GEOCHEMISTRY OF TERTIARY IGNEOUS ROCKS FROM ARANDAS-ATOTONILCO AREA, NORTHEAST JALISCO, MEXICO

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RESUMEN

Se presentan los análisis de elementos mayores para diez muestras de basalto y andesita, seleccionadas de diez sitios paleomagnéticos en el noreste de Jalisco, México. Se reportan también los datos de fechas radiométricas K-Ar y de Tierras Raras (TR) en cuatro muestras, así como de contenidos de elementos alcalinos (K, Rb y Cs) y tierras alcalinas (Ba y Sr) y razones isotópicas de estroncio ($^{87}Sr/^{86}Sr$) en ocho muestras. Se presenta evidencia de actividad volcánica hace 11 Ma en esta área. Las razones iniciales de $^{87}Sr/^{86}Sr$ varían desde 0.7033 hasta 0.7039 y no se correlacionan con los elementos mayores o trazas ni con las razones de elementos. Las razones de $^{87}Sr/^{86}Sr$ son similares a las observadas en otras áreas del Cinturón Volcánico Mexicano (CVM) y son compatibles con un origen sub-cortical para los magmas jalicienses.

ABSTRACT

Major element analyses for ten samples of basalt and andesite, selected one each from ten paleomagnetic sites in northeast Jalisco, Mexico are presented. K-Ar dates and REE data on four samples and contents of alkali (K, Rb and Cs) and alkaline earth (Ba and Sr) elements and ^{87}Sr ^{86}Sr ratios on eight samples are also reported. Evidence of volcanic activity at about 11 Ma is shown. Initial $^{87}Sr/^{86}Sr$ ratios range from 0.7033 to 0.7039 and are not correlated with major or trace elements or element ratios. $^{87}Sr/^{86}Sr$ ratios are similar to those observed in other areas of the Mexican Volcanic Belt and are compatible with a sub-crustal origin for the Jalisco magmas.

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INTRODUCTION

The area of study is situated in the Mexican Volcanic Belt (MVB), near Lake Chapala, in northeastern Jalisco, Mexico (Fig. 1). A middle Cenozoic age (Oligocene to lower Pliocene) has been assigned to the extensive outcrops of igneous rocks present in this area (López-Ramos and Sánchez-Mejorada, 1976). Although it is certain that the study area is almost completely underlain by extrusive igneous rocks (see, e.g., 1:50 000 maps F-13-D-68 and F-13-D-69 of DETENAL), the stratigraphic and other field relations are almost unknown.
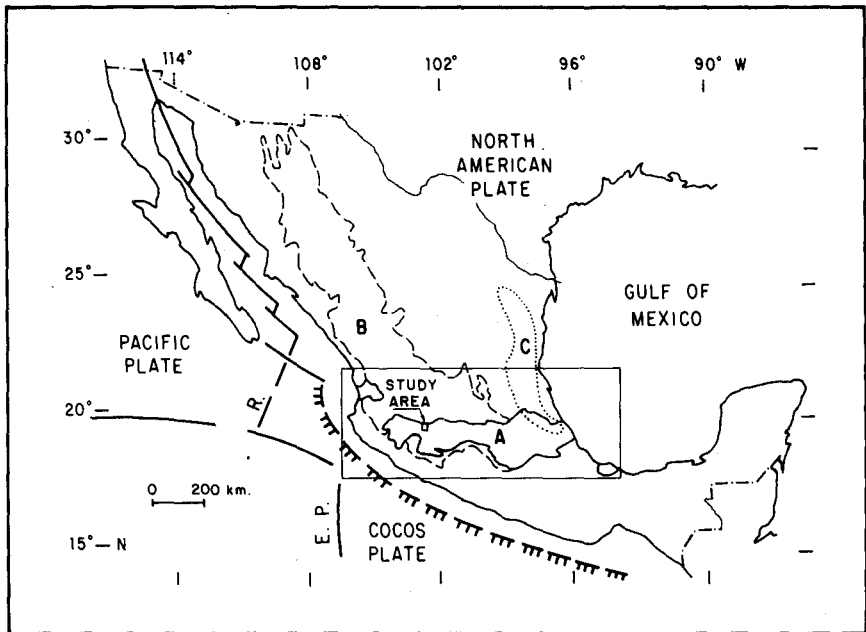

Fig. 1. Location of the study area (the map is simplified after López-Ramos and Sánchez-Mejorada, 1976 and Atwater, 1970). A = Mexican Volcanic Belt, B = Sierra Madre Occidental and C = Eastern Cordillera (after Demant and Robin, 1975). The rectangular box is amplified in Fig. 4.

A paleomagnetic study carried out on samples of volcanic rocks collected from eight different sites suggested the possibility of a tectonic rotation of this area with respect to "stable" North America (Urrutia and Pal, 1977; Pal and Urrutia, 1977; Pal, 1979). A geochemical study on selected samples from ten sites has been undertaken with the hope of obtaining constraints on the nature of the source of these magmas and the tectonic regime in which they were erupted.

There is no general agreement on the Cenozoic evolution of the oceanic crust off the west coast of Mexico (Atwater, 1970; Lynn and Lewis, 1976; Menard, 1978). However, it seems certain that the Cocos plate (which is presently subducting along the Middle-America trench; e.g., Karig *et al.,* 1978; Nixon, 1982) represents a remnant of the large Farallon or Guadalupe plate as a result of the associated subduction processes.

ANALYTICAL METHODS

Fresh rock samples were collected from ten localities in the Arandas-Atotonilco area. Their geographical coordinates based on DETENAL maps are included in the footnotes of Table 2. The samples were washed with distilled millipore-filtered water and dried before crushing. The coarsely crushed powder was quartered and a representative fraction was pulverized in a ceramic disc-grinder to ~100 mesh. A mixture of HF and HNO_3 was used for decomposing the sample aliquots.

Ar measurements were carried out by E. Linares (Instituto de Geocronología y Geología Isotópica, Argentina) using the techniques described elsewhere (Linares *et al.,* 1973 and Linares and Valencio, 1975). Major-element chemistry was obtained by a combination of various techniques: gravimetry (SiO_2, H_2O, and L.O.I.), atomic absorption spectrophotometry (Al_2O_3, total Fe, MnO, MgO, and CaO), flame photometry (Na_2O and K_2O), colorimetry (TiO_2, P_2O_5, and total Fe), and volumetry (FeO). The experimental details are given by López-M. (1977) and Pal and Hernández-Chacón (1973). K, Rb, Cs, Ba, and Sr were measured by mass spectrometric isotope dilution (MSID). A V.G. Micromass 30 mass spectrometer was employed for these as well as the isotopic analyses of $^{87}Sr/^{86}Sr$ ratios. The experimental details and the accuracies obtained are given by Verma (1981). Rare earth elements (REE) were measured by spark source mass spectrometry on an AEI MS702 mass spectrometer, following the method of Nicholls *et al.* · (1967).

PETROGRAPHY

The Arandas-Atotonilco extrusive igneous rocks show a subophitic (samples S2, S3, S5A, S5B, S6 and S8), ophitic (S4), microporphyritic (S1) and pilotaxitic (S7) textures. The most common mineralogy in-

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cludes euhedral to subhedral andesine-oligoclase plagioclase phenocrysts
in a fine-grained mesostasis of plagioclase microlites of similar composi-
tion and some of the following: augite, magnetite, olivine, K-feldspar,
biotite, hornblende and some other ferromagnesian minerals. Minor
hematite and traces of limonite and chlorite are present as a result of
low-temperature surface weathering.

RESULTS AND DISCUSSION

1. *K-Ar Dates.*

Four K-Ar dates have been obtained and the results are given in Table 1.
The measurements of argon were carried out at the Instituto de Geocro-
nología y Geología Isotópica, Argentina (E. Linares, written commun-
ication, 1977). We have used our precise MSID K values for the com-
putation of the K-Ar dates. Three of the four samples show apparently

Table 1

K-Ar Dates on four Arandas-Atotonilco volcanic rocks

Sample	K %o	^{40}Ar rad. 10^{-11} mol/g	^{40}Ar atm. %o	Date Ma
S1	1.06	2.17	78.9	12 ± 2
S5B	0.90	5.03	80.8	32 ± 6
S6	.1.51	2.90	39.8	11 ± 2
S8	0.71	1.26	43.9	10 ± 2

K (%o) by MSID (Table 4); Argon data provided by
E. Linares.
Constants used are: λ_e = 0.581 x 10^{-10}y^{-1}; λ_β = 4.962 x
10^{-10}y^{-1}; $(^{40}$Ar/^{36}Ar$)_{atm}$ = 295.5; ^{40}K/K$_{(molar)}$ = 1.167
x 10^{-4}.

consistent dates, at 11 ± 1 Ma. These are only slightly higher than the
period of the older igneous activity (9.5 to 8.7 Ma) reported for Río
Grande de Santiago area situated about 100 km west of the present one
(Watkins *et al.*, 1971). A K-Ar date of 8.5 Ma on a calc-alkaline basalt
from the latter area is also reported recently by Nieto-Obregón *et al.*
(1985). The fourth sample (S5B) yields a much higher date (32 ± 6 Ma).
Thus, the two samples (S5A and S5B) may be considerably older (about
32 Ma). On the other hand, it is also possible that this particular flow
may have the problem of initially inherited excess ^{40}Ar.

Our dates in combination with those of Watkins *et al.* (1971) and Nieto-Obregón *et al.* (1985) suggest the presence of volcanic activity in this area of the MVB between 11 and 8 Ma and throw some light on the age connotation of the MVB. Demant (1978) considers that the MVB should be defined by only the Plio-Quaternary volcanic activity (about 1 Ma to present). Cantagrel and Robin (1979) and Robin (1981) extend it (of better speaking, its neovolcanic phase) to about 2.6 Ma whereas others (Mooser, 1969, 1972; Gunn and Mooser, 1971; Negendank, 1973; Pal and Urrutia-Fucugauchi, 1977) recognize that the volcanic activity in this Province could be extended to at least late Oligocene. There is a large number of young radiometric dates (e.g., Bloomfield and Valastro, 1974; Cantagrel *et al.*, 1981; Mahood and Drake, 1982; Ferriz and Mahood, 1984; Gilbert *et al.*, 1985) but older dates are also commonly found in this province (e.g., Watkins *et al.*, 1971; Mooser, 1972; Cantagrel and Robin, 1979; Gilbert *et al.*, 1985; Nieto-Obregón *et al.*, 1985). Tectonic rotation of Arandas-Atotonilco sites suggested from a paleomagnetic study (Urrutia and Pal, 1977) have important bearing on the evolution of this Volcanic Province (Pal and Urrutia, 1977).

2. Major-elements.

Major-element analyses and CIPW norms are given in Table 2. The rocks show a relatively narrow range ($\sim$49-56%) in their SiO_2 contents, but K_2O concentrations vary widely from about 1 to 2%. They are classified as basalts and andesites (Fig. 2) according to the scheme of Peccerillo and Taylor (1976). All but two samples, S2 and S4 (both high-K basalts), belong to the calc- alkaline series of Peccerillo and Taylor (1976). The calc-alkaline nature of these volcanic rocks is consistent with the results of a compilation of the bulk chemical analyses in the MVB (Pal *et al.*, 1978). The Arandas-Atotonilco samples are further characterized by rather low Mg-value, implying that none of them represent parental magmas. All but one sample (S3, which is OL-normative) show normative-Q in their CIPW norms.

Table 2

Major element chemistry and CIPW norm for Arandas-Atotonilco volcanic rocks

	S1	S2	S3	S4	S5A	S5B	S6	S7	S7A	S8
Chemical analysis:										
SiO_2	49.1	51.5	49.6	50.6	53.4	53.1	56.2	50.4	50.1	49.5
TiO_2	1.27	1.25	1.13	1.03	0.89	0.89	0.97	1.49	1.44	1.13
Al_2O_3	17.6	17.8	16.6	16.2	17.2	17.9	17.4	17.5	17.5	16.7
Fe_2O_3	6.77	5.22	4.64	4.77	4.95	6.16	4.19	6.22	6.37	5.03
FeO	4.11	3.64	5.98	4.32	3.18	2.38	3.15	4.34	4.46	6.66
MgO	5.53	5.03	7.3	7.2	6.01	4.04	3.93	5.21	4.67	6.37
CaO	8.6	7.8	8.9	7.9	8.0	8.1	6.7	8.1	8.2	8.3
MnO	0.16	0.14	0.16	0.14	0.13	0.13	0.11	0.14	0.14	0.17
Na_2O	3.31	3.52	3.23	3.02	3.45	3.36	3.89	3.76	3.69	3.21
K_2O	1.28	1.74	1.21	2.05	1.14	1.24	1.80	1.05	1.02	0.85
P_2O_5	0.47	0.53	0.40	0.54	0.37	0.39	0.56	0.42	0.42	0.36
H_2O^-	0.78	0.72	0.46	1.33	0.77	0.57	0.97	1.24	0.93	0.51
L.O.I.	0.72	0.77	0.93	0.86	0.63	1.40	0.51	0.54	0.52	0.56
Sum	99.7	99.7	100.6	100.0	100.1	99.7	100.4	100.4	99.5	99.4
$[FeO^*/$ $(FeO^*+MgO)]$	0.65	0.62	0.58	0.54	0.56	0.66	0.64	0.66	0.69	0.64
(FeO^*/MgO)	1.84	1.66	1.39	1.19	1.27	1.96	1.76	1.91	2.18	1.76
Mg-value	51.8	54.4	58.8	62.4	60.9	50.2	52.9	50.9	47.6	53.0

Table 2 (Cont.).

	S1	S2	S3	S4	S5A	S5B	S6	S7	S7A	S8
CIPW norm										
Q	1.81	3.05	–	0.23	5.7	8.3	8.8	2.34	3.27	0.58
OR	7.7	10.5	7.2	12.4	6.8	7.5	10.8	6.3	6.2	5.1
AB	28.6	30.3	27.5	26.2	29.6	29.1	33.3	32.3	31.9	27.6
AN	29.9	28.1	27.5	25.1	28.5	30.8	25.1	28.2	28.7	29.2
DIMg	7.9	6.0	9.1	8.1	7.1	6.1	3.41	7.3	7.3	6.1
DIFe	0.08	0.24	2.42	1.00	0.22	–	0.28	0.31	0.44	2.19
HYMg	10.4	10.0	8.3	14.6	11.9	7.5	8.3	9.8	8.5	13.3
HYFe	0.12	0.45	2.54	2.08	0.41	–	0.79	0.47	0.59	5.47
OLMg	–	–	4.10	–	–	–	–	–	–	–
OLFe	–	–	1.38	–	–	–	–	–	–	–
MT	10.0	7.7	6.8	7.1	7.3	5.7	6.1	9.1	9.4	7.4
IL	2.46	2.42	2.16	2.00	1.71	1.73	1.86	2.87	2.79	2.18
AP	1.13	1.28	0.95	1.31	0.89	0.95	1.34	1.01	1.02	0.87
HM	–	–	–	–	–	2.41	–	–	–	–
SALIC	67.9	71.9	62.3	63.8	70.6	75.7	77.9	69.1	70.0	62.5
FEMIC	32.1	28.1	37.7	36.2	29.5	24.3	22.1	30.9	30.0	37.5
C.I.	54.2	48.1	57.0	52.8	52.1	49.1	38.3	50.9	50.4	51.7
D.I.	38.1	43.9	34.8	38.8	42.1	44.9	52.8	40.9	41.3	33.3
S.I.	26.3	26.3	32.7	33.7	32.1	23.5	23.2	25.3	23.1	28.8
A.R.	1.43	1.52	1.42	1.53	1.44	1.43	1.62	1.46	1.45	1.39

Footnotes Table 2:

Sample locations are as follows.

S1	$(20^{\circ}40.9'$,	$102^{\circ}12.5'$);	S2	$(20^{\circ}42.2'$, $102^{\circ}14.3'$);
S3	$(20^{\circ}40.4'$,	$102^{\circ}09.5'$);	S4	$(20^{\circ}37.3'$, $102^{\circ}12.8'$);
S5A	$(20^{\circ}43.1'$,	$102^{\circ}31.9)$;	S5B	$(20^{\circ}43.1'$, $102^{\circ}31.9'$);
S6	$(20^{\circ}41.3'$,	$102^{\circ}32.6'$);	S7, S7A	$(20^{\circ}34.1'$, $102^{\circ}29.9'$);
S8	$(20^{\circ}46.9'$,	$102^{\circ}26.1'$);		

Precisions and accuracies of the chemical analysis range between 1 and 5%.

FeO* = total iron expressed as FeO;

Mg-value = $100\ Mg^{2+}/(Mg^{2+} + 0.9(Fe^{2+} + Fe^{3+}))$, atomic;

DIMg = $CaO.MgO.2SiO_2$; DIFe = $CaO.FeO.2SiO_2$; HYMg = $MgO.SiO_2$; HYFe = $FeO.SiO_2$;

SALIC = sum of the salic normative minerals (Q + OR + AB + AN);

FEMIC = sum of the femic normative minerals (DIMg + DIFe + HYMg + HYFe + FO + FA + MT + IL + HM);

C.I. = crystalization index (AN + 2.1570577 DIMg + FO + 0.7007616 HYMg);

D.I. = differentiation index (Q + OR + AB + NE + LC);

S.I. = solidification index $(100\ MgO/(MgO + FeO + Fe_2O_3 + Na_2O + K_2O))$;

A.R. = alkalinity ratio $(Al_2O_3 + CaO + \text{total alkalies})/Al_2O_3 + CaO - \text{total alkalies})$. However, when $SiO_2 > 50\%$ and $1 < (K_2O/Na_2O) < 2.5$, then $2(Na_2O)$ is used in place of total alkalies.

CIPW norms are computed on an anhydrous basis, using a program written by one of us (SPV) following the method of Kelsey (1965).
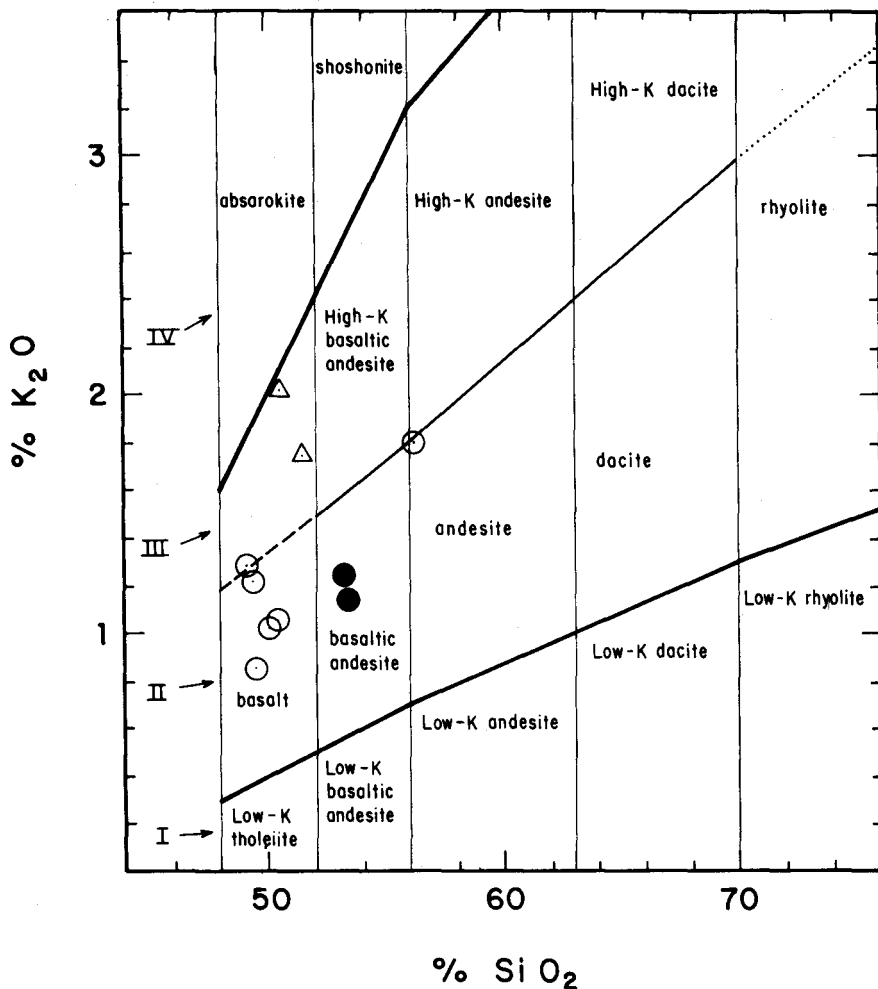
Fig. 2. K_2O vs. SiO_2 plot for Arandas-Atotonilco volcanic rocks. The boundaries and nomenclature shown are from Peccerillo and Taylor (1976). The sequences I through IV are: tholeiitic series (I), calc-alkaline series (II), high-K calc-alkaline series (III) and shoshonite series (IV). The symbols used are: Open triangles for S2 and S4; filled circles for S5A and S5B and open circles for the other samples.

3. Minor elements and REE data.

The results of the mass spectrometric measurements of alkali and alkaline earth elements are given in Table 3. In spite of the rather mafic nature of most samples, the contents of these elements show somewhat large range. The variations in these trace element concentrations and

Table 3
Alkali and alkaline earth elements and $^{87}Sr/^{86}Sr$ ratios in Arandas-Atotonilco volcanic rocks

Sample	K ppm	Rb ppm	Cs ppm	Ba ppm	Sr ppm	$^{87}Sr/^{86}Sr$ measured	$^{87}Sr/^{86}Sr$ initial
S1	10,580 ± 80	32.0 ± 0.3	0.27 ±0.01	940 ± 12	466 ± 1.2	0.70368 ± 3	0.70365
S2	14,690 ± 70	37.1 ± 0.2	0.33 ±0.01	523 ± 3	1,076 ± 3	0.70346 ± 2	0.70344
S3	9,750 ± 80	33.5 ± 0.4	0.23 ±0.01	361 ± 4	409 ± 1.2	0.70371 ± 6	0.70367
S4	17,700 ± 100	71.4 ± 0.5	0.48 ±0.01	636 ± 4	444 ± 1.2	0.70396 ± 5	0.70388
S5A	9,290 ± 90	15.7 ± 0.1	0.24 ±0.01	473 ± 3	979 ± 3	0.70333 ± 3	0.70331
S5B	9,000 ± 40	16.4 ± 0.1	0.49 ±0.01	602 ± 5	1,004 ± 3	0.70346 ± 6	0.70344
S6	15,100 ± 90	30.5 ± 0.3	0.37 ±0.01	1,670 ± 20	669 ± 3	0.70390 ± 5	0.70388
S8	7,080 ± 60	18.6 ± 0.2	0.14 ±0.01	483 ± 3	398 ± 1.1	0.70359 ± 4	0.70357

The measured $^{87}Sr/^{86}Sr$ ratios are normalized to $^{86}Sr/^{88}Sr = 0.11940$ and adjusted to SRM 987 $^{87}Sr/^{86}Sr$ ratio of 0.71021. The measured ratio for the SRM 987 standard is $0.710280 ± 40$ (2σ, n = 18) during the period of measurements of about one year. In this period, E&A $SrCO_3$ standard gave a value of $0.708071 ± 34$ (2σ, n= 9). The errors reported on individual $^{87}Sr/^{86}Sr$ ratios are two times the standard error of the mean multiplied by 10^5. The initial $^{87}Sr/^{86}Sr$ ratios are obtained by correcting the measured $^{87}Sr/^{86}Sr$ ratios for the radiogenic ^{87}Sr growth during 11 m.y. for all samples except S5A and S5B for which the correction applied is for 32 m.y.

their ratios may be due to small differences in partial melting of the source region and to fractional crystallization of the partial melts in terms of the observed modal phases dominated by hornblende and pyroxene (Verma, 1984 for a compilation of the corresponding solid-liquid partition coefficients).

The REE data on four Arandas-Atotonilco rocks are reported in Table 4 and the normalized REE concentrations are plotted in Fig. 3. These plots show that the Arandas-Atotonilco rocks are characterized by LREE-enrichment [(Ce/Yb)n ~8-chondrite normalized ratio], absence of Eu-anomaly, and flat- to depleted-HREE patterns. It could be suggested that the REE data are compatible with the derivation of these magmas from the partial melting of a source with some residual garnet (e.g., Harrison, 1981) or from that of a LREE-enriched source. The absence of a significant Eu anomaly in these patterns further suggests that

plagioclase has not been a dominant phase in the fractional crystalliza-
tion of these magmas (Schnetzler and Philpotts, 1970; Sun *et al.*, 1974;
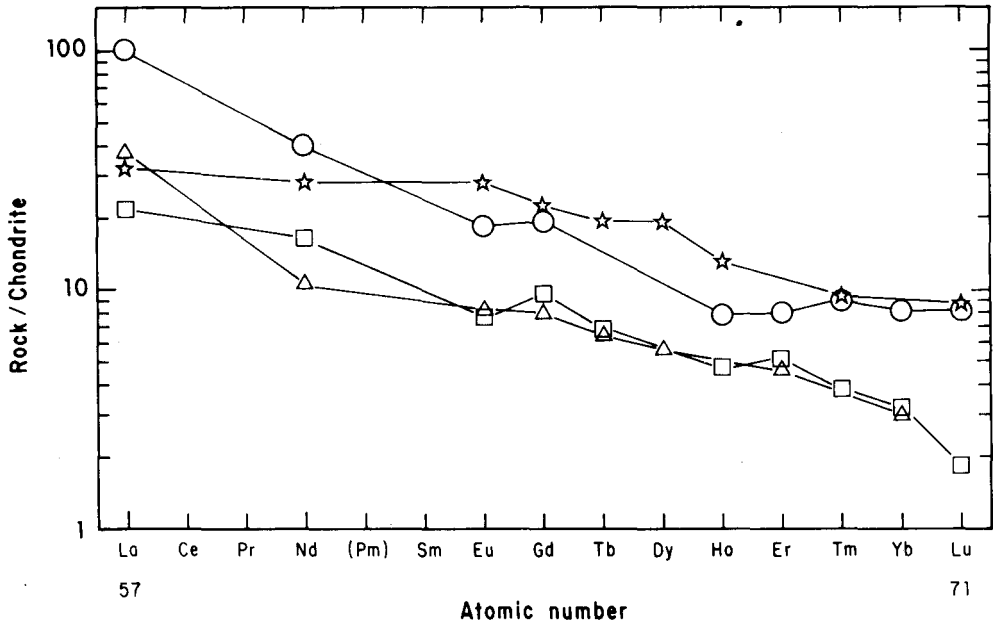Drake and Weill, 1975).

Fig. 3. Leedey Chondrite-normalized REE plots of Arandas-Atotonilco volcanic rocks. Sym-
bols used are: circles for S1, triangles for S2, stars for S7A and squares for S8.

Table 4

Rare earth elements in Arandas-Atotonilco volcanic rocks

	S1	S2	S7A	S8
La	33	14.2	12.3	8.2
Nd	28	7.4	20	12
Eu	1.60	0.73	2.45	0.77
Gd	6.0	2.49	7.1	3.00
Tb	--	0.39	1.16	0.39
Dy	--	2.2	7.6	--
Ho	0.70	--	1.23	0.42
Er	2.04	1.18	--	1.30
Tm	0.35	--	0.35	0.15
Yb	2.01	0.74	--	0.78
Lu	0.32	--	0.33	0.07

Precisions and accuracies for the REE range from 10 to 30%.

4. *Sr isotope ratios.*

Both the measured (present day) as well as the age-corrected (initial) $^{87}Sr/^{86}Sr$ ratios are presented in Table 3. The initial $^{87}Sr/^{86}Sr$ ratios show a relatively narrow range in Arandas-Atotonilco (NE Jalisco) rocks (0.7033-0.7039). Fig. 4 compares these ratios with those observed in the studied areas of the MVB (based on a compilation by Verma, 1984). It is seen from this figure that the older rocks from Arandas-
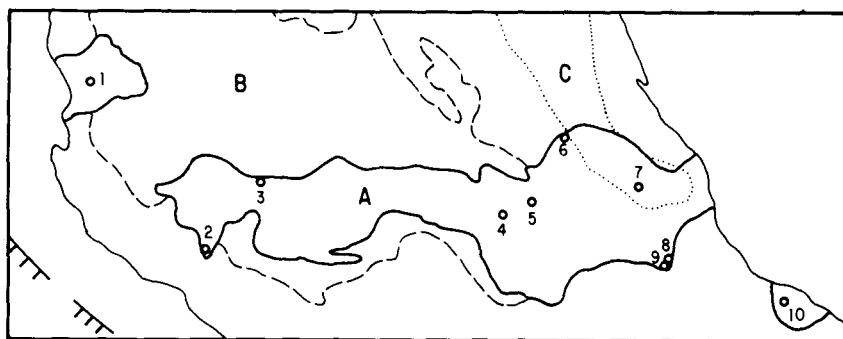
Fig. 4. Locations of the areas where $^{87}Sr/^{86}Sr$ ratios have been measured (after a compilation by Verma, 1984). The trace of the MVB (identified as letter A) is also shown for reference (B and C, see footnotes Fig. 1). The numbers 1 to 10 stand for the following areas (the corresponding range, mean and the number of $^{87}Sr/^{86}Sr$ analyses are given in parentheses, after each area): 1. Ceboruco (0.7041-0.7043, 0.7042, 4); 2. Colima and Nevado de Colima (0.7036-0.7040, 0.7038, 8); 3. Arandas-Atotonilco, NE Jalisco (0.7033-0.7039, 0.7036, 8); 4. Toluca and Nevado de Toluca (0.7032-0.7045, 0.7039, 24); 5. Valley of Mexico (0.7034-0.7045, 0.7039, 9); 6. Pachuca (0.7034-0.7044, 0.7040, 7); 7. Los Humeros (0.7039-0.7048, 0.7042, 27); 8. NE of Pico de Orizaba (0.7035-0.7042, 0.7038, 5); 9. SE of Pico de Orizaba (0.7041-0.7046, 0.7044, 8); 10. San Martín (0.7036-0.7038, 0.7037, 4).

Atotonilco (11 ± 1 Ma) have similar $^{87}Sr/^{86}Sr$ ratios to those of the younger ones studied in the MVB so far. No correlation is observed between the $^{87}Sr/^{86}Sr$ ratios and the distance of the locality from the Middle America Trench (MAT). It may be interesting in the future to increase the Sr isotope data base by studying volcanic rocks (late Cenozoic to Recent) from localities lying along lines perpendicular to the MAT.

The Arandas-Atotonilco rocks do not show a significant correlation of the $^{87}Sr/^{86}Sr$ ratios with any of the major elements, trace elements or element ratios. These observations are consistent with the derivation of the Arandas-Atotonilco magmas from isotopically homogeneous source(s) (subducted oceanic plate and/or the overlying mantle wedge) involving

different degrees of partial melting and fractional crystallization proces-
ses. Nd isotope data are needed in order to further constrain the source
region of these rocks (e.g., Verma, 1983). However, from the low and
rather uniform $^{87}Sr/^{86}Sr$ ratios observed we may suggest that the con-
tinental crust has not played an important role in the evolution of these
rocks.

CONCLUSIONS

The following conclusions can be drawn from this study:

(1) The present results when combined with other studies show that a
calc-alkaline volcanism occurred in Jalisco between about 11 and 8
Ma.

(2) The rocks studied do not show a significant contamination effects
from the underlying continental crust.

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