reservoir have remained relatively unchanged during the past 0.27 million years.

ACKNOWLEDGMENTS

Without the cooperation and logistical support of the following individuals and organizations, the participation of Tilling and Duffield in the reconnaissance study of the proximal effects and products of the El Chichón eruption would not have been possible: Drs. José Guerrero G. and Luis Silva M., Instituto de Geología, Universidad Nacional Autónoma de México; Ing. Ricardo Riva Palacio C.S., Comisión Federal de Electricidad, Tuxtla Gutiérrez; Ing. René Canul D., Comisión Federal de Electricidad, Morelia; and the Office of Foreign Disaster Assistance of USAID, U. S. Department of State. Our thanks also go to R. T. Helz and H. E. Belkin, U. S. Geological Survey, and to two anonymous reviewers, for offering constructive comments and suggestions to improve the manuscript.

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(Received: May 6, 1985)
(Accepted: November 21, 1985)

It is recommended that reference to this paper be made as follows:

J. J. McGee, R. I. Tilling and W. A. Duffield, 1987. Petrologic characteristics of the 1982 and pre-1982 eruptive products of El Chichón Volcano, Chiapas, Mexico. *Geofís. Int.,* Special Volume on Mexican Volcanic Belt - Part 3A *(Ed. S. P. Verma),* Vol. 26-1, pp. 85-108.