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Geochemistry and mineralogy of the Eocene-Oligocene volcanic sequence, Southern Sierra Madre Occidental, Juchipila, Zacatecas, Mexico

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RESUMEN

La provincia volcánica de la Sierra Madre Occidental (SMO) en el occidente de México es el remanente de un amplio cinturón orogénico de tipo margen continental formado como resultado de la subducción de la placa Farallón debajo de México durante el Terciario Medio. El mayor volumen de rocas expuestas en la SMO son tobas originadas por flujo de cenizas de composición riolítica (AFT) que fueron extruídas a lo largo de la mayor parte de la provincia desde hace 36 a 27 Ma. El registro de otros dos episodios magmáticos en la SMO incluye un evento Eoceno (53-40 Ma) caracterizado por flujos de lava de composición máfica-intermedia, y un evento post-ignimbrítico (29-20 Ma) caracterizado por la erupción de andesitas basálticas relacionadas con extensión. Este artículo presenta datos nuevos para un área en la porción sur de la SMO que aportan evidencia acerca del volcanismo Eoceno y Oligoceno.

La secuencia estratigráfica del área cercana a Juchipila, Zacatecas, consiste de flujos de lava de andesita basáltica a andesítica de edad Eoceno, que son cubiertos discordantemente por flujos de lava basálticos a andesítico-basálticos de edad Oligoceno y/o AFT riolíticas. Una secuencia de flujos de lava basáltica a andesítica se observa hacia la cima. La secuencia calci-alcalina con alto K de edad Oligoceno está compuesta predominantemente de AFT riolíticas (-25 Ma) que son más jóvenes que la mayoría de las otras ocurrencias reportadas para la SMO. Esto sugiere un rejuvenecimiento del volcanismo de la SMO hacia el sur.

Aunque las AFT de Juchipila son pobres en fenocristales, una unidad de AFT ampliamente distribuída está caracterizada por la presencia de feldespato alcalino con núcleos ricos en Ba poco comunes (hasta 14 % de componente celsiano). Esta es la primera ocurrencia reportada de esta composición de feldespatos en la SMO.

PALABRAS CLAVE: Sierra Madre Occidental, tobas de flujos de ceniza, riolita, andesita, feldspato de bario

ABSTRACT

The Sierra Madre Occidental (SMO) volcanic province of western Mexico is a remnant of a broad continental-margin orogenic belt formed as a result of mid-Tertiary subduction of the Farallon plate beneath Mexico. The most voluminous rocks exposed in the SMO are rhyolitic ash-flow tuffs (AFT) erupted throughout most of the province from 36 to 27 Ma. Two other magmatic episodes recorded in the SMO include an Eocene event (53-40 Ma) characterized by mafic-intermediate composition lava flows, and a post-ignimbrite event (29-20 Ma) characterized by the eruption of extension-related basaltic-andesites. This paper presents new data for an area in the southern SMO which has evidence for both Eocene and Oligocene volcanism.

The stratigraphic sequence established for the area near Juchipila, Zacatecas, consists of Eocene basaltic andesite to andesite lava flows which are unconformably overlain by Oligocene basalt to basaltic andesite lava flows and/or Oligocene rhyolitic ash-flow tuffs. An upper sequence of basalt to andesite lava flows caps the section. The high-K calc-alkaline Oligocene sequence is composed predominantly of rhyolitic AFT (~25 Ma) which are younger than most other reported SMO occurrences. This suggests a younging to the south of SMO volcanism.

Although Juchipila AFT are phenocryst poor, one widespread AFT unit is characterized by alkali feldspar with unusually Ba-rich cores (up to 14% celsian component). This is the first reported occurrence for this composition feldspar in the SMO.

KEY WORDS: Sierra Madre Occidental, ash-flow tuff, rhyolite, andesite, barium feldspar

INTRODUCTION

The Sierra Madre Occidental (SMO) of western Mexico forms a long linear plateau that extends for 1200 km from the U.S.-Mexico border south to Guadalajara where it is covered by the younger volcanic rocks of the east-west trending Trans Mexican Volcanic Belt (Figure 1). The SMO consists predominantly of mid-Tertiary rhyolitic ash-flow tuffs that reach composite thicknesses of close to 1 km. McDowell and Keizer (1977) have characterized the SMO as the world's largest continuous rhyolitic province.

Despite the geographic extent of the SMO, detailed studies of the volcanic rocks have been restricted to a few areas. A series of stratigraphic studies and a description of regional chemical and petrographic variations for a transect from Durango to Mazatlan (Figure 1) have been detailed by McDowell and Keizer (1977) and McDowell and Clabaugh (1979). Based on their work they subdivided the SMO into two igneous sequences informally called the Lower Volcanic Complex and the Upper Volcanic Supergroup. The Upper Volcanic Supergroup is comprised primarily of calc-alkaline rhyolitic ash-flow tuffs (36-27 Ma) which form

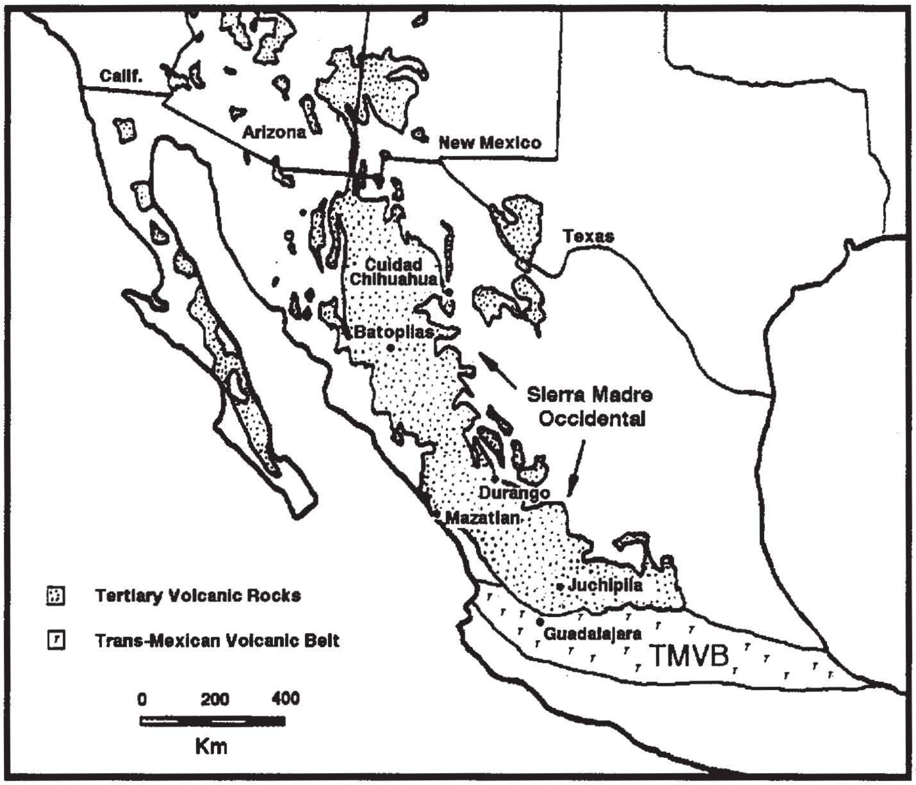

Fig. 1. Generalized distribution of Tertiary volcanic rocks in Mexico and the southwestern US (modified from M. Cameron *et al.*, 1980). The three Tertiary volcanic provinces in Mexico include from west to east the Sierra Madre Occidental (SMO), the Chihuahua Basin and Range (CBR) and Trans-Pecos Texas. The area described in this paper is located in the southern SMO near the town of Juchipila, ~120 km northeast of Guadalajara on Highway 54. The SMO is bounded on the south by the younger Miocene-Holocene volcanic rocks of the Trans-Mexican Volcanic Belt (TMVB, modified from Sedlock *et al.*, 1993).

the generally undeformed central plateau of the SMO. These rocks unconformably overlie a volcano-plutonic complex in which rocks of intermediate composition predominate (Bagby *et al.*, 1981). Aguirre-Diaz and McDowell (1991) have recently described widespread Eocene volcanism (51 to 40 Ma) for the volcanic section at Nazas, Durango, Mexico. They describe SMO volcanism in terms of Eocene and Oligocene volcanic episodes and avoid the Lower Volcanic Complex and Upper Volcanic Supergroup usage.

The petrogenesis of a sequence of ash-flow tuffs (AFT) exposed near Batopilas (Figure 1) in the northern SMO has been addressed in a series of papers (M. Cameron *et al.*, 1980; Lanphere *et al.*, 1980; Cameron and Hanson, 1982; Barreiro *et al.*, 1982). According to Cameron *et al.*, (1986) the geochemical data obtained from these studies are consistent with the Batopilas rhyolites being generated by closed-system fractional crystallization of subcrustal magmas, with less than 25% of a crustal component. Cameron *et al.* (1980) and Moll (1981) examined AFT from the eastern Chihuahua Basin and Range Province (CBR) and found them to be more alkaline than AFT from Batopilas. Hence they refer to AFT from Batopilas as belonging to a moderate-K facies, whereas the more alkaline rocks of the CBR are referred to as the high-K facies. The west to east increase in alkalinity across the SMO to the CBR and Trans-Pecos Texas corresponds with increasing distance from the mid-Tertiary Pacific plate margin, and an inferred increase in depth to the subduction zone (K. Cameron *et al.*, 1980). A series of younger (29-20 Ma) mildly alkaline basalts and basaltic andesites, the SCORBA suite of Cameron *et al.*, (1989) overlies the calc-alkaline ash-flow tuff sequence from both the SMO and the CBR.

Cameron and Cameron (1985) examined dacitic lavas and AFT from Baja California, northwestern Mexico, and west Texas in order to evaluate the role of continental crust in the formation of orogenic dacites. Based on $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic data coupled with rare-earth-element data they concluded that the parental magmas of these rocks had been contaminated by only small amounts of Precambrian crust and showed strong evidence for the predominance of a subcrustal component. However, Ruiz *et al.* (1988) collected $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic data on lower crustal xenoliths believed to be Paleozoic or older, which occur in alkali basalts exposed on the eastern edge of the SMO in order to evaluate the role of the lower crust as a potential source for the mid-Tertiary AFT of the SMO. They concluded that the Nd and Sr isotopic compositions of the orthogneiss xenoliths were similar to those obtained for AFT which could have been derived exclusively from the lower crust.

The volcanic sequence described in this paper is located in the southern Sierra Madre Occidental, approximately 120 km northeast of Guadalajara, near the city of Juchipila, Zacatecas (Figure 1). We have divided the 1 km thick volcanic sequence into 4 magmatic episodes on the basis of age and rock type. The oldest volcanic rocks in the area are (1) Eocene (48.1 ± 2.6 Ma) basaltic andesite to andesite lava flows, which are unconformably overlain by (2) Oligocene (23.7 ± 1.4 Ma) basalt to basaltic andesite lava flows and/or (3) rhyolitic ash-flow tuffs (25 ± 2.5 Ma). The unconformity between the Eocene and Oligocene volcanic rocks is marked by as much as 200 m of coarse red sandstones and conglomerates (Roesler, 1987). Basaltic to andesitic lava flows (4) are intercalated with AFT in the upper part of the stratigraphic section and are found capping many sections as the youngest volcanic rocks in the area. The absolute age of the youngest capping lavas has not yet been determined. However, field evidence does not support a sustained volcanic hiatus between rhyolitic AFT and basaltic-andesitic volcanism in the southern SMO.

LOCAL GEOLOGY AND STRATIGRAPHY

The Juchipila area in the southern SMO was initially chosen for study as the volcanic rocks are well exposed, laterally extensive and flat lying. The stratigraphic sequence we have established for the volcanic rocks exposed in the Juchipila, Tepechitlan, and Jalpa 1:50,000 quadrangles is outlined in Table 1 and described below. All stratigraphic names are used informally and were often derived from prominent topographic features close to the best exposure of each unit. More detailed descriptions of the area can be found in the theses of Krause (1984), Roesler (1987) and Montague (1992). Rhyolitic AFT comprise the dominant volume of the volcanic section. The AFT were erupted from at least two calderas, which the authors informally call the Juchipila and Jalpa calderas (Figure 2) as they are centered around the towns of Juchipila and Jalpa respectively. Fissure vents mapped by Roesler (1987) help delineate the boundaries of the Jalpa caldera. Subsequent to Oligocene volcanism the study area was extensively modified by extensional tectonism which now defines the physiography of the region. The fault-bounded Rio Juchipila valley is bordered by two north-northeast trending major ridges, the Sierra de Morones on the west, and the Sierra de Nochistlan on the east (Figure 2). The elevation in the area ranges from 1200 m in the valley to over 2600 m in the sierras. Much of the central portion of the Rio Juchipila valley is covered with up to 200 m of late Miocene/early Pliocene volcaniclastic and carbonate lacustrine sediments which were deposited in a caldera lake developed after the formation of the Juchipila caldera (Lopez, 1991; Krause, 1984; Lahiere, 1982).

Lower Volcanic Complex (Eocene) Series Rocks

The oldest rocks found in the study area belong to the Lower Volcanic Complex of McDowell and Clabaugh (1979) and consist of predominantly intermediate composition lava flows. A single K-Ar age determination obtained from a porphyritic basaltic andesite (#BFA, feldspar separate) gives an age of 48.1 ± 2.6 Ma. Rocks belonging to this sequence are only found in the most deeply dissected valleys of the Sierra de Morones. A package of red sandstones and conglomerates up to 200 m thick and composed almost entirely of andesitic composition lithic fragments unconformably overlie the lava flows (Roesler, 1987). This location extends the known Eocene occurrences of volcanic rocks of Aguirre-Diaz and McDowell (1991) to the southern SMO.

Lower Basalt-Basaltic Andesite Series

Aphanitic high-K basalts and basaltic andesites are found in several locations at the base of the section in the Sierra de Nochistlan. The nature of the lower contact between this series and older rocks is not known, but they are overlain by rhyolitic AFT. A single whole-rock K-Ar age determination of 23.7 ± 1.4 Ma was obtained from #FM291.

Rhyolitic Ash-Flow Tuff Series

Eight rhyolitic AFT units which correlate across the Sierra de Morones and the Sierra de Nochistlan have been identified and informally named. Subdivisions have been made based on field aspects of the units and their mineralogy. Zircon fission-track dates from four of the AFT are presented in Table 1, along with their sample numbers and field coordinates, and demonstrate the relatively short time period in which the bulk of the rhyolitic sequence was emplaced. The thickest AFT are the San Miguel, Boquillas and Los Indios Tuffs.

The San Miguel Tuff is up to 50 m thick and consists of a series of poorly-welded AFT, air-fall tuffs, and reworked volcaniclastic sediments. The eruption of this unit marked the beginnings of voluminous rhyolitic volcanism in the Juchipila area and effectively blanketed much of the area. Graded bedding and cross bedding is present in several locations.

The widespread Boquillas Tuff directly overlies the San Miguel Tuff. It is a composite AFT consisting of a lower poorly to moderately welded zone and a middle moderately to densely welded zone, both characterized by red lithic fragments, and an upper moderately to densely welded zone characterized by abundant lithophysal cavities. The pheno-

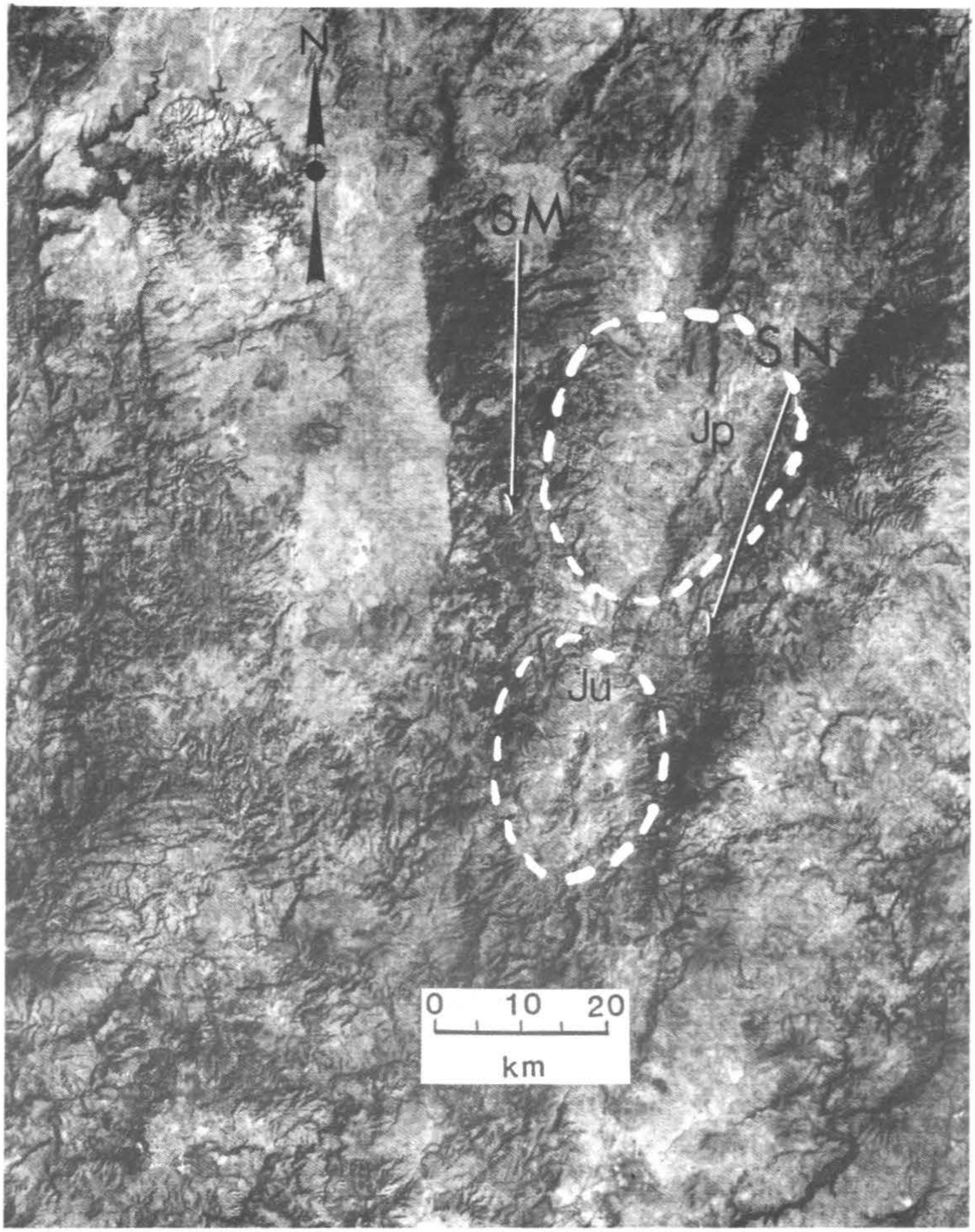

Fig. 2. Satellite image of the study area shows the extent of the Sierra de Morones (SM) and the Sierra de Nochistlan (SN). The towns of Juchipila (21°24'32"N; 103°07'08" W) and Jalpa (21°38'00"N; 102°58'40"W) are located between the SM and SN and are indicated with Ju and Jp respectively. The probable limits of the proposed Juchipila (southern) and Jalpa (northern) calderas are shown in white.

cryst-poor Boquillas Tuff, with a composite thickness of over 100 m, was erupted from the Jalpa Caldera.

The Yellow Tuff Member of the Los Indios Tuff is comprised predominantly of horizontally-bedded air-fall tuffs up to 100 m thick which were erupted prior to the caldera-forming eruption of the Los Indios Tuff from the Juchipila Caldera. Small anorthoclase crystals characterize the Yellow Tuff Member. A sharp contact exists between the Yellow Tuff and the overlying Los Indios Tuff. The Los Indios Tuff is the thickest and most extensive AFT found in the study area and reaches a maximum thickness of over 150 m in the Sierra de Morones west of Juchipila. It is characterized mineralogically by pheno-

Table 1

Volcanic stratigraphy of the Juchipila region

Stratigraphic Unit	Unit No.	Fission Track Age (Ma)	K-Ar Age (Ma)	Sample No.	Coordinates
Upper Basalts-Andesites	12				
Presa Los Luna Tuff	11				
Cerro Caballos Tuff	10				
Los Indios Tuff	9	25.9 ± 2.5		LP476	21° 30' 47" N 103° 00' 36" W
Yellow Tuff Member	8	25.3 ± 2.4		HR467	21° 30' 08" N 103° 11' 05" W
Mesa Galena Tuff	7	24.9 ± 2.7		HR460	21° 30' 21" N 103° 10' 04" W
Las Presas Tuff	6				
Mesa La Laguna Tuff	5				
Boquillas Tuff	4				
San Miguel Tuff	3	25.2 ± 2.2		BQ483	21° 27' 23" N 103° 02' 19" W
Lower Basalts-Basaltic Andesites	2		23.7 ± 1.4	FM291	21° 26' 38" N 103° 01' 30" W
unconformity					
Lower Volcanic Complex	1		48.1 ± 2.6	BFA	21° 39' 04" N 103° 09' 03" W

Fission track age determinations based on 6 zircons per sample; 800-1000 counted tracks per sample; decay constant of 7.03×10^{-17} yr^{-1}; 2σ standard deviation. Analyses performed by C. W. Naeser, U.S.G.S. Constants used for K-Ar age determinations are: $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; $\lambda_{\varepsilon+\varepsilon'} = 0.581 \times 10^{-10}$ yr^{-1}; $^{40}K/K = 1.193 \times 10^{-4}$g/g. Whole rock powder used for FM291(3 analyses); avg. %K = .925; avg. $^{40*}Ar$, ppm = .001533; ^{40}K, ppm = 1.104. Plagioclase separate used for BFA (3 analyses); avg. %K = .585; avg. $^{40*}Ar$, ppm = .001975; ^{40}K, ppm = .698. Analyses performed by Geochron Laboratories.

crysts of anorthoclase to sodic sanidine, many of which have barium-rich corroded cores (up to 14% celsian component).

Upper Basalt-Andesite Series

Lava flows from this series have been found intercalated with the Los Indios, Cerro Caballos and Presa Los Luna Tuffs and are found capping the volcanic sequence in numerous locations. No absolute age determinations are available for the lava flows of this series.

GEOCHEMISTRY

Representative whole-rock chemical analyses of samples from the Juchipila volcanic sequence can be found in Table 2. Major element abundances were determined by XRF techniques using pressed powder pellets. Trace element abundances were determined by both XRF and INAA techniques. The data from Table 2 along with additional analyses from Krause (1984), Montague (1992) and Roesler (1987) are plotted on silica variation diagrams for major elements (Figure 3) and trace elements (Figure 4). Samples from the moderate-K Batopilas location in the northern SMO (Cameron and Hanson, 1982) and the high-K Sierra el Virulento location in the CBR (Moll, 1981) are shown for comparison.

According to the International Union of Geological Sciences (IUGS) classification (LeBas *et al.*, 1986) Juchipila lava flows range from basaltic to andesitic in composition, and several can be classified as trachybasalts and basaltic trachyandesites (Figure 5). Most Juchipila AFT are classified as rhyolites, and a few can be classified as trachydacites. The Juchipila sequence can be characterized as high-K according to the classification of Ewart (1982) and calc-alkaline with an alkali-lime index of 58.5. All samples are peraluminous.

Major elements define a fairly continuous trend on variation diagrams (Figure 3) among the rhyolitic AFT and between the AFT and the majority of samples from the Upper Basalt-Andesite Series. Samples from the Lower Volcanic Complex and the Lower Basalt-Basaltic Andesite

Table 2

Representative chemical analyses of Oligocene-Eocene Southern Sierra Madre Occidental rocks

Series	Mid-Tertiary Ash Flow Tuffs											Upper Bas-Andesite		Lower B-B.A.		Eocene Volcanics**		
Sample #	TA138	BQ483	LP79	LP477	LI386	HR460	LA376	HR467	LP476	LI414	BQ52*	SR170	JAL11**	LP66	FM291	BFA	MIL2	PAD2
Strat Unit	3	3	4	6	6	7	7	8	9	9	10	12	12	2	2	1	1	1
SiO2	68.53	71.06	74.32	76.27	74.88	73.61	73.51	72.11	73.92	73.80	70.21	55.83	56.70	51.54	47.93	53.11	54.93	61.96
TiO2	0.32	0.23	0.16	0.15	0.21	0.14	0.15	0.13	0.11	0.11	0.47	1.01	0.96	2.07	1.32	1.48	1.11	1.06
Al2O3	14.52	15.20	12.83	11.79	12.44	13.59	13.56	14.41	13.35	13.37	15.12	17.83	17.30	17.71	18.43	18.41	16.66	15.77
FeO*	4.60	2.29	2.07	1.53	2.03	1.68	1.84	1.90	1.65	1.57	2.37	6.41	6.55	7.82	9.06	7.41	8.54	6.88
MnO	0.13	0.06	0.03	0.06	0.03	0.05	0.03	0.04	0.04	0.05	0.05	0.15	0.11	0.19	0.20	0.11	0.13	0.14
MgO	0.26	0.77	0.42	0.17	0.42	0.42	0.17	0.16	0.35	0.28	0.39	4.19	4.20	3.54	7.04	2.21	4.84	1.49
CaO	0.95	1.08	0.45	0.47	1.11	0.92	0.99	0.27	0.58	0.49	1.26	7.59	7.64	6.63	9.03	7.00	7.22	3.37
Na2O	3.55	2.90	3.22	3.07	2.30	3.47	3.63	2.78	3.18	4.13	3.61	3.08	3.30	3.63	3.04	3.03	2.99	4.09
K2O	6.50	4.54	4.93	5.45	5.41	5.19	5.24	5.78	5.50	5.27	5.19	1.56	1.60	3.38	1.28	3.23	1.69	2.77
P2O5	0.09	0.06	0.05	0.03	0.03	0.02	0.02	0.01	0.02	0.02	0.08	0.23	0.23	1.17	0.62	0.35	0.22	0.32
Total	99.45	98.19	98.48	98.99	98.86	99.09	99.14	97.59	98.70	99.09	98.75	97.88	98.59	97.68	97.95	96.34	98.33	97.85
Zr (XRF)	572	287	268	235	300	188	203	273	278	273	300	126	143	322	135	275	149	211
Y	59	93	117	292	243	39	61	74	95	111	46	24	21	20	24	65	36	64
Sr	141	60	32	16	74	95	93	25	39	28	176	741	664	826	660	401	337	254
Rb	128	189	173	327	318	165	169	203	184	188	179	18	21	84	26	134	50	96
Zn	91	101	86	110	141	45	78	73	76	71	67	85	77	84	78	83	100	134
La (INAA)	42	41	53	77	79	26	34	52	27	47	88	16	-	-	-	-	-	-
Ce	117	101	119	173	194	65	72	109	83	85	85	34	-	-	-	-	-	-
Nd	60.0	44.2	37.5	85.7	86.9	33.2	40.5	27.9	41.9	40.1	101.0	-	-	-	-	-	-	-
Sm	11.1	9.3	12.0	17.4	17.8	4.7	7.3	6.7	6.4	9.5	14.5	4.9	-	-	-	-	-	-
Eu	4.1	1.0	1.1	0.2	0.8	0.8	0.9	0.9	0.8	1.0	2.6	1.6	-	-	-	-	-	-
Tb	2.0	1.7	2.1	2.5	2.5	1.2	1.6	1.2	1.0	1.5	0.8	1.6	-	-	-	-	-	-
Yb	4.4	4.4	5.3	7.4	6.7	3.2	4.7	4.5	3.9	5.1	6.2	2.0	-	-	-	-	-	-
Lu	1.1	1.0	1.2	1.4	1.4	0.7	1.0	1.1	0.9	1.1	1.0	0.2	-	-	-	-	-	-
Th	10.4	17.2	18.7	36.7	29.2	13.9	14.2	23.7	20.4	23.4	15.5	2.6	-	-	-	-	-	-
Hf	13.1	9.2	9.0	10.8	10.7	8.0	7.2	10.2	10.5	10.2	9.1	4.0	-	-	-	-	-	-
Cs	0.5	6.8	4.3	10.6	11.4	2.8	3.5	4.4	2.5	6.2	3.5	0.0	-	-	-	-	-	-
Sc	20.8	5.0	3.4	2.4	4.3	7.1	8.0	5.2	5.1	4.6	9.7	19.7	-	-	-	-	-	-
U	4.6	3.1	5.7	8.7	7.9	4.8	5.8	5.7	5.2	6.0	3.1	2.6	-	-	-	-	-	-
Ba	2086	218	449	301	317	649	711	879	906	753	1205	533	-	-	-	-	-	-

*Analysis from Montague (1992) **Analyses from Roesler (1987); Total Fe as FeO*; Major elements in wt%, trace elements in ppm. Estimated errors in XRF analyses are as follows, expressed as a percentage of the amount present: SiO2 (0.8%), TiO2 (2%), Al2O3 (2%), FeO* (0.9%), MnO (5%), MgO (3%), CaO (0.7%), Na2O (3%), K2O (0.6%), P2O5 (3%), Zr (4%), Y (10%), Sr (5%), Rb(8%), Zn (10%) after Nelson and Livieres (1986). Estimated errors in INAA analyses expressed as a percentage of the amount present are: La (7%), Ce (9%), Nd (18%), Sm (2%), Eu (6%), Tb (28%), Yb (17%), Lu (11%), Th (9%), Hf (6%), Cs (13%), Sc (6%), U (36%), Ba (6%) after Simmons et al. (1987)

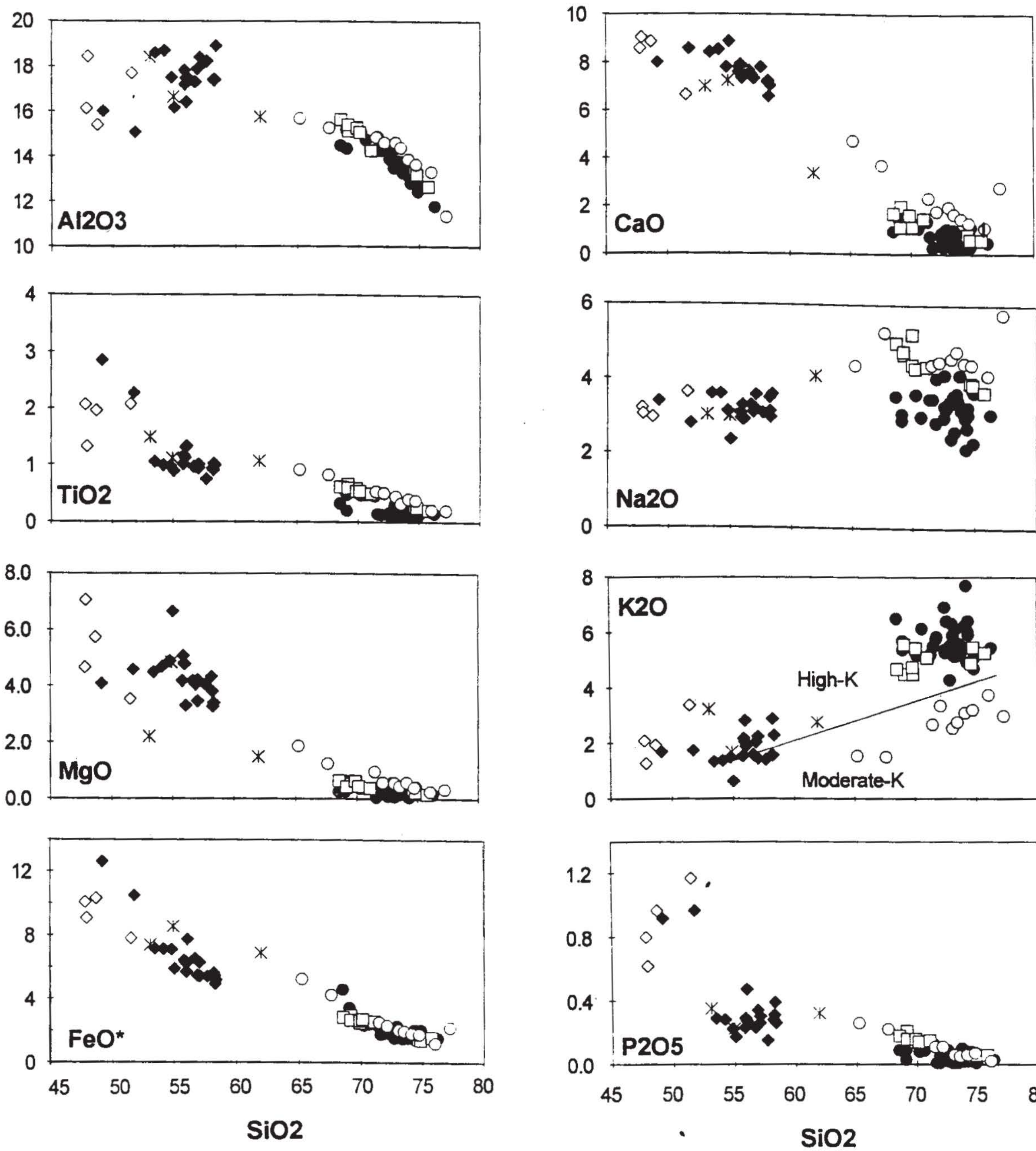

Fig. 3. Major element variation diagrams. Symbols are as follows: filled circles: Juchipila AFT, filled diamonds: Juchipila Upper Basalt-Andesite Series; open diamonds: Juchipila Lower Basalt-Basaltic Andesite Series; stars: Juchipila LVC series; open squares: Hi-K CBR samples from Moll (1981); open circles: Moderate-K Batopilas samples from Cameron and Hanson(1982).

Series typically diverge from this trend. Trace-element patterns (Figure 4) show much more variation among the AFT and the Upper Basalt-Andesite Series themselves suggesting several differentiation schemes may be necessary to explain the variation. The Ba/Rb ratio vs. Rb abundance (ppm) for AFT and the youngest lavas of Unit 12 is shown in Figure 6. The variation among the lavas with respect to SiO_2 is small compared to the variation displayed in their Ba/Rb ratios. This suggests that processes other than fractional crystallization, such as crustal assimilation, are necessary to explain the variation among these lavas and AFT (Davidson *et al.*, 1988).

A geochemical comparison between Juchipila AFT, moderate-K Batopilas AFT and high-K CBR clearly indicates a closer similarity between Juchipila and CBR AFT.

REE abundances for nine of the stratigraphic units are displayed in Figure 7. All rhyolitic AFT display strong

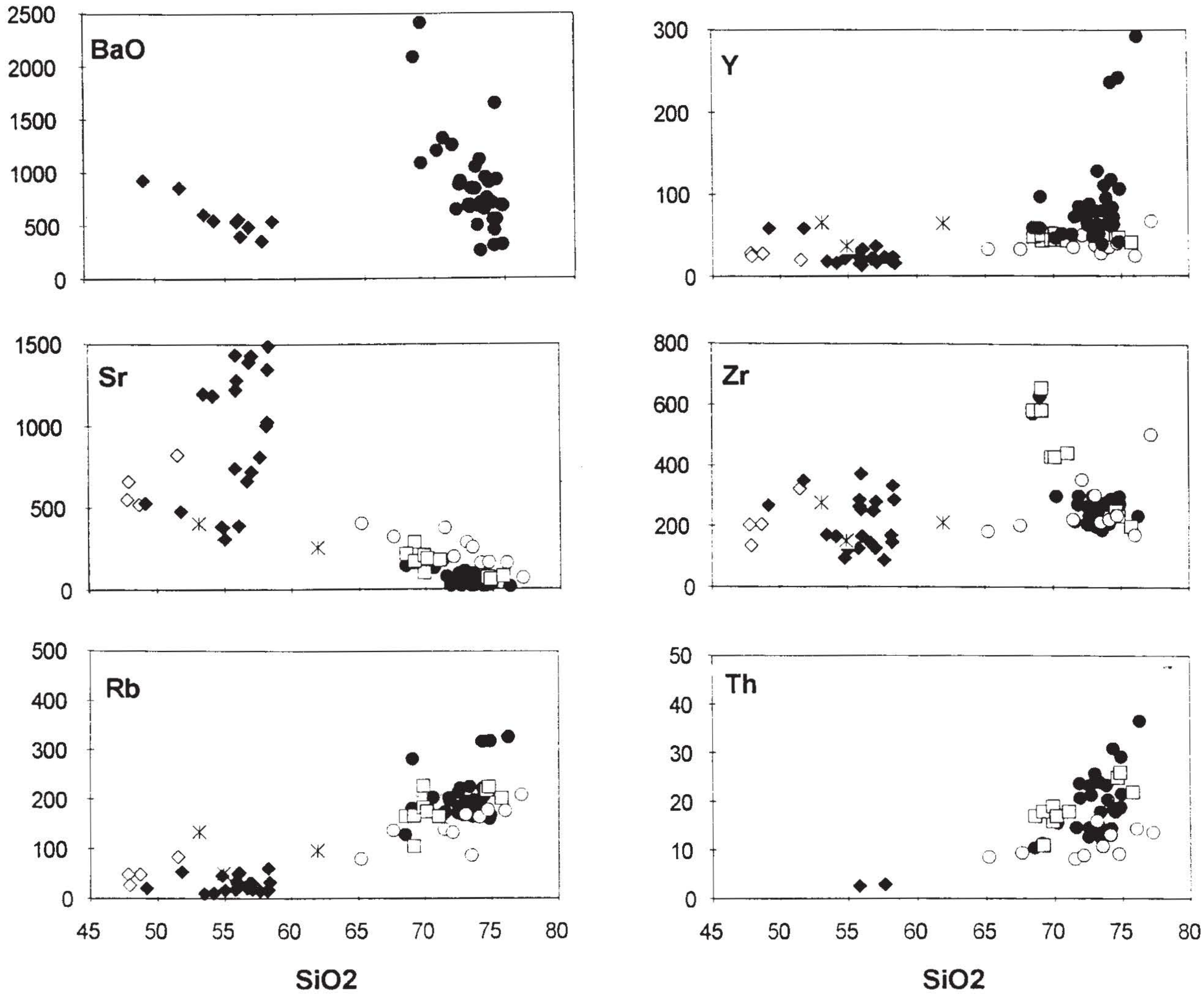

Fig. 4. Trace element variation di ;rams. Symbols as in Fig. 3.

negative Eu anomalies with the exception of #10-BQ52.This sample is from the Cerro Caballos Tuff which is characterized mineralogically as a plagioclase–only AFT (no kspar). Samples from Units 2 and 12 (mafic lava flows) also display no significant Eu anomaly. Sample #6-LI386 from the Las Presas Tuff has the highest overall concentration of REE. This AFT (2 fspr plus quartz) unit is also characterized by high Zr and Y concentrations. Overall the AFT are LREE enriched with LREE concentrations ~150-200 times chondrite and HREE concentrations ~25-30 times chondrite.

MINERALOGY

The basalt and andesite lava flows from Units 2 and 12 are aphanitic and contain small microphenocrysts of plagioclase, clinopyroxene +/- olivine. Phenocrysts are typically altered and plagioclase is often resorbed.

Juchipila AFT are phenocryst poor and typically contain less than 20% phenocrysts. The dominant phenocryst in all the tuffs is feldspar, accounting for over 80-90% of the phenocryst total. Subordinate mineral phases include Fe-Ti oxides, quartz, and trace amounts of pyroxene. The Las Presas, Mesa Galena and Presa Los Luna Tuff are two feldspar rhyolites with both sanidine (Or_{60} to Or_{70}) and oligoclase/andesine (An_{20} to An_{42}), along with small amounts of quartz. No other AFT contain more than a trace amount of quartz. The Cerro Caballos Tuff contains only andesine plagioclase (no kspar or quartz) ranging in composition from An_{32} to An_{45}.

The Los Indios Tuff is mineralogically the most unusual AFT in the entire Juchipila sequence. It contains only alkali feldspar that ranges in composition from sanidine to anorthoclase (Or_{58} to Or_{20}) with .5% to 4.0% celsian. In hand specimen many (30-50%) of the phenocrysts can be seen to have a white cloudy core surrounded by a clear rim. Microprobe analyses reveal that many of the anorthoclase phenocrysts have corroded cores with up to 14% celsian component, the highest barium content ever reported for rhyolitic peraluminous AFT. Grains with cor-

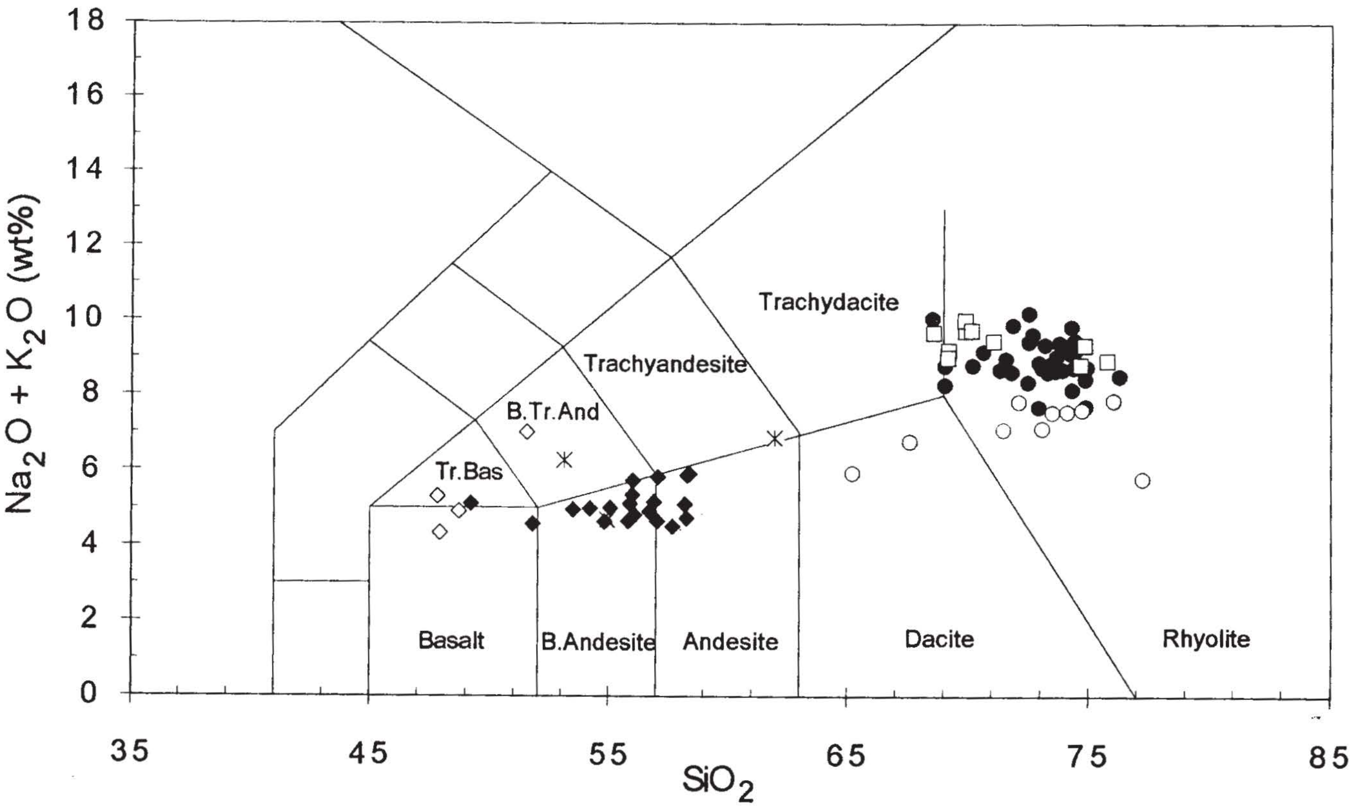

Fig. 5. IUGS chemical classification of SMO volcanic rocks. After LeBas *et al.* (1986). Symbols as in Fig. 3.

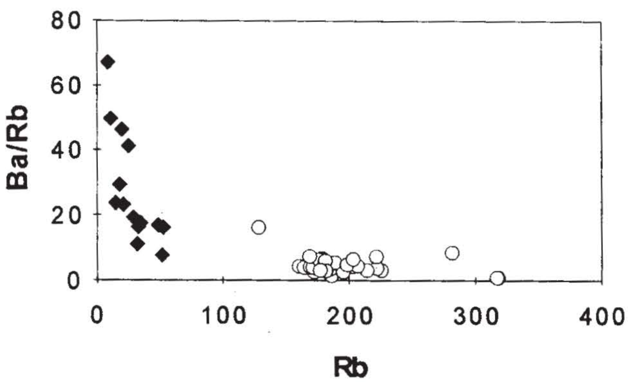

Fig. 6. Ba/Rb vs. Rb for Juchipila AFT (open circles) and Upper Basalt-Andesites (filled diamonds).

roded Ba-rich cores are surrounded by non-corroded Ba-poor rims. Additionally the phenocrysts are often complexly zoned, appear strained and some show perthitic blebs. Tenary An-Ab-Or and Cn-Ab-Or compositions for feldspars from the Los Indios Tuff can be found in Figure 8. Figures 9 and 10 are SEM images of two alkali feldspar grain with well developed cores. The grain in Figure 9 is not strongly corroded but displays sector zoning. The grain in Figure 10 shows a strongly corroded core. Most grains with Ba-rich cores show a core-to-rim increase in Na and Ca and a decrease in K and Ba. The disequilibrium textures and the sharp contrast in Ba between cores and rims suggest that the cores are xenocrystic in origin and record two distinct equilibration sites.

SUMMARY

The high-K calc-alkaline Juchipila Volcanic Sequence records both Eocene and Oligocene volcanic activity. This extends the known locations of Eocene volcanism to the southern SMO. Oligocene volcanic activity in Juchipila is on average younger than that reported for other areas in the SMO (Aguirre-Diaz and McDowell, 1991) north of Juchipila, suggesting a younging to the south of volcanic activity. The entire 1 km thick Juchipila AFT package was erupted in a very short period of time and no significant break is apparent between the transition from rhyolitic to andesitic volcanism. The close proximity of our study area to the TMVB to the south suggests that a very different tectonic regime may have been operating in the southern SMO. The petrogenetic relationship between the AFT and the younger mafic lavas, which may be related to the SCORBA suite of Cameron *et al.* (1989), is not clear.

Juchipila AFT are on strike with the moderate-K AFT sequence of Batopilas in the northern SMO (Cameron and Hanson, 1982) with respect to the former position of the mid-Tertiary convergent margin. However, the two sequences are geochemically and mineralogically quite distinct, particularly with respect to trace-element concentrations. Juchipila AFT are much more similar to the high-K AFT of the CBR (Moll, 1981). Much of this difference may be due to the fact that the Juchipila sequence was erupted through the Tahue tectonostratigraphic terrane, which is different from the crust that underlies Batopilas and the CBR (Sedlock *et al.*, 1993). However, differences

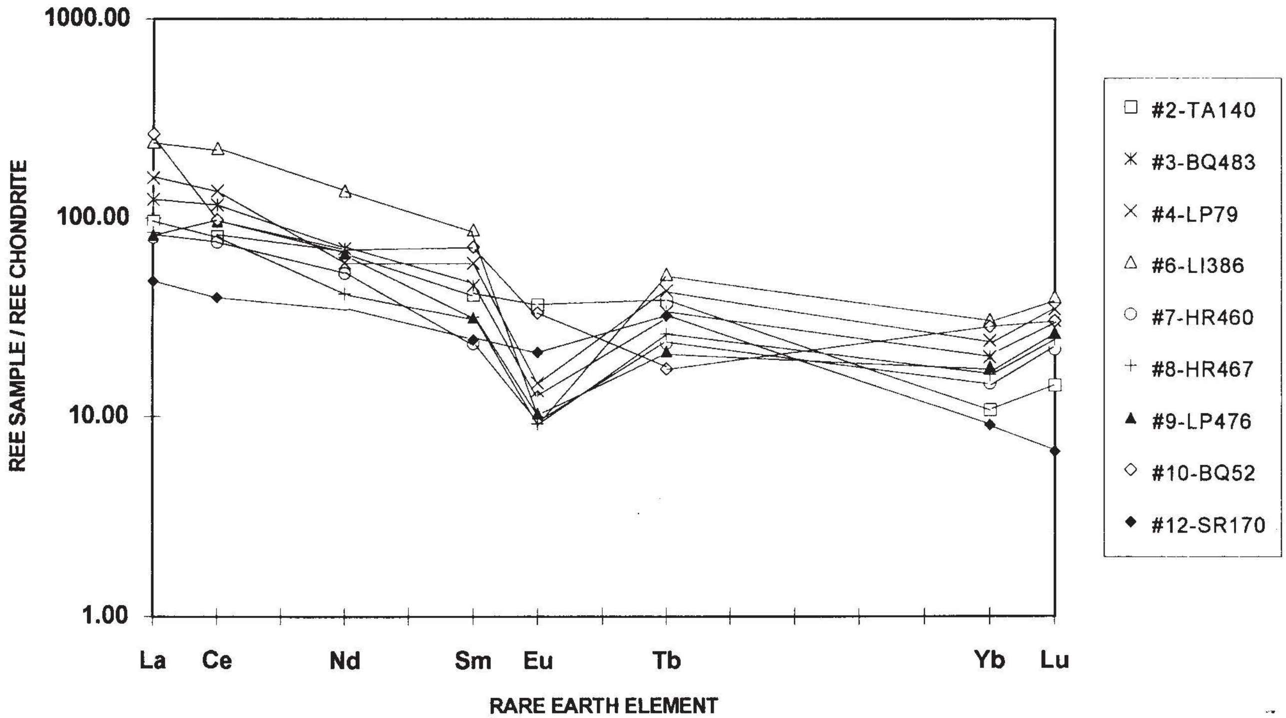

Fig. 7. Rare-earth-element patterns for 9 of the Juchipila stratigraphic units. The legend lists all the sample numbers and their corresponding stratigraphic unit (Table 1). All analyses were normalized to the chondrite values of Nakamura (1974).

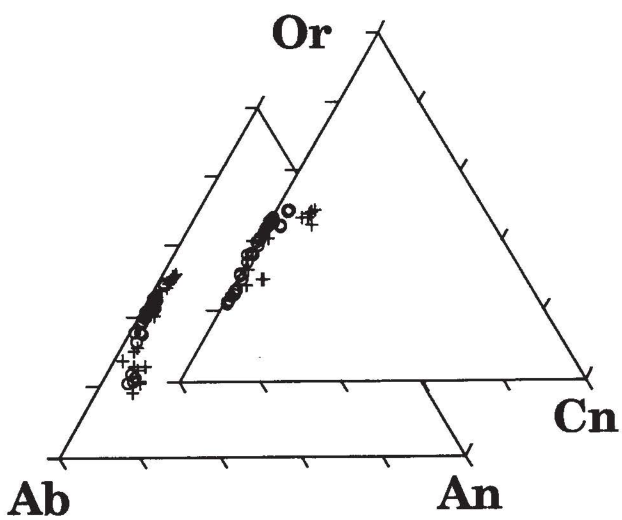

Fig. 8. Ternary Ab-Or-An and Ab-Or-Cn diagrams for alkali feldspar from the Los Indios Tuff (Unit #9). Crosses correspond to core analyses and circles correspond to rim analyses. The highest Cn contents are found in grains with corroded cores.

between the amount of magma-crust interaction are probably just as important (Hildreth and Moorbath, 1988). According to Cameron *et al.* (1986) Batopilas rhyolites can be generated by closed-system fractional crystallization with only a very small crustal component. Trace element data for Juchipila samples, particularly Ba/Rb vs. Rb, strongly suggest that crustal contamination played an important role in the generation of the Juchipila sequence. Additionally, anorthoclase phenocrysts which characterize the most voluminous Juchipila AFT show evidence for disequilibrium in the form of corroded Ba-rich cores surrounded by non-corroded Ba-poor rims. These textural and chemical distinctions are strong evidence that the cores are xenocrystic. They probably represent grains which equilibrated in the lower crust and were incorporated into the melt during partial melting, and subsequently emplaced into a lower pressure and temperature regime. The phenocrysts responded first by reaction with the melt becoming partially resorbed. The partially resorbed and corroded crystals formed nuclei for subsequent overgrowth of a second generation of alkali feldspar which now mantles the corroded cores. Further work including isotopic analyses is now under way which we hope will further elucidate the origin of these xenocrysts and the role of the lower crust in the evolution of the Juchipila magmas.

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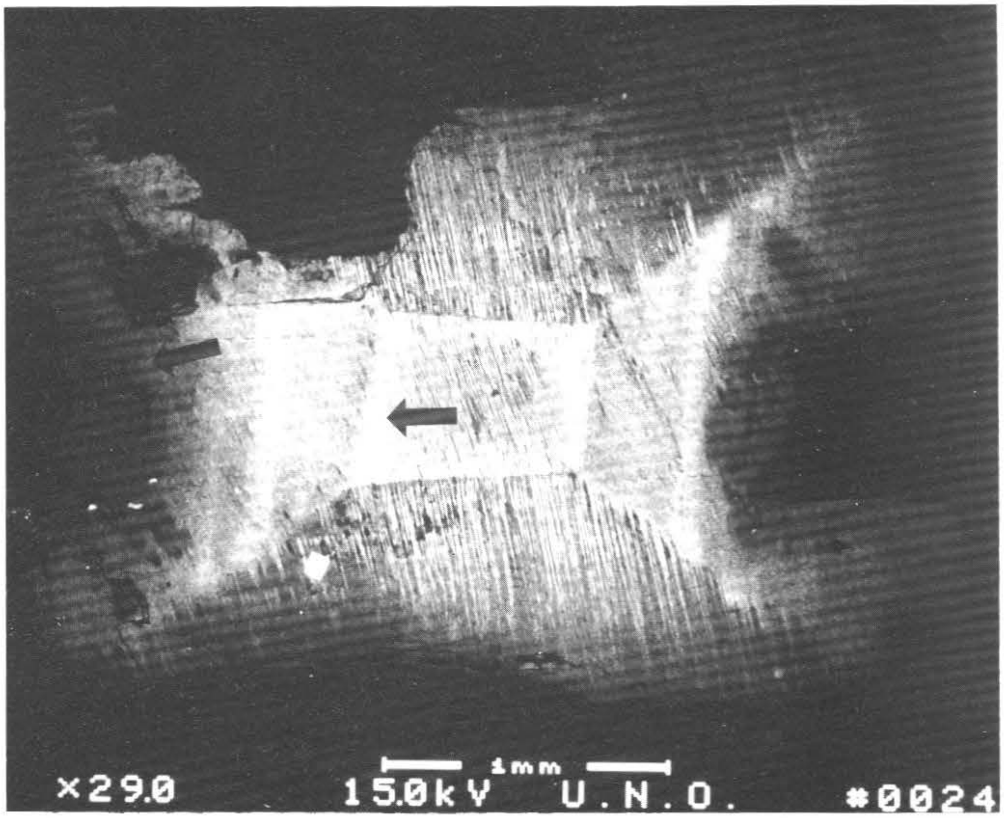

Fig. 9. SEM photograph of alkali feldspar grain from the Los Indios Tuff (Unit #9) which displays well developed sector zoning adjacent to the core. Arrows show the locations of the following core and rim compositions : Core: $(K_{.286}\ Na_{.679}\ Ba_{.026}\ Ca_{.082}\ Fe_{.006})_{\Sigma 1.073}\ Al_{1.087}\ Si_{2.886}\ O_{8.000}$. Rim: $(K_{.444}\ Na_{.555}\ Ba_{.009}\ Ca_{.021}\ Fe_{.004})_{\Sigma 1.029}\ Al_{.995}\ Si_{2.985}\ O_{8.000}$

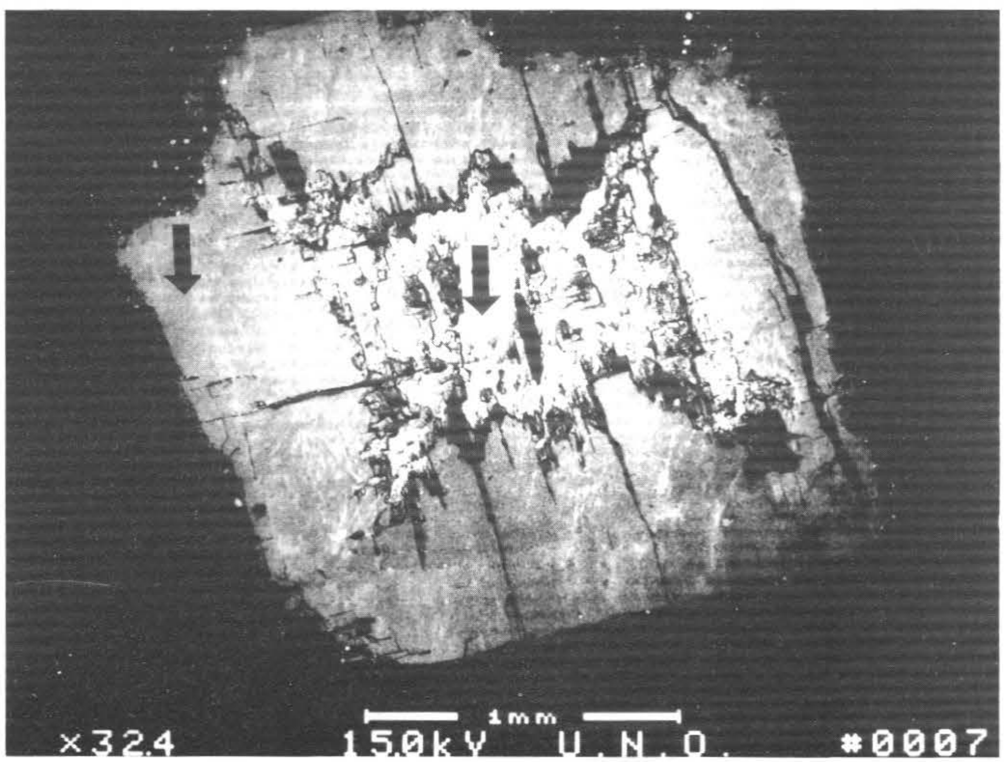

Fig. 10. SEM photograph of alkali feldspar grain from the Los Indios Tuff (Unit #9) which displays a very corroded Ba-rich core. Arrows show the locations of the following core and rim compositions: Core: $(K_{.765}\ Na_{.135}\ Ba_{.157}\ Ca_{.005}\ Fe_{.000})_{\Sigma 1.062}\ Al_{1.105}\ Si_{2.865}\ O_{8.000}$. Rim: $(K_{.287}\ Na_{.688}\ Ba_{.021}\ Ca_{.057}\ Fe_{.003})\ S_{1.052}\ Al_{1.060}\ Si_{2.920}\ O_{8.000}$

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