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GEOCHEMISTRY OF VOLCANIC SERIES OF THE LOS AZUFRES GEOTHERMAL FIELD (MEXICO)

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RESUMEN

El campo geotérmico de Los Azufres (Michoacán, México) se localiza en el Cinturón Volcánico Mexicano (CVM). Las series volcánicas consisten en acumulaciones de flujos andesíticos, cubiertos por domos y flujos de riolita y dacita. La mayoría de las rocas muestreadas en superficie son del Pleistoceno Tardío. La mineralogía y la naturaleza calco-alcalina de todas estas series muestran una buena coherencia con otras series de volcanes del CVM, pero algunos análisis relacionados con la tendencia química magmática indican relaciones complejas y ambiguas entre las unidades estudiadas.

ABSTRACT

The Los Azufres Geothermal Field (Michoacán, México) is located in the Trans-Mexican Volcanic Belt (MVB). The volcanic series consists of a pile of andesitic flows, overlained by rhyolitic and dacitic domes and flows. Most of the rocks sampled from surface outcrops are of Late Pleistocene age. The mineralogy and the calc-alkaline nature of the whole series show a good coherence with other suites of the MVB volcanoes, but an analysis of the magmatic chemical trends indicates complex and ambiguous relationships between the studied units.

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INTRODUCTION

The Los Azufres Geothermal Field in the Sierra de San Andrés (Michoacán, México) is the third geothermal resource in Mexico to undergo development, after Pathé (Hidalgo) and Cerro Prieto (Baja California) fields. It is located in the Trans-Mexican Volcanic Belt (MVB, after Pal *et al.*, 1978). This belt (Fig. 1) extends from the Gulf of Mexico to the Pacific Coast, and comprises Late Tertiary to Quaternary volcanic activity (Mooser, 1972, 1975; Demant, 1978, 1981). This recent activity has superimposed a large number of cinder cones, domes and stratovolcanoes, along an approximate east-west axis, on an earlier volcanic belt axis (oriented NNW-SSE).

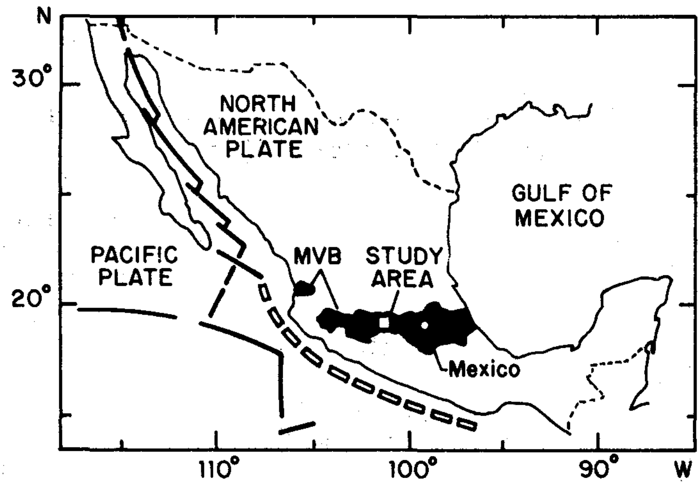

Fig. 1. Location of study area in the Mexican Volcanic Belt (MBV) (simplified after Verma, 1983).

The superficial activity, fumaroles and hot springs (Blásquez, 1961) observed in the Los Azufres area represent one of the evidences of Quaternary volcanic activity, better known by works on the eruptions of the Colima and Paricutín volcanoes (Foshag and González, 1956; Demant *et al.*, 1976).

The study of the water-rock interactions in the geothermal field (Gutiérrez and Aumento, 1982; Cathelineau *et al.*, 1983; Combredet, 1983; Cathelineau and Nieva, 1985; Cathelineau *et al.*, 1985) require a detailed knowledge of the "fresh-rock" petrology and geochemistry.

Very few studies, apart from the regional work on the MVB (Demant, 1981) or Michoacán (Mora, 1979) concern the geology of the Los Azufres area. Data are available mainly from work performed during field exploration for geothermal prospecting and development (Camacho, 1976; Garfias and González, 1978; Aumento and Gutiérrez, 1980a ;Gutiérrez, 1980; Gutiérrez and Aumento, 1982 ;Dobson,1984).

GEOLOGY

A simplified geologic map is proposed here (Fig. 2), modified from maps established by the "Comisión Federal de Electricidad". Surface relations between the four main

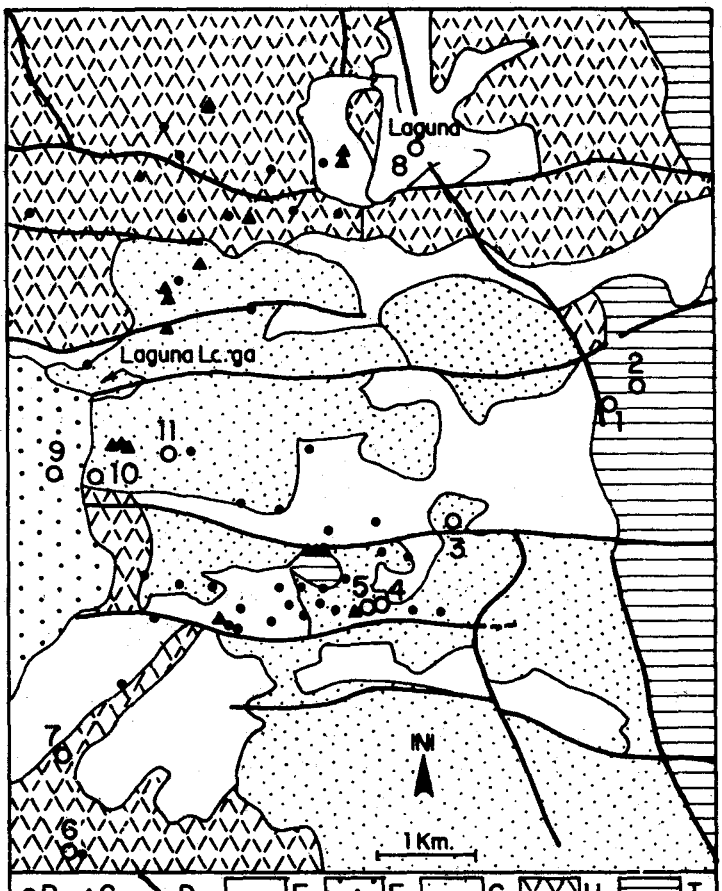

Fig. 2. Generalized geologic map of the Los Azufres area. (B) drilled well, (C) surface emission, (D) major fault, (E) tuffs, (F) vitreous rhyolite (R_2), (G) flow rhyolite (R_1), (H) andesite, (I) dacite. The numbers adjacent to them refer to the sample numbers of Table 2 when considered in conjunction with LA 0; e.g. 8 is LA 08.

geologic units can be explained by the following sequence of volcanic events, which does not differ significantly from the one proposed by Gutiérrez and Aumento (1982):

(1) The local basement consists of a sequence of andesites and minor basalts. Lava flows dominate largely and a few pyroclastic materials are observed. Ages of these andesites are not well-constrained at present because of the lack of suitable geochronological data. Andesites which form the basis of the San Andrés dome (Eastern part of the field) are interpreted as part of an Oligocene paleorelief (Mora, 1979), but without any field evidence or geochronological support. Using K-Ar radiometric dating and paleomagnetic investigations, Aumento and Gutiérrez (1980b) obtain an age of 5.9 ± 0.6 Ma for the andesites.

Detailed studies would be necessary to solve the problem of geochronological ages. Ages of volcanism in the MVB have often been put into question. Several examples for the Michoacán area can be given: Miocene age has been obtained (Demant *et al.*, 1975) on andesitic lavas of Mil Cumbres area, considered Oligocene from field analogies; ignimbritic tuffs of Tlalpujahua are interpreted as Quaternary by Fries *et al.* (1965) and Miocene by Mora (1979). Similar discrepancies can be related in the case of the last great volcanic cycles considered initially as Pliocene (Mooser, 1961; Bloomfield and Valastro, 1977), and dated Quaternary (Steele, 1971; Heine and Heide-Weiss, 1973). In the case of the Los Azufres area, a Quaternary age for the andesite flows located immediately below the rhyolites is most likely. Older andesites (Pliocene, may be Oligocene) can be encountered further below in the stratigraphic sequence.

(2) The "acidic series" overlies the andesites in the main area of the geothermal field. These consist of the following formations from oldest to youngest.

a) A partially to completely vitreous rhyolite (R_1); *b)* Dacitic (DA) domes and flows (Cerro de San Andrés); *c)* A rhyolitic dome (R_2), with associated aerial deposits of ashes and pumices. All these units have been reworked and overlaid by a volcanosedimentary sequence of heterogeneous conglomerates and tuffs.

This second cycle is dated using K-Ar radiometric dating. The vitreous rhyolite (R_1) dated as Upper Pleistocene with measured ages of 1.2 ± 0.6 Ma (Aumento and Gutiérrez, 1980b); and 1.57 ± 0.15 Ma (Demant *et al.*, 1975). The dacitic domes have measured ages of 0.7 Ma (Aumento and Gutiérrez, 1980b) and 0.38 Ma ± 0.01 Ma (Demant *et al.*, 1975).

(3) Recent basaltic veins intersect the rhyolites and andesites; also basaltic cinder cones constitute the last important activity in the area.

PETROGRAPHY AND MINERALOGY

a) Basalts, andesites and dacites

Numerous variations have been registered in the mineralogy from basalts and basaltic andesites, to andesites and dacites. Significant changes in texture and mineralogy can occur in each type within distances of a few centimeters. Among other variations the following could be mentioned:

- Increase in the amount of phenocrysts which show local accumulation and sedimentation by gravity.

- Variation in the nature of phenocrysts are observed from the basaltic andesites to the dacites, as follows: plagioclase - olivine; plagioclase; plagioclase - orthopyroxene; plagioclase - orthopyroxene - clinopyroxene; plagioclase - orthopyroxene - clinopyroxene - amphibole.

- Mesostasis is microlitic; the amount of glass is variable. Textures vary rapidly. In some cases, the regular orientation of microlites give a strong magmatic foliation which serves as a major plane for fractures.

Mineral compositions of andesites, characterized by plagioclase phenocrysts (An 80 - 40), microlites (An 70 - 50), olivine (Fo = 75 - 65) and pyroxenes (Fig. 3), are very similar to those of Plio-Pleistocene andesites described by Mora (1979) in Northeastern Michoacán.

Ortho- and clinopyroxene compositions (Table 1) follow a flat trend in the Ca-Mg-Fe diagram, with a regular increase of the Fe-content (Fig. 3) similar to the trends described for calc-alkaline series by Best and Mercy (1967). The trend also correlated with an increase of the rock acidity, a phenomenon described frequently (Aoki, 1964, for instance).

In the case of the dacites, heterogeneous mineralogy has been observed. All dacites contain plagioclase, hornblende (pargasite), quartz, orthopyroxene, clinopyroxene and magnetite. However, the composition of plagioclase phenocrysts (An 80 - 50) differs largely from the composition of microlites (An 30 - 45). Pyroxenes could be distributed in four types, according to their composition: augite and clino-enstatite, similar to those of andesites (Table 1), and Fe-augite and Fe-hyperstene (Fig. 3).

Table 1 - Microprobe analysis of ortho-and clinopyroxenes of andesite (LA 06) and dacite (LA 01).

	LA 06			LA 01		
n	5	5	3	3	3	2
Na2O	0.07	0.31	0.10	0.27	0.00	0.20
K2O	0.00	0.00	0.02	0.03	0.03	0.02
FeO	12.13	6.94	12.75	6.83	37.79	17.62
MnO	0.25	0.20	0.27	0.00	0.97	0.60
SiO2	54.35	52.80	54.60	52.66	50.20	51.18
CaO	1.80	19.79	1.64	19.57	1.23	19.12
NiO	0.00	0.00	0.00	0.00	0.00	0.00
Al2O3	2.03	2.51	1.94	1.58	0.24	0.53
TiO2	0.27	0.51	0.29	0.24	0.10	0.09
MgO	29.29	17.28	28.95	18.24	11.56	10.90
Cr2O3	0.02	0.14	0.21	0.04	0.02	0.04
Σ	100.21	100.48	100.77	99.46	102.14	100.30
Si	1.93	1.93	1.94	1.94	2.04	1.97
Al	0.07	0.07	0.06	0.06	0.00	0.03
K	0.02	0.04	0.02	0.01	0.01	0.00
Fe	0.36	0.21	0.38	0.21	1.11	0.57
Mg	1.55	0.94	1.53	1.00	0.70	0.63
Mn	0.01	0.01	0.01	0.00	0.03	0.02
Ti	0.01	0.01	0.01	0.01	0.00	0.00
Cr	0.00	0.00	0.01	0.00	0.00	0.00
Ca	0.07	0.77	0.06	0.77	0.05	0.79
Na	0.00	0.02	0.01	0.02	0.00	0.01

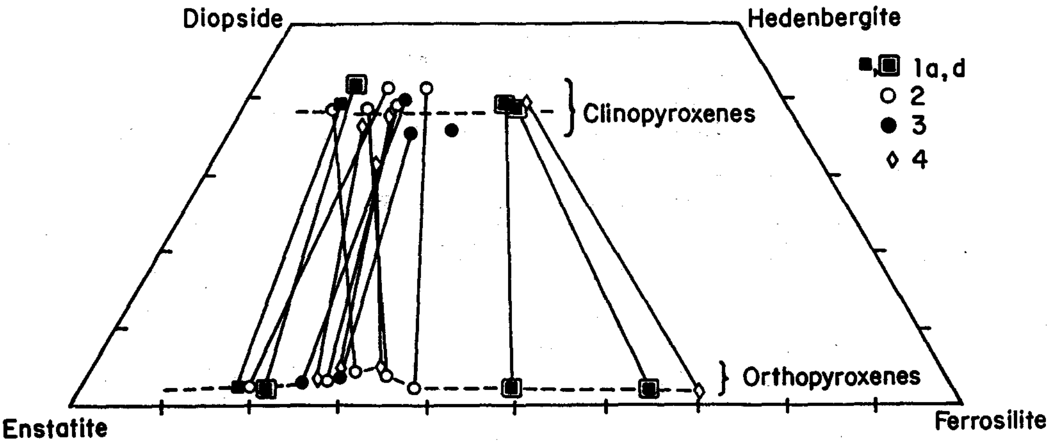

Fig. 3. Compositional evolution of pyroxenes of andesites (1a) and dacites (1d) from Los Azufres, compared to pyroxenes analyzed in samples from regional series. Oligocene (2), Pliocene (3), Quaternary (4), after Mora, 1979. Solid lines connect points corresponding to co-existing pyroxenes.

b) Rhyolites

Rhyolites are mainly glassy (60 to 100 percent of glass) or pumiceous. Different textures encountered include those of flow rhyolite with oriented microlites and spherulitic rhyolite (recrystallization of the glass). Phenocrysts are oligoclase, sanidine, quartz, rare Fe-biotite, and in minor amounts, apatite, zircon and allanite.

GEOCHEMISTRY

Major oxide abundances and CIPW norms are given in Table 2 which also includes some data from the literature (Aumento and Gutiérrez, 1980a; Mora, 1979).

The plot of K_2O versus SiO_2 (Fig. 4) shows that volcanic rocks from Los Azufres belong to a quite regular trend of evolution from basaltic andesites to rhyolites (according to the classification of Peccerillo and Taylor, 1976). The trend is located on the boundary limit between the calc-alkaline and high-K calc-alkaline series. A linear regression of the data plotted in Fig. 4 gives a good correlation of K_2O and SiO_2 (regression coefficient $r = 0.98$, $n = 27$) but a slight break is observed in the slopes of the two trends defined by the basalt - andesites and the dacite - rhyolite groups.

Table 2: Major element chemistry and CIPW norm of Los Azufres series. LA, LAS, A = this work; AUM = Aumento and Gutierrez (1980a). CIPW norm have been calculated on anhydrous basis using a computer program written by S.P. Verma (Verma et al., 1986) following the method of Kelsey (1965).

	LA 08	A9 1705	AUM 8	LAS 06	A9 1600	A9 2359	A9 1440	AUM 11	AUM 5
SiO_2	49.90	50.70	54.10	57.81	58.73	59.57	60.60	60.10	60.30
TiO_2	1.61	1.61	1.28	0.93	0.89	0.73	0.76	1.07	1.02
Al_2O_3	16.73	16.86	16.80	17.23	16.15	17.31	16.41	16.10	16.70
Fe_2O_3	4.67	4.40	9.34	2.55	3.51	1.88	3.14	8.73	7.18
FeO	5.84	4.12	0.00	3.27	2.18	2.64	1.90	0.00	0.00
MnO	0.17	0.17	0.10	0.09	0.10	0.11	0.09	0.08	0.10
MgO	5.87	5.05	3.96	4.29	3.18	3.02	2.02	1.73	2.35
CaO	8.25	6.87	6.60	6.54	6.03	5.28	5.93	4.53	5.29
Na_2O	3.70	4.14	3.54	3.57	3.87	3.27	3.73	3.98	3.72
K_2O	1.27	0.52	1.54	1.77	2.11	2.57	1.93	2.27	2.23
P_2O_5	0.45	0.47	0.00	0.21	0.25	0.15	0.18	0.00	0.00
H_2O^+	0.89	4.31	0.00	1.00	2.04	2.97	2.21	0.00	0.00
H_2O^-	0.47	0.22	0.00	0.49	0.28	0.09	0.24	0.00	0.00
L.O.I.	1.06	3.50	0.89	1.30	2.36	1.98	2.64	0.25	0.32
Σ	99.82	99.44	98.15	99.75	99.32	99.59	99.14	98.84	99.21
FeOt/(FeOt+MgO)	0.63	0.62	0.68	0.56	0.63	0.59	0.70	0.82	0.73
FeOt/MgO	1.71	1.60	2.12	1.30	1.68	1.43	2.33	4.54	2.75
Mg-value	53.65	55.31	48.27	60.42	54.12	57.99	45.84	30.36	41.87
CIPW norm									
Q	0.00	4.31	9.41	10.64	13.28	14.85	18.19	16.09	16.33
C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OR	7.62	3.24	9.36	10.64	12.85	15.73	11.80	13.61	13.33
AB	31.80	36.91	30.80	30.74	33.76	28.66	32.64	34.16	31.83
AN	25.69	27.27	26.12	26.22	21.10	25.86	23.10	19.64	22.53
NE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DI-Mg	8.13	3.84	2.62	3.57	6.27	0.16	4.76	0.00	0.63
DI-Fe	2.19	0.42	0.00	0.74	0.00	0.04	0.00	0.00	0.00
Hy-Mg	8.45	11.47	8.92	9.22	5.26	7.72	3.00	4.37	5.63
Hy-Fe	2.62	1.45	0.00	2.18	0.00	2.35	0.00	0.00	0.00
Ol-Fo	1.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ol-Fa	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MT	6.88	6.72	0.00	3.76	4.92	2.82	4.36	0.00	0.00
IL	3.11	3.22	0.22	1.80	1.74	1.44	1.49	0.17	0.22
AP	1.08	1.17	0.00	0.51	0.61	0.37	0.44	0.00	0.00
HM	0.00	0.00	9.60	0.00	0.22	0.00	0.24	8.85	7.26
T.N.			2.95					2.22	2.25
SALIC	65.11	71.73	75.69	78.24	80.99	85.10	85.72	84.29	84.02
FEMIC	34.92	28.30	24.31	21.77	19.03	14.90	14.29	15.71	15.99
C.I.	50.98	43.59	38.03	40.37	38.31	31.62	35.46	22.70	27.84
D.I.	39.42	44.46	49.57	52.02	59.89	59.24	62.62	64.65	61.48
S.I.	27.50	27.70	21.54	27.77	21.41	22.57	15.88	10.35	15.18
A.K.	1.50	1.49	1.55	1.58	1.74	1.70	1.68	1.82	1.74

TABLE 2 (continuation)

(For more details, refer to Verma and Lopez-M., 1982). Location of samples LA, LAS and A are given in Fig. 2. LA 01, 02 = Dacite of San Andres; LA 03 = Spherulitic fluidal rhyolite; LA 04b = Andesite; LA 06 = Microlitic andesite showing strong magmatic foliation.

	LAS 07	A9 2288	LA 01	SM 943	SM 968	SM 455	LA 04B	AUM 9	AUM 10
SiO_2	60.19	60.45	66.30	65.77	66.11	67.59	69.95	70.80	71.70
TiO_2	1.13	0.82	0.55	0.79	0.67	0.67	0.38	0.17	0.23
Al_2O_3	17.43	16.67	16.24	14.50	15.17	15.06	15.03	13.40	13.20
Fe_2O_3	3.08	2.40	1.40	1.50	1.50	0.31	2.61	2.05	2.39
FeO	2.93	2.29	2.23	2.57	2.47	2.66	0.33	0.00	0.00
MnO	0.10	0.10	0.07	0.07	0.06	0.06	0.05	0.04	0.04
MgO	1.55	2.63	1.32	1.97	1.47	0.98	0.09	0.26	0.24
CaO	5.03	4.91	3.30	3.97	3.48	2.81	0.57	0.90	0.92
Na_2O	4.32	4.04	4.02	4.12	4.29	3.89	3.87	3.43	3.48
K_2O	2.35	2.48	3.27	3.01	2.95	3.88	4.30	4.59	4.48
P_2O_5	0.24	0.31	0.08	0.17	0.16	0.12	0.00	0.00	0.00
H_2O^+	0.89	2.22	0.74	0.93	0.48	1.86	1.51	0.00	0.00
H_2O^-	0.57	0.31	0.34	0.13	0.33	0.16	0.76	0.00	0.00
L.O.I.	1.35	2.76	0.91				2.25	2.78	2.57
Σ	99.81	99.63	99.86	99.50	99.14	100.05	99.43	98.42	99.25
FeOt/(FeOt+MgO)	0.79	0.63	0.73	0.66	0.72	0.75	0.97	0.88	0.90
FeOt/MgO	3.68	1.69	2.64	1.99	2.60	2.99	29.75	7.09	8.96
Mg-value	35.00	53.93	42.83	49.88	43.25	39.77	6.24	21.82	18.10
CIPW norm									
Q	13.83	14.33	20.86	19.97	20.57	21.96	30.49	32.38	33.08
C	0.00	0.00	0.28	0.00	0.00	0.00	3.06	1.21	0.99
OR	14.12	15.09	19.56	18.07	17.73	23.39	26.15	28.36	27.38
AB	37.17	35.21	34.44	35.41	36.92	33.58	33.70	30.35	30.46
AN	21.58	20.62	16.04	12.37	13.65	12.42	2.91	4.67	4.72
NE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DI-Mg	1.39	1.65	0.00	3.73	1.50	0.37	0.00	0.00	0.00
DI-Fe	0.36	0.23	0.00	1.53	0.82	0.48	0.00	0.00	0.00
Hy-Mg	3.28	5.98	3.33	3.26	3.03	2.32	0.23	0.68	0.62
Hy-Fe	0.98	0.96	2.19	1.53	1.90	3.45	0.00	0.00	0.00
Ol-Fo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ol-Fa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MT	4.54	3.58	2.05	2.21	2.21	0.46	0.13	0.00	0.00
IL	2.18	1.60	1.06	1.52	1.29	1.30	0.74	0.09	0.09
AP	0.58	0.76	0.19	0.41	0.39	0.29	0.00	0.00	0.00
HM	0.00	0.00	0.00	0.00	0.00	0.00	2.60	2.14	2.47
SALIC	86.70	85.25	91.19	85.82	88.87	91.34	96.30	96.96	96.63
FEMIC	12.32	14.77	8.82	14.18	11.14	8.66	3.70	3.04	3.37
C.I.	26.88	28.37	18.38	22.70	19.00	14.83	3.07	5.14	5.15
D.I.	65.11	64.63	74.86	73.45	75.22	78.93	90.33	91.09	90.92
S.I.	10.89	19.00	10.78	14.96	11.59	8.36	0.80	2.52	2.27
A.R.	1.84	1.87	2.19	2.26	2.27	2.54	3.20	3.55	3.58

TABLE 2 (continuation)

LA 07, 08 = Microlitic andesite; LA 10 = Glassy rhyolite. A9-1705, 1600, 2395, 1440 and 2288 refer to drill cores of well A9 sampled at 1705, 1600, 2359, 1440 and 2288 meters. In the table samples LA 08 to A9 2288 correspond to andesites, LA 01 to LA 02 to dacites and AUM 7 to LA 03 to rhyolites.

	LA 02	AUM 7	AUM 6	SM 389	SM 447	LA 10	AUM 1	AUM 2	LA 03
SiO_2	71.70	72.80	73.80	73.74	74.71	74.73	74.60	75.70	75.50
TiO_2	0.65	0.01	0.01	0.12	0.30	0.09	0.00	0.00	0.09
Al_2O_3	12.19	14.20	13.80	12.65	12.78	12.60	12.23	12.10	13.28
Fe_2O_3	1.04	1.76	2.54	0.35	0.19	0.52	3.02	2.61	0.78
FeO	0.00	0.00	0.00	1.15	0.97	0.65	0.00	0.00	0.14
MnO	0.08	0.04	0.02	0.06	0.04	0.04	0.03	0.03	0.02
MgO	0.03	0.11	0.10	0.59	0.33	0.21	0.33	0.15	0.03
CaO	0.07	0.83	0.87	0.01	0.66	0.37	1.47	0.83	0.08
Na_2O	3.30	3.78	3.77	3.80	3.97	3.79	3.65	3.68	3.53
K_2O	4.45	4.25	4.25	4.68	4.89	4.43	4.64	4.68	4.70
P_2O_5	0.11	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.00
H_2O^+	3.58	0.00	0.00	2.55	1.69	1.31	0.00	0.00	0.97
H_2O^-	2.73	0.00	0.00	0.20	0.16	0.45	0.00	0.00	0.33
L.O.I.	6.10	2.08	0.65			1.99	0.83	0.03	1.46
Σ	99.93	99.86	99.81	99.93	100.70	99.19	100.80	99.81	99.45
FeOt/ (FeOt+MgO)	0.97	8.94	0.96	0.71	0.78	0.84	0.89	0.94	0.97
FeOt/MgO	31.21	14.40	22.86	2.48	3.46	5.32	8.23	15.66	28.03
Mg-value	5.97	12.09	7.97	44.37	36.42	27.11	19.39	11.23	6.59
CIPW norm									
Q	38.02	33.35	33.88	33.05	30.96	35.22	32.85	34.77	37.46
C	2.22	1.91	1.43	1.43	0.00	0.92	0.00	0.00	2.28
OR	28.09	25.68	25.33	28.46	29.23	26.87	27.43	27.72	28.30
AB	29.83	32.71	32.17	33.09	33.98	32.92	30.89	31.21	30.13
AN		4.21	4.35		2.64	1.88	3.20	2.68	0.40
NE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DI-Mg	0.00	0.00	0.00	0.00	0.22	0.00	1.77	0.81	0.00
DI-Fe	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.00
Hy-Mg	0.08	0.28	0.25	1.51	0.73	0.54	0.00	0.00	0.08
Hy-Fe	0.00	0.00	0.00	1.79	1.07	0.71	0.00	0.00	0.00
Ol-Fo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ol-Fa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MT	0.00	0.10	0.04	0.52	0.28	0.77	0.10	0.10	0.26
IL	0.18	0.02	0.02	0.23	0.58	0.18	0.00	0.00	0.17
AP	0.28	0.00	0.00	0.07	0.02	0.00	0.00	0.00	0.00
HM	1.11	1.73	2.54	0.00	0.00	0.00	2.95	2.55	0.62
SALIC	97.76	97.87	97.16	95.87	96.82	97.81	94.45	96.38	98.88
FEMIC	2.25	2.13	2.84	4.13	3.18	2.19	5.55	3.62	1.13
C.I.		4.41	4.53	0.91	3.63	2.26	7.11	4.42	0.46
D.I.	95.93	91.74	91.38	94.60	94.18	95.00	91.17	93.69	96.19
S.I.	0.34	1.11	0.94	5.58	3.19	2.19	2.84	1.35	0.33
A.R.	4.44	3.30	3.41	5.06	4.87	4.46	4.07	4.66	4.21

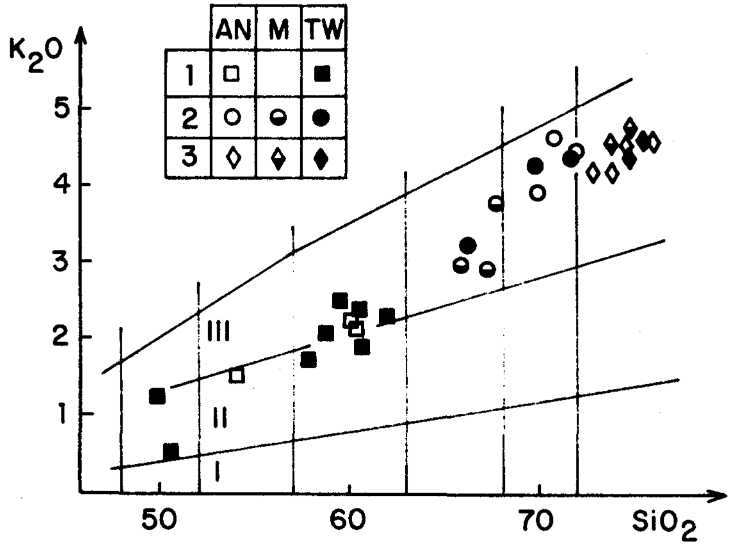

Fig. 4. K_2O-SiO_2 relationship for Los Azufres volcanic rocks (boundaries and nomenclature from Peccerillo and Taylor, 1976): I: arc tholeiitic series, II: calc-alkaline series, III: high-K calc-alkaline series. Symbols represent three main series: 1: basalts and andesites, 2: dacites and rhyodacites, 3: rhyolites. Data from the literature (A. N. Aumento and Gutiérrez, 1980a;M-Mora, 1979 ;T. W. - our data).

The plot of total alkalis ($Na_2O + K_2O$) versus SiO_2 is shown in Fig. 5. According to boundaries defined by Schwarzer and Rogers (1974), the rocks under study be-

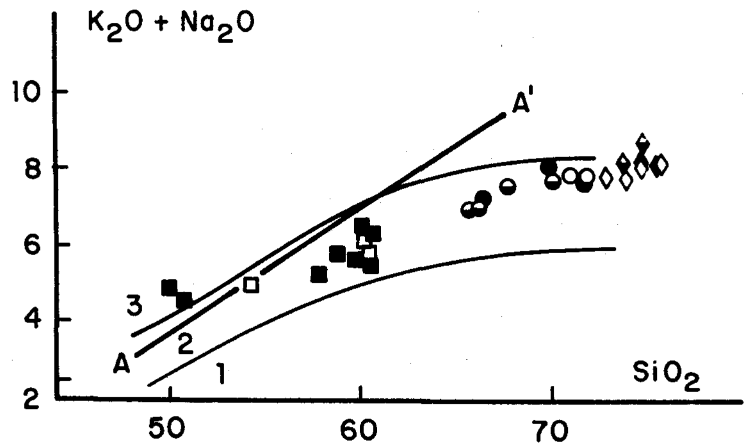

Fig. 5. Total alkali-SiO_2 diagram (Kuno, 1966) for Los Azufres volcanic rocks. Boundaries dividing the fields of the tholeiitic (1), high alumina (2) and alkaline (3) basaltic series. Symbols are the same às those in Fig. 3. A-A'= Line of Schwarzer and Rogers (1974).

long typically to the calc-alkaline series. Also points are located in the boundary of hyperstene series (Kuno, 1959) and of high alumina basalts (Kuno, 1966).

Only two analyses of basalts (LA 08 and A9-1705; Table 2 and Fig. 5) are located slightly above the boundary between high alumina and moderately alkaline series.

The AFM diagram (not presented here) confirms the calc-alkaline nature of the series. The trends are similar to those of hyperstene series of Japan (Kuno, 1968).

The occurrence of such magmas (lavas rich in alumina and alkalis) in the Los Azufres area is coherent with the dominant calc-alkaline feature of the MVB (Pal *et al.*, 1978; Aguilar-y-Vargas and Verma, 1987). These magmas are characteristic of orogenic lavas of continental margins (Kuno, 1966).

DISCUSSION AND CONCLUSIONS

The studied rocks are considered to belong for the most part to the same group of Quaternary events. The relationships between the different units are discussed below from the petrographic and geochemical data.

The main features of andesites and dacites are:

(a) an evolution of pyroxene compositions with increasing silica, in the rock, going from magnesium to iron pyroxenes.

(b) quasi-linear correlations between contents of major elements.

This suggests that andesites and dacites belong to the same suite of differentiation from a co-magmatic source. The relationships between the rhyolites and the basic rocks have been examined using the R_1R_2 diagram (La Roche *et al.*, 1980). This diagram shows that (Fig. 6).

(a) The quasi-linear trend of evolution of basalts to andesites does not follow a typical differentiation suite. More samples of the most evolved units are needed, but the available data indicate that the rhyolites do not belong to the same evolutionary suite of the basalts and andesites.

(b) The alignment of dacites between the andesites and rhyolites suggests mixing

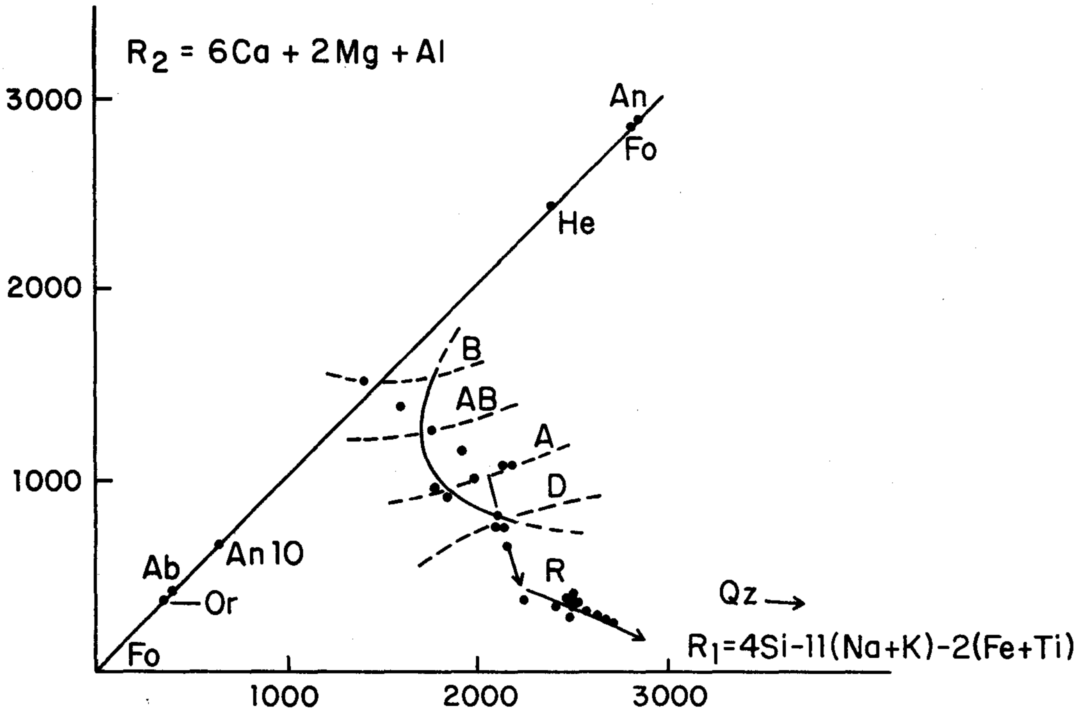

Fig. 6. R_1R_2 diagram (La Roche *et al.,* 1980) applied to Los Azufres volcanic rocks. Dashed lines depict the boundaries between basalts (B), basaltic andesite (A B), andesite (A), dacites (D) and rhyolites (R). Solid curve indicates a possible trend of differentiation. Arrows show the evolution of the compositions of dacites and rhyolites.

of magmas as a more viable process than a simple magmatic evolution. This point is suggested by the heterogeneous mineralogy of some of the dacites, which exhibit mixing of two mineral paragenesis , one typical of andesites and the other typical of more differentiated rocks.

Further analysis of the geochemical data on andesites, dacites and rhyolites of the last cycle shows three small suites of differentiation. Some dacites can result by fractional crystallization from the same liquid which has generated the andesites, as discussed below.

Table 3 gives the major-element composition of the least-differentiated basalt from Los Humeros (HF 117, in Verma, 1984) and the average compositions of basalts to rhyolites from Los Azufres. Details of the complete data are reported in Table 2. Unfortunately, no data are yet available on olivine basalt of Los Azufres.

TABLE 4: Major-element composition of, (1) dacite LA 01; (2) andesite LA 06; (3) rhyolite LA 03; (4) CPX of andesite LA 06 and (5) biotite of rhyolite. All data are adjusted to a total of 100 % and are on water and L.O.I. (loss on ignition) free basis. (1), (2), (3), and (4) = This work. (5) = Mora (1979).

	LA 01 (1)	LA 06 (2)	LA 03 (3)	CPX 06 (4)	BIO SM (5)
SiO2	67.21	58.98	76.99	52.62	35.99
TiO2	0.56	0.95	0.09	0.51	4.45
Al2O3	16.46	17.59	13.54	2.51	11.45
FeOt	3.54	5.68	0.86	6.91	31.99
MnO	0.07	0.09	0.02	0.20	0.28
MgO	1.34	4.38	0.03	17.22	6.19
CaO	3.35	6.67	0.08	19.72	0.13
Na2O	4.07	3.64	3.60	0.31	0.57
K2O	3.32	1.81	4.79	0.00	8.95
P2O5	0.08	0.21	0.00	0.00	0.00
Σ	100.00	100.00	100.00	100.00	100.00

Furthermore, many important mineral compositions are also unknown for Los Azufres. Therefore, there are certain difficulties in undertaking precise major-element modeling of Los Azufres magmas by mass-balance calculations (Bryan *et al.*, 1968). Nevertheless, such least-squares approximations can be carried out by taking mineral compositions for clinopyroxene (CPX) of the andesite LA 06, and average compositions from the literature for other minerals. Thus, if plagioclase (PLA), olivine (OLI) and clinopyroxene (CPX) are the fractionating phases, the average basalt composition can be successfully modeled from the olivine basalt (HF 117) by separating a total of about 43wt % of these minerals (about 21% PLA, 17% OLI and 5% CPX; Σ Residuals^2 = 1). On the other hand, modeling of the major-element chemistry of average andesite indicates that about 59 wt % of these minerals need to be separated (about 41% PLA, 5% OLI and 13% CPX). But the residuals for this estimate are large especially those for CaO, Na_2O, K_2O and P_2O_5 (Σ Residuals^2 = 6). This residual could be considerably lowered (Σ Residuals^2 = 2) by incorporating (about 6%) titanomagnetite among the separating phases. The production of average dacite from average andesite by fractional crystallization needs about 44 wt %

of these minerals to be separated from the andesitic magma (about 31% PLA, 3% OLI, 6% CPX and 4% TMT (titanomagnetite); Σ Residuals^2 = 0.5). Finally, the average rhyolite composition can be modeled from average dacite by separating about 15.5 wt % of total minerals (13% PLA, 1% OLI, 0.5% CPX and 1% TMT; Σ Residuals^2 = 0.1) from the dacitic magma.

But the dacites may also result from a hybridization of the andesitic magma with the rhyolitic one. Table 4 shows the major-element composition of the andesite LA 06 and rhyolite LA 03 of Los Azufres, clinopyroxene (CPX) of andesite LA 06 and biotite (BIO) of rhyolite taken from the literature. The modeling of the major-element data indicates that 100 mean units of andesitic magma need to mix with nearly 56.9 mean units of rhyolitic magma, and 10.3 and 1.8 mean units of CPX and biotite, respectively, need to be separated (Σ Residuals^2 = 0.9) in order to produce a dacitic magma.

In conclusion, in spite of relatively well defined features, the Los Azufres series is complicated in many aspects. Field evidence, geochemical data (particularly trace elements) and geochronology would be necessary to obtain a clearer idea of the relationships between the different units and their genetic history. The identification of earlier volcanic cycles (Oligo-Pliocene andesites) and their structural relationships with the recent one, remain to be investigated. The search for the evidence of a caldera structure may also be the major point of understanding of the Los Azufres series.

In spite of the uncertainties, it is emphasized that this Quaternary cycle shows features similar to those observed in numerous other volcanic activities of the MVB (Demant, 1981; Robin, 1982; Verma and López-M., 1982; Verma, 1983).

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BIBLIOGRAPHY

AGUILAR-y-VARGAS, V. H. and S. P. VERMA, 1987. Composición química (elementos mayores) de los magmas en el Cinturón Volcánico Mexicano. *Geofís. Int.*, Volumen especial sobre el Cinturón Volcánico Mexicano, Parte 3A *(Ed. S. P. Verma), 26,* this issue.

AOKI, K., 1964. Clinopyroxenes from alkaline rocks of Japan. *Am. Mineral, 49,* 1199-1223.

AUMENTO, F. and L. C. A. GUTIERREZ N., 1980a. El campo geotérmico de Los Azufres, Michoacán, CFE (Internal Report). 14-80.

AUMENTO, F. and L. C. A. GUTIERREZ N., 1980b. Geocronología de Los Azufres, Michoacán. CFE (internal report). 3-30, 6 p.

BEST, M. G. and E. L. P. MERCY, 1967. Composition and crystallization of mafic minerals in the Guadalupe igneous complex, California, *Am. Mineral. 52,* 436-474.

BLASQUEZ, L., 1961. Los geisers, solfataras y manantiales de la Sierra de San Andrés, Michoacán. *Bol. Inst. Geol. UNAM, 61,* 1-34.

BLOOMFIELD, K. and S. VALASTRO, 1977. Late quaternary tephrochronology of Nevado de Toluca Volcano, central Mexico. *Overseas Geol. Mineral, 46,* 15.

BRYAN, W. B., L. W. FINGER and F. CHAYES, 1968. Estimating proportions in petrographic mixing equations by least-squares approximation. *Science, 163,* 926-927.

CAMACHO, P., 1976. Mapa preliminar del área geotérmica de Los Azufres, Michoacán, CFE (Internal Report).

CATHELINEAU, M., R. OLIVER, G. IZQUIERDO, A. GARFIAS, D. NIEVA and O. IZAGUIRRE, 1983. Mineralogy and distribution of hydrothermal mineral zones in Los Azufres (Mexico) geothermal field. Proc. Ninth Int. Workshop on Reserv. Eng. Stanford. 269-274.

CATHELINEAU, M., R. OLIVER, D. NIEVA, A. GARFIAS, 1985. Mineralogy and distribution of hydrothermal mineral zones in Los Azufres (Mexico) geothermal field. *Geothermics, 14,* 49-57.

CATHELINEAU, M. and D. NIEVA, 1985. Geothermometric applications of chlorite solid solutions. *Contrib. Mineral. Petrol., 91,* 235-244.

COMBREDET, N., 1983. Etude du puits Al du champ géothermique de Los Azufres (Michoacán, Mexique) 3rd cycle thesis, Paris VI.

DEMANT, A., 1978. Algunos caracteres petrográficos de las rocas del Eje Volcánico Mexicano. IV Cong. Soc. Geol. Mexicana, 17 (abstract).

DEMANT, A., 1981. L'axe volcanique transmexicain. Etude volcanologique et pétrographique. Signification géodynamique. Thèses Univ. Aix-Marseille, 259 p.

DEMANT, A., R. MAUVOIS, M. L. SILVA, 1975. Estudio geológico de las hojas Morelia y Maravatío de Michoacán. CFE/UNAM, 30 p.
DEMANT, A., R. MAUVOIS y M. L. SILVA, 1976. El Eje Neovolcánico. III Congr. Latinoamer. Geol., Acapulco, Libreto guía 4, 30 p.
DOBSON, P. F., 1984. Volcanic stratigraphy and geochemistry of the Los Azufres geothermal center, Mexico. Stanford University (Unpublished M.S. Thesis), 58 p.
FERRIZ, H., 1985. Zoneamiento composicional y mineralógico en los productos eruptivos del centro volcánico de Los Humeros, Puebla, Mexico. *Geofís. Int.*, Volumen especial sobre el Cinturón Volcánico Mexicano *(Ed. S. P. Verma), 24,* 1, 97-157.
FOSHAG, W. P. and R. J. GONZALEZ, 1956. Birth and development of Paricutín Volcano, México, *U. S. Geol. Surv. Bull.*, 965 D, 355-487.
FRIES, C., Jr., C. S. ROSS y A. OBREGON, 1965. Mezclas de vidrios en los derrames cineríticos Las Américas de la región de El Oro, Tlalpujahua, Estados de México y Michoacán. CFE, (internal report) 42 p.
GARFIAS, A. and A. GONZALEZ, 1978. Resultados de las exploraciones en la zona geotérmica de Los Azufres, Michoacán, México. CFE (internal report) 42 p.
GUTIERREZ N., L. C. A., 1980. Correlación litológica y mineralógica en pozos de Los Azufres, Michoacán, CFE (internal report) 1-80. 15 p.
GUTIERREZ, A. N. and F. AUMENTO, 1982. The Los Azufres, Michoacán, Mexico, geothermal field, *J. Hydrol., 56,* 137-162.
HEINE, K. and M. HEIDE-WEISE, 1973. Jungquartare Forderfolgen des Malinche Vulkans und des Popocatépetl (Sierra Nevada, Mexico). *Münster Forsch. Geol. Paläont. 31*/12, 303-322.
KELSEY, C. H., 1965. Calculation of the CIPW Norm. *Mineral. Mag., 34* (Tilley volume), 276-282.
KUNO, H., 1959. Origin of Cenozoic petrographic provinces of Japan and surrounding areas. *Bull. Volcanol., 20,* 37-76.
KUNO, H., 1966. Lateral Variation of Basaltic Magma Type across Continental Margins and Island Arcs. *Bull. Volcanol., 29,* 195-222.
KUNO, H., 1968. Differentiation of Basalts Magmas: *in* Basalts, 2, 623-688 (H. H. Hess and A. Poldesvaart, Eds.), *Interscience,* N.Y.
LA ROCHE, H. de, J. LETERRIER, P. GRANDCLAUDE and M. MARCHAL, 1980. A classification of volcanic and plutonic rocks using R_1R_2 diagram and major element analysis. Its relationships with current nomenclature. *Chem. Geol., 29,* 183-210.
MOOSER, F., 1961. Los volcanes de Colima. *Bol. Inst. Geol. UNAM, 61,* 49-71.

MOOSER, F., 1972. The Mexican volcanic belt, structure and tectonics. *Geofís. Int., 12,* 55-70.
MOOSER, F., 1975. The Mexican volcanic belt: interpretation derived from fractures and forms. *Trans. Am. Geophys. Union, 56,* 1066 (abstract).
MORA, S. L., 1979. Contribution à la connaissance de l'axe Volcanique Transmexicain: étude géologique et pétrologie des laves du Michoacán oriental. Thèse Doct. Ing. Aix Marseille III, 46 p.
PAL, S., M. LOPEZ M., J. PEREZ R. and D. J. TERRELL, 1978. Magma characterization of the Mexican Volcanic Belt (Mexico). *Bull. Volcanol., 41,* 379-389.
PECCERILLO, A. and S. R. TAYLOR, 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastomonu area, Northern Turkey. *Contrib. Mineral. Petrol., 58,* 63-81.
ROBIN, C., 1982. Relations volcanologie - magmatologie géodynamique: applications au passage entre volcanismes alcalin et andésitique dans le Sud Mexicain (axe transmexicain et province alcaline orientale). Thesis Clermont Ferrand II, 70, 503 p.
SCHWARZER, R. R. and J. J. W. ROGERS, 1974. A worldwide comparison of alkali olivine basalts and their differentiation trends. *Earth Planet. Sci. Lett., 23,* 286-296.
STEELE, W., 1971. Paleomagnetic alineation from the Iztaccíhuatl volcano, Mexico, *Earth Planet. Sci. Lett., 83,* 1727-1739.
VERMA, M. P., V. H. AGUILAR-y-VARGAS and S. P. VERMA, 1986. A program package for major-element data handling and CIPW norm calculation. *Computers & Geosci.* (in press).
VERMA, S. P.,1983. Magma genesis and chamber processes and Los Humeros Calra, México. Nd and Sr Isotopes data. *Nature, 301,* 52-53.
VERMA, S. P., 1984. Alkali and alkaline earth element geochemistry of Los Humeros Caldera, Puebla, México. *J. Volcanol. Geotherm. Res., 20,* 21-40.
VERMA, S. P. and M. LOPEZ-M., 1982. Geochemistry of Los Humeros caldera, Puebla, México, *Bull. Volcanol., 45,* 63-79.

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