Geof. Int., Vol. 26-1, 1987, pp.29-84.

A SYNTHESIS AND COMPARISON OF THE GEOCHEMISTRY OF VOLCANIC ROCKS OF THE SIERRA MADRE OCCIDENTAL AND MEXICAN VOLCANIC BELT

M. CAMERON*
K. SPAULDING*
K. L. CAMERON**

RESUMEN

Las rocas volcánicas del Cenozoico al Reciente en la parte continental de México están confinadas principalmente en tres provincias geológicas: la Sierra Madre Occidental (SMO), el Cinturón Volcánico Mexicano (CVM) y la provincia alcalina oriental. Las dos primeras provincias están dominadas por series de rocas calci-alcalinas, pero también se encuentran rocas alcalinas contemporáneas. La tercera provincia está compuesta en su mayor parte por rocas volcánicas alcalinas.

La comparación entre las dos provincias calci-alcalinas revela que cada una tiene características diferentes. Las rocas volcánicas del Terciario Medio de la SMO están constituidas principalmente por ignimbritas riolíticas, mientras que el CVM se caracteriza por centros neovolcánicos prominentes cuya composición es primordialmente andesítica. Las andesitas calci-alcalinas del oeste del CVM (Ceboruco) tienen características químicas distintas de las andesitas del CVM central (Colima, Paricutín, Orizaba, Jorullo, Popocatépetl, Toluca). Las andesitas del Ceboruco tienen contenidos más altos de Na_2O+ K_2O, K_2O, Na_2O, TiO_2, P_2O_5, Ba, La y $(Ce/Yb)_N$, y más bajos de CaO, MgO, Cr y Ba/La que las andesitas del CVM central. Las andesitas del norte de la SMO (área de Batopilas y de la parte central del CVM tienen álcalis totales similares, K_2O, Na_2O, CaO, Sr, Zr y $(Ce/Yb)_N$. Las andesitas de la

* *School of Geology & Geophysics, University of Oklahoma, Norman, Oklahoma 73019, U.S.A.*
** *University of California at Santa Cruz, California, 95064, U.S.A.*

SMO tienen también contenidos más bajos de MgO y K/Rb, y más altos de FeO*, TiO_2, Rb, Th, La y Y que las rocas calci-alcalinas de la parte central del CVM. Las proporciones isotópicas iniciales de Sr de las rocas volcánicas del CVM composicionalmente intermedias están restringidas al rango 0.7035 - 0.7047, mientras que los contenidos de Sr_I de las rocas volcánicas félsicas intermedias de la SMO fluctúan entre 0.7033 y 0.7614. Tales proporciones indican interacción significativa de magmas primarios con la corteza radiogénica anterior para las rocas volcánicas de la SMO, pero relativamente menor interacción, si acaso hubo alguna, con magmas primarios de las rocas volcánicas del CVM. Los pocos datos isotópicos de Nd disponibles para las rocas volcánicas calci-alcalinas del CVM (Colima, Los Humeros, Paricutín y La Primavera) generalmente tienen ϵ_{Nd} mayores que la tierra total (hasta +5 y +6). Las rocas volcánicas del norte de la SMO (área de Batopilas) y el sureste de Chihuahua tienen ϵ_{Nd} hasta ± 2.5 unidades de Tierra total.

La evolución de las secuencias rocosas en centros eruptivos individuales parece haber estado determinada principalmente por fraccionación cristalina. Otros procesos simultáneamente operativos pueden incluir mezcla de magmas y asimilación por la corteza (la última, especialmente en la SMO). La naturaleza de las regiones de procedencia para los magmas primarios de las rocas volcánicas tanto en el CVM como en las áreas de la SMO y la provincia oriental no ha sido todavía tratada en forma global.

ABSTRACT

The Cenozoic-Recent volcanic rocks of mainland Mexico are largely confined to three provinces: the Sierra Madre Occidental (SMO), the Trans-Mexican Volcanic Belt (MVB), and the Eastern Alkalic province. The first two provinces are dominated by calc-alkalic rock series, but minor amounts of contemporaneous alkaline rocks are also present. The third province is comprised largely of alkaline volcanics.

Comparison of the two calc-alkalic provinces reveals that each has distinct characteristics. The mid-Tertiary SMO volcanics are comprised largely of rhyolitic ignimbrites whereas the MVB is characterized by prominent neovolcanic centers that are primarily andesitic in composition. Calc-alkalic andesites from the western MVB (e.g., Ceboruco) have chemical characteristics that are distinct from andesites of the central MVB (e.g., Colima, Paricutín, Orizaba, Jorullo, Popocatépetl, Toluca). The andesites of Ceboruco have higher $Na_2O + K_2O$, K_2O, Na_2O, TiO_2, P_2O_5, Ba, La, and $(Ce/Yb)_N$ and lower CaO, MgO, Cr, and Ba/La than andesites of the central MVB. Calc-alkalic andesites from the northern SMO (Batopilas area) and from the central MVB have similar total alkalies, K_2O, Na_2O, CaO, Sr, Zr and $(Ce/Yb)_N$. The SMO andesites also have lower MgO and K/Rb and higher FeO*, TiO_2, Rb, Th, La, and Y than calc-alkalic rocks of the central MVB. Initial Sr isotopic ratios of compositionally-intermediate MVB volcanics are restricted to the range 0.7035 - 0.7047 whereas the intermediate-felsic volcanics of the SMO have Sr_I ranging between 0.7033 and 0.7614. Such ratios indicate significant interaction of parental magmas with old radiogenic crust for the SMO volcanics, but relatively minor, if any, interaction with magmas parental to the MVB volcanics. Limited Nd isotopic data for MVB calc-alkalic volcanics (Colima, Los Humeros, Paricutín, and La Primavera) generally have ϵ_{Nd} greater than Bulk Earth (up to +5 to +6). Volcanics of the northern SMO (Batopilas area) and southeastern Chihuahua have ϵ_{Nd} within ±2.5 units of Bulk Earth.

Evolution of the rock suites at individual eruptive centers appears to have been controlled largely by crystal fractionation. Other processes operative at the same time may include magma mixing and crustal assimilation (the latter especially in the SMO). The nature of the source regions for parental magmas of volcanics in both the MVB and SMO-SEC areas has yet to be addressed in a comprehensive manner.

INTRODUCTION

The Cenozoic-Recent volcanic rocks of mainland Mexico occur in three major provinces: (1) the Sierra Madre Occidental (SMO) of western Mexico, (2) the Alkalic province of eastern Mexico, and (3) the Trans-Mexican Volcanic Belt (MVB) of south-central Mexico. The Sierra Madre Occidental (Fig. 1) is a vast plateau 1 300 km in length that is capped by a 1-km volcanic section composed predominantly of Oligocene rhyolitic ignimbrites (McDowell and Clabaugh, 1979; K. Cameron *et al.*, 1980). In the northern SMO near the town of Batopilas this ignimbrite section is underlain by a poorly-dated ?Tertiary-Cretaceous volcano-plutonic complex (e.g., Bagby *et al.*, 1981). Both the mid-Tertiary and older rock sequences have calc-alkalic affinities, and were erupted when there was active subduction off the west coast of North America.

The Eastern volcanic province, which is located along the coastal plains of the Gulf of Mexico, includes isolated, Oligocene-Quaternary volcanic centers comprised predominantly of undersaturated mafic alkaline rocks (Bloomfield and Cepeda-Dávila, 1973; Cantagrel and Robin, 1979). The rocks were emplaced during a period of thinning and rifting of the continental crust, and were generated along a destructive plate margin (Robin and Demant, 1975; Robin, 1982; Thorpe, 1977).

The Trans-Mexican Volcanic Belt (MVB), which extends approximately 1 000 km across southern Mexico (Fig. 1), contains volcanic rocks ranging in age from Recent to Late Oligocene (e.g., see reviews of the geochronology in Verma, 1985 and Verma *et al.*, 1985). The prominent neovolcanic cones for which the area is well known are comprised dominantly of andesites and basaltic andesites whose origin has been related to various processes, but commonly to subduction of the Cocos (and Rivera?) plate beneath the North American plate (e.g., Gunn and Mooser, 1971; Demant and Robin, 1975; Pal and Urrutia-Fucugauchi, 1977; Robin and Nicolas, 1978; Demant, 1978; Nixon, 1982).

The main objectives of this paper are to synthesize and compare the data on petrology, geochemistry, and petrogenesis of calc-alkalic mid-Tertiary volcanics of the Sierra Madre Occidental and Quaternary volcanics of the Trans-Mexican Volcanic Belt. Brief discussions of associated alkaline rocks are also included for comparative purposes. Our discussion focuses on the mid-Tertiary ignimbrite sequence of the SMO and the Quaternary volcanic cones of the MVB because they appear to be the sequences/

Fig. 1. Generalized map of Mexico showing location of towns and geographic features mentioned in text. Key to abbreviations: BAT = Batopilas; BP = Benavides-Pozos; CEB = Ceboruco; CHI = Sierra Chichinautzin; CHX = Choix; COL = Colima; CR = Creel; CN = Calera del Nido; CUA = Cuauhtémoc; HUM = Los Humeros; JOR = Jorullo; LJ = La Junta; LP = La Perla; NAV = Navidad; OC = Ocampo; ORIZ = Orizaba; POP = Popocatépetl; PAR = Paricutín; PRI = La Primavera; SAN = Sangangüey; SC = Sierra los Cajones; SLP = San Luis Potosí; SV = Sierra el Virulento; TEP = Tepic; TER = Terlingua; TEQ = Tequila; TOL = Toluca; TV = Tres Vírgenes; TUX = Tuxtla; Y = Yahuirachic.

units studied in the most detail. Except for fO_2 data on Batopilas samples and mineralogical/geochemical analyses on the La Perla area in southeastern Chihuahua, all of the data presented are or will be published by the time this paper appears.

FIELD AND PETROLOGIC CHARACTERISTICS

Igneous rocks of the Sierra Madre Occidental (SMO) are informally divided into a ?Late Cretaceous/mid-Tertiary volcano-plutonic complex, a mid-Tertiary sequence that is dominantly rhyolitic ignimbrites, and a young series of mildly-alkaline basalts. Volcanics of the Trans-Mexican Belt (MVB) include both calc-alkalic and alkaline rocks that range in age from Recent to late Oligocene (e.g., Verma *et al.*, 1985).

Sierra Madre Occidental

The oldest unit exposed in the Sierra Madre Occidental forms a volcano-plutonic complex that crops out in the western portion of the sierras in the bottoms of deep barrancas. The volcanic rocks of this complex, referred to as the Lower Volcanic sequence (McDowell and Keizer, 1977; McDowell and Clabaugh, 1979) include volcaniclastic sediments, lajars, and pervasively-altered lavas of intermediate/felsic composition. In the Batopilas area of the northern SMO, the plutonic rocks include Late Cretaceous to mid-Tertiary granodiorites and quartz diorites (Bagby *et al.*, 1981). Overlying this volcano-plutonic complex is the mid-Tertiary Upper Volcanic sequence, which is predominantly rhyolitic ignimbrite with minor amounts of rhyolitic lavas. Interlayered lava flows of intermediate composition (andesites and dacites) constitute less than 10% by volume. The entire sequence is approximately one km thick, and its volume may total 296 000 km^3 (Swanson and McDowell, 1984). Published dates on this sequence are confined largely to the interval 35-27 m.y. (McDowell and Keizer, 1977; Swanson *et al.*, 1978; McDowell and Clabaugh, 1979; K. Cameron *et al.*, 1980; Swanson and McDowell, 1985). Overlying the Upper Volcanic sequence around the town of Batopilas in the northern SMO are isolated fields of mildly-alkaline basalt, one of which was dated at ~21 m.y. (Bagby, 1979). Basalts with similar chemistry and stratigraphic position occur throughout the state of Chihuahua (e.g., K. Cameron *et al.*, 1980; Keller *et al.*, 1982). Significantly younger Mio-Pliocene basaltic volcanics (?alkali-rich continental tholeiites) were also reported near the Chihuahua-Sonora border (Demant and Cocheme, 1983). To the east and northeast of the SMO proper, volcanics believed to be correlative with the Upper Volcanic supergroup crop out in the Basin and Range region of southeastern Chihuahua (SEC). These SEC volcanics are underlain by Cretaceous limestones, by Tertiary alkaline rocks, and by older volcanic rocks that may be correlative with the Lower Volcanic sequence of the SMO proper (Swanson and McDowell, 1984; Gunderson *et al.*, 1986). They are overlain by alkaline rocks (K. Cameron *et al.*, 1980; Gunderson *et al.*, 1986), and in some areas are intercalated with ferroaugite rhyolites (e.g., Campbell, 1977; K. Cameron *et al.*, 1980; Mauger, 1981).

Petrologic and geochemical characteristics of the Upper Volcanic sequence of the SMO proper are detailed in numerous publications (e.g., Gunn and Mooser, 1971; McDowell and Keizer, 1977; Swanson *et al.*, 1978; McDowell and Clabaugh, 1979; Capps, 1981; Megaw and McDowell, 1983; Keller *et al.*, 1982; K. Cameron *et al.*, 1980; M. Cameron *et al.*, 1980; Verma, 1984a; Huspeni *et al.*, 1984). In general, rocks of the Upper Volcanic supergroup lack significant Fe-enrichment and are calc-alkalic based on the guidelines established by Miyashiro (1978). Volcanics in the Batopilas area (axial portion of the SMO) are calcic according to Peacock's (1931) classification scheme. They have 2.7% K_2O at 68% SiO_2, and were described as a moderate-K calc-alkalic series by K. Cameron *et al.* (1980). Their characteristic phenocryst assemblage is plagioclase plus two pyroxenes. In the Batopilas area rhyolites with quartz and/or K-spar phenocrysts are uncommon, and only high-SiO_2 rhyolites (>75% SiO_2) contain biotite and/or hornblende. To the south, in the region between Mazatlán and Durango, the calc-alkalic rhyolites have other phenocryst assemblages. In the western portion of this region, plagioclase is the dominant phenocryst, whereas quartz, sanidine, and plagioclase are common phenocrysts in the calc alkalic rhyolites to the east near Durango (McDowell and Keizer, 1977, p. 1483).

Rocks of the southeastern Chihuahuan Basin and Range, which contain 4.7% K_2O at 68% SiO_2, were characterized as high-K calc-alkalic by K. Cameron *et al.* (1980). Characteristic phenocrysts in these high-K dacites and rhyolites include anorthoclase, clinopyroxene, orthopyroxene, biotite, and/or hornblende. These rocks are easily distinguished in thin section from geographically-associated ferroaugite rhyolites because the latter lack orthopyroxene and contain fayalite. The geographic extent of the moderate-K and high-K facies and the nature of the boundary between the two are not known.

Trans-Mexican Volcanic Belt

Volcanic rocks of the Trans-Mexican Volcanic Belt (MVB) considered in this paper are mostly those erupted at the neovolcanic centers. This group of volcanics comprises a broad east-west belt of ~10 - 15 major volcanic complexes and several thousand simple monogenetic cones (Robin, 1982) that can be divided geographically into three segments (e.g., Nixon, 1982). The westernmost segment, which includes eruptive centers at Ceboruco, Tequila, Tepic, and Sangangüey, extends from the Pacific coast southeastward to the Colima graben. The volcanic belt is ~60 km wide in this region, and the caldera complexes are comprised predominantly of calc-alkalic two-pyroxene andesite. Associated with some of these calc-alkalic centers are small volumes of contemporaneous alkaline magmas erupted from graben areas (e.g., Nelson and Carmichael, 1984; Allan and Carmichael, 1984). The characteristic phenocryst assemblage of calc-alkalic andesites from the western MVB is plagioclase + orthopyroxene + clinopyroxene (±olivine). The mineralogy of the alkaline rocks is variable, as discussed below.

The central segment of the MVB averages ~100 - 200 km in width, and includes the volcanic centers of Colima, Paricutín, Toluca, Popocatépetl, Jorullo, Orizaba, Primavera, and Los Humeros. The first five volcanoes listed delineate the main volcanic front, with Los Humeros and Primavera located in the back arc area. Rock types are dominantly calc-alkalic basaltic andesite and hornblende/pyroxene andesite, but more evolved and alkali-rich volcanics occur in the back-arc volcanic centers. The characteristic phenocryst assemblage of calc-alkalic andesites from the central MVB is plagioclase + orthopyroxene + amphibole (±olivine ±clinopyroxene). Alkaline rocks were also reported near Jorullo (Luhr and Carmichael, 1985).

The boundary between the western and central segments is the north-south-trending Colima graben, a zone of crustal extension that contains both calc-alkalic and alkalic volcanic rocks. At the southern end of the graben are Volcán Colima and Nevado de Colima, both of which are comprised predominantly of calc-alkalic hornblende andesite. Lavas or cinder cones associated with these volcanoes are comprised of mafic alkaline rocks that include lamprophyres (Allan and Carmichael, 1984) and basanites to minettes (Luhr and Carmichael, 1982). At the northern end of the graben is the La Primavera volcanic complex, a series of mildly-peralkaline rhyolitic domes and pyroclastics (Mahood, 1981a, b).

The third geographically-distinct segment of the MVB is actually part of the Eastern Alkaline province. It contains sodic alkaline rocks ranging in composition from picritic basalt to basanitoid to hawaiite (Thorpe, 1977; Cantagrel and Robin, 1978; Nixon, 1982). One of the best studied volcanic centers in this segment is San Martin Tuxtla, a low shield volcano 11 km in diameter (Pichler and Weyl, 1975; Thorpe, 1977; Robin and Tournon, 1978). The boundary between the central calc-alkalic zone and the eastern alkaline segment is a fault zone believed to represent the structural break between the mexican land mass and the Gulf of Mexico-Caribbean region (Robin, 1982).

Petrologic and geochemical characteristics of volcanics of the MVB are discussed in numerous publications that are cited in Table 1 and in the following sections. The articles by Robin (1982), Pal *et al.* (1978), Robin and Nicholas (1978), and Verma and M. P. Verma (1986) provide good overviews.

MINERALOGY

In this section we discuss variations in mineral chemistry of mid-Tertiary volcanics of the SMO-SEC and Quaternary volcanics of the MVB. Our compilations of data are generally taken only from studies that report numerous mineral analyses. Sources of data are either given in each figure or are listed in Table 1.

Table 1. Sources of data for major/trace element, Sr isotopic, and mineral chemical figures.

I. MINERAL CHEMISTRY (Fig. 2)	
Pyroxenes	
Ceboruco calc-alkalic	Nelson (1980)
Colima alkaline	Allan and Carmichael (1984) Luhr and Carmichael (1981)
Colima calc-alkalic	Luhr and Carmichael (1980) Luhr and Carmichael (1982)
Jorullo calc-alkalic	Luhr and Carmichael (1985)
Primavera alkaline	Mahood (1981b)
Sanganguey alkaline	Nelson and Carmichael (1984)
Batopilas calc-alkalic	M. Cameron *et al.* (1980)
SEC (=southeastern Chihuahua)	
BP (Benavides-Pozos):	Gunderson (1983)
SV (Sierra El Virulento):	Moll (1981)
LP (La Perla):	Spaulding (1985)
II. SR ISOTOPIC ANALYSES (Fig. 15)	
MVB-Western Zone	
CEBORUCO	Moorbath *et al.* (1978)
MVB-Colima Graben	
COLIMA	Moorbath *et al.* (1978) Carmichael and DePaolo (1980)
PRIMAVERA	Halliday *et al.* (1985)

(Cont. Tab. 1)

MVB-Central Zone	
CHICHINAUTZIN	Verma and Armienta-H. (1985)
HUMEROS	Verma (1983)
ORIZABA	Cantagrel and Robin (1978)
PARICUTIN	Reid (1983) Tilley *et al*. (1968)
TOLUCA	Whitford and Bloomfield (1976)
MVB-Eastern Zone	
TUXTLA	Moorbath *et al*. (1978)
SMO	
BATOPILAS	Lanphere et al. (1980) Cameron *et al*. (1985)
CALERA DEL NIDO	Spruill *et al*. (1981)
CREEL	Lanphere *et al*. (1980)
CUAUHTEMOC	McDowell et al. (1978) Duex (1983)
DURANGO-MAZATLAN	McDowell et al. (1978) Duex (1983)
NAVIDAD	Ruiz *et al*. (1985)
LA SALITERA	Ruiz *et al*. (1983b)
ZACATECAS	Verma (1984a)
SEC	
SOUTHEASTERN CHIHUAHUA	Gunderson et al. (1986) Cameron and Cameron (1985) Moll (1981)

III. MAJOR AND TRACE ELEMENT PLOTS (Figs. 4-14)

MVB-Western Zone	
CER (Ceboruco)	Nelson (1980) Demant (1979) Thorpe and Francis (1975)
SAN (Sanganguey)	Nelson and Carmichael (1984)
MVB-Colima Graben	
COLC (Colima calc-alkalic)	Luhr and Carmichael (1980) Luhr and Carmichael (1981)
COLA (Colima alkaline)	Luhr and Carmichael (1981) Luhr and Carmichael (1982) Allan and Carmichael (1984)
PRI	Mahood (1981b)

(Cont. Tab. 1)

MVB-Central Zone	
COLC (Colima calc-alkalic)	Luhr and Carmichael (1980) Luhr and Carmichael (1981)
JOR (Jorullo)	Luhr and Carmichael (1985)
PAR (Paricutin)	Wilcox (1954) Williams (1954)
ORIZ (Orizaba)	Robin (1982) Robin and Nicolas (1978)
POP (Popocatepetl)	Gunn and Mooser (1971) Robin and Nicolas (1978)
TOL (Toluca)	Cantagrel et al. (1981) Gunn and Mooser (1971) Robin (1982) Whitford and Bloomfield (1976)
ZLOS (Los Humeros)	Ferriz and Mahood (1984) Verma and Lopez (1982)
MVB-Eastern Zone	
TUX (Tuxtla)	Robin and Tournon (1978) Thorpe (1977)
SMO-SEC	
MK (moderate-K facies)	M. Cameron et al. (1980)
HK (high-K facies)	Cameron and Hanson (1982) K. Cameron et al. (1980) Gunderson et al. (1986)

Feldspars

Plagioclase in andesites of the moderate-K calc-alkalic suite of the Batopilas area in the SMO is mostly labradorite whereas that in the associated rhyolites ranges from sodic andesine to K-rich oligoclase (M. Cameron *et al.*, 1980). Feldspars in the high-K calc-alkalic rocks of SEC show larger compositional variations, and for any given rock type the SEC feldspars are generally more Na- and K-rich. The latter also contain anorthoclase and sanidine, mostly as rims and mantles on plagioclase. Limited data on dacites from the SMO and SEC areas indicate that plagioclase in the high-K dacites and rhyolites of SEC has an Or content significantly higher (~4 - 6% Or vs ~1 - 3% Or) than plagioclase of the moderate-K SMO volcanics (Gunderson, 1983; Moll, 1981; Spaulding, 1985).

Plagioclase in the alkali-rich calc-alkalic andesites of Ceboruco (western MVB) is more sodic than that in calc-alkalic andesites from V. Colima (central MVB). Typical compositions are labradorite to calcic andesine for Ceboruco and sodic bytownite to andesine for Colima (Nelson, 1980; Luhr and Carmichael, 1984). Or contents of plagioclase from Ceboruco and Colima are low, and are similar to values observed in the moderate-K SMO andesites. Feldspars from the alkaline cinder cones at V. Colima contain complex feldspar crystals with plagioclase cores, anorthoclase mantles, and sanidine rims (Luhr and Carmichael, 1984). The peralkaline comendites of Primavera contain alkali feldspars with compositions in the range Or_{45-60} (Mahood, 1981b).

Pyroxenes and Amphiboles

Variations in pyroxene compositions in the MVB and SMO-SEC rocks are shown in Figures 2a-d. Notable features in data for moderate-K calc-alkalic rocks from the Batopilas area (Fig. 2c) include the restricted compositional ranges, especially for clinopyroxenes, and the Mg-rich nature of pyroxenes in felsic rocks. These Mg-rich compositions presumably reflect relatively high oxygen fugacities. Pyroxenes from the high-K calc-alkalic facies of SEC (Fig. 2d; Sierra Virulento, Benavides-Pozos, and La Perla) show a greater range in Fe/Mg and Ca contents than do those of the moderate-K SMO rocks. Compositional variations similar to those of Sierra Virulento were reported by Campbell (1977) and Mauger (1981) for other SEC rocks. (Compositions of pyroxenes in andesites from SEC should be used with care because some of these rocks formed in part by magma mixing -- Gunderson, 1983).

Analyses of pyroxenes in rocks from the MVB volcanic centers are plotted in Figures 2a and 2b. Pyroxenes in andesites of V. Colima and basaltic andesites of Jorullo are slightly more Mg-rich than pyroxenes in andesites of the Batopilas area of the SMO, but all exhibit very limited compositional variations. In contrast, compositions of pyroxenes in alkali-rich andesites and dacites of Ceboruco (Nelson, 1980) are more variable with respect to both iron enrichment and Wo content. Pyroxenes in the comenditic rhyolites of La Primavera are hedenbergitic (Fig. 2b) whereas those from the mafic alkaline rocks at Colima, Sangangüey and Tuxtla are principally diopside/salite/Mg-augite with Wo contents distinctly higher than clinopyroxenes in the calc-alkalic andesites and dacites.

Calcic amphiboles are present in some of the more evolved calc-alkalic rocks of the SMO-SEC areas and in calc-alkalic andesites and basaltic andesites of the central MVB zone. Silica contents range from 41 - 44 % in hornblendes/basaltic hornblendes of Colima and Jorullo volcanics (Luhr and Carmichael, 1980; Luhr and Carmichael, 1985) to 45 - 46 % in magnesio-hornblende in rhyolites from the Batopilas area in the SMO (M. Cameron *et al.*, 1980) and edenite of rhyolites from Sierra Virulento and Benavides-Pozos areas of SEC (Moll, 1981; Gunderson *et al.*, 1986). The principal differences in amphibole compositions of the moderate-K SMO and high-K SEC rhyolites are the higher alkali content and Fe/Fe + Mg of the latter.

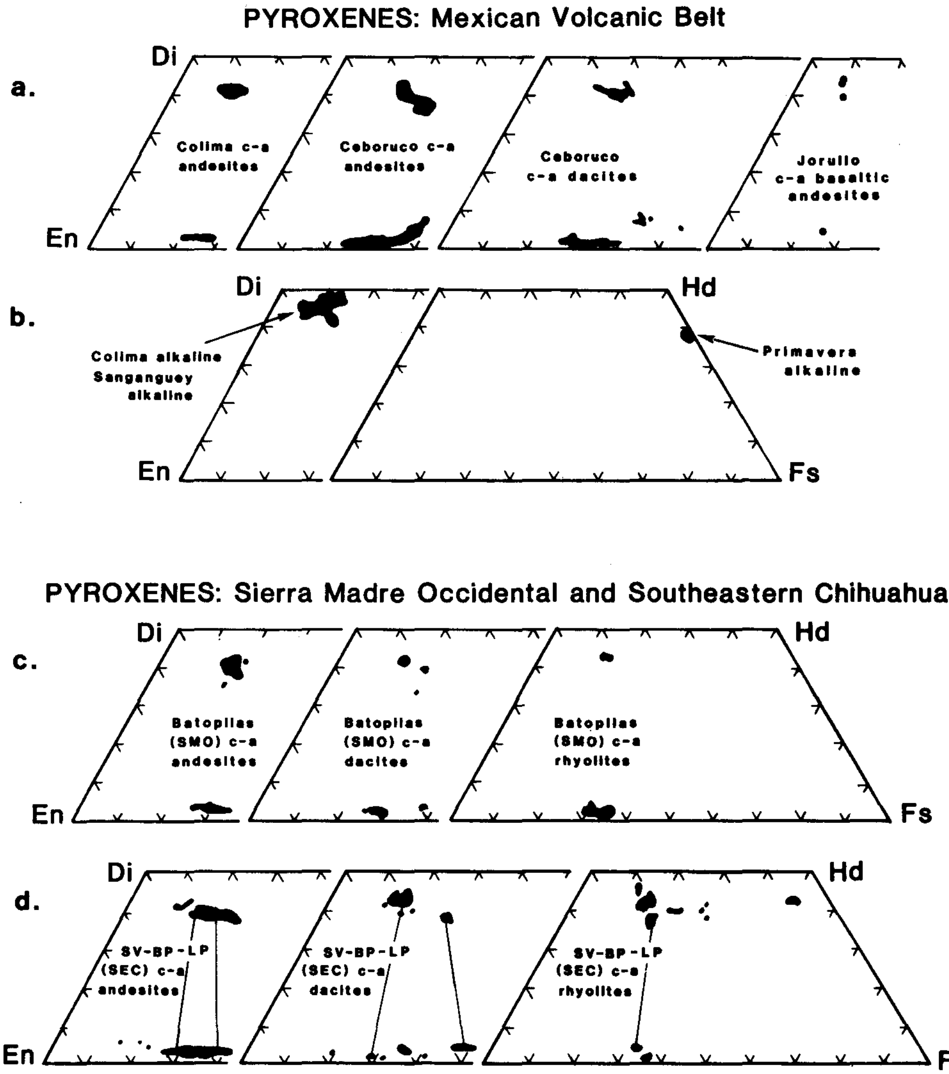


Fig. 2. Pyroxene compositions for: (A) calc-alkalic andesites and dacites of the MVB; (B) alkaline volcanics from the MVB; (C) moderate-K calc-alkalic rocks from the Upper Volcanic sequence of the SMO; and (D) high-K calc-alkalic rocks from SEC. Sources of data are listed in Table 1.

Fe-Ti Oxides

Temperature-oxygen fugacity relationships obtained by calculation and determined from compositions of FeTi oxides are shown in Figure 3. The T-fO_2 data for MVB volcanics represent a range in rock compositions, whereas those for the SMO and SEC are restricted to dacites and rhyolites. The SMO and SEC calc-alkalic rhyolites define a buffer curve between the Ni-NiO and HM buffers, with rhyolites of SEC

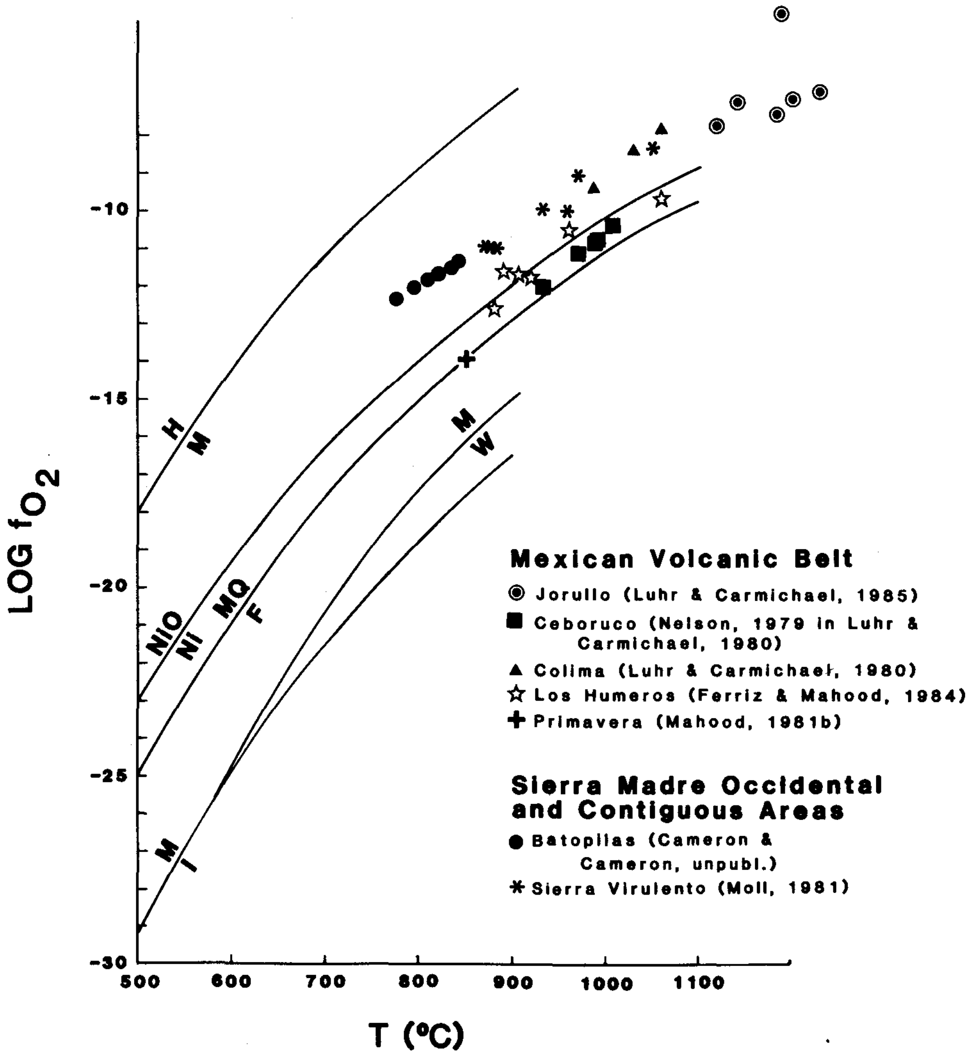


Fig. 3. Temperature-oxygen fugacity relationships obtained either by calculation or from compositions of Fe-Ti oxides. Sources of data are given in figure.

displaying slightly higher equilibration temperatures than rhyolites of the SMO (860°-890°C vs 775°-850°C). The SMO-SEC buffer curve(s) are similar to those reported by Ewart (1979, 1982) for silicic andesites, dacites, and rhyolites of the western United States and Alaska.

Temperature-oxygen fugacity data on four volcanic centers in the MVB are also shown in Figure 3. The post-caldera hornblende andesites of V. Colima define a buffer curve similar to that of the SMO-SEC volcanics whereas the post-caldera pyroxene andesites of Ceboruco appear to have equilibrated at lower oxygen fugacities, between the Ni-NiO and MQF buffers. Luhr and Carmichael (1980) attributed the apparent difference in fO_2 between the two volcanoes to different oxygen fugacities of the magmas and not to differences in magma compositions. The data for Los Humeros represent rock types ranging from andesite to high-silica rhyolite, and indicate T-fO_2 conditions that straddle the Ni-NiO buffer curve. Rhyolites from Los Humeros equilibrated in the range 800° - 880° C, which overlaps with both moderate-K SMO rhyolites and high-K SEC rhyolites.

BULK-ROCK CHEMISTRY

Selected major and trace element data for volcanic rocks of the SMO-SEC and MVB areas are shown in Figures 4 to 14. For clarity, the data for each element are presented in a series of four or five diagrams. The MVB volcanoes are separated into a western segment (Ceboruco and Sangangüey), a segment including the Colima graben (Colima and Primavera), a central segment (Colima, Popocatépetl, Orizaba, Paricutín, Jorullo, Toluca, and Los Humeros), and an eastern segment (Tuxtla). The Colima calc-alkalic data (COLC) are presented in figures for both the Colima graben and the MVB central segment. Data for the SMO-SEC are presented together in one figure. To facilitate comparison among the four to five figures for each element, *arbitrary dotted guidelines* are included. An explanation of abbreviations used in figures and sources of data discussed below is given in Table 1. We usually plotted data only on those volcanoes for which a significant number of major and trace element analyses or isotopic ratios are available. There are numerous other studies that contain only major element or few trace element data which are not included in the diagrams.

Major Elements

Plots of total alkalies (Na_2O + K_2O) vs SiO_2 for the SMO-SEC and MVB volcanic rocks are shown in Figure 4. The moderate-K calc-alkalic rocks of the northern SMO (Batopilas area) plot in the subalkaline field of Miyashiro (1978) whereas most of the high-K calc-alkalic rocks of SEC plot in the alkaline field (Fig. 4e). There is little doubt that the latter have calc-alkalic affinities based on mineralogy (e.g., presence of opx) and trace element chemistry (K. Cameron *et al.*, 1980; Moll, 1981). Data from other areas of the SMO (Swanson *et al.*, 1978; Keller *et al.*, 1982; Hus-

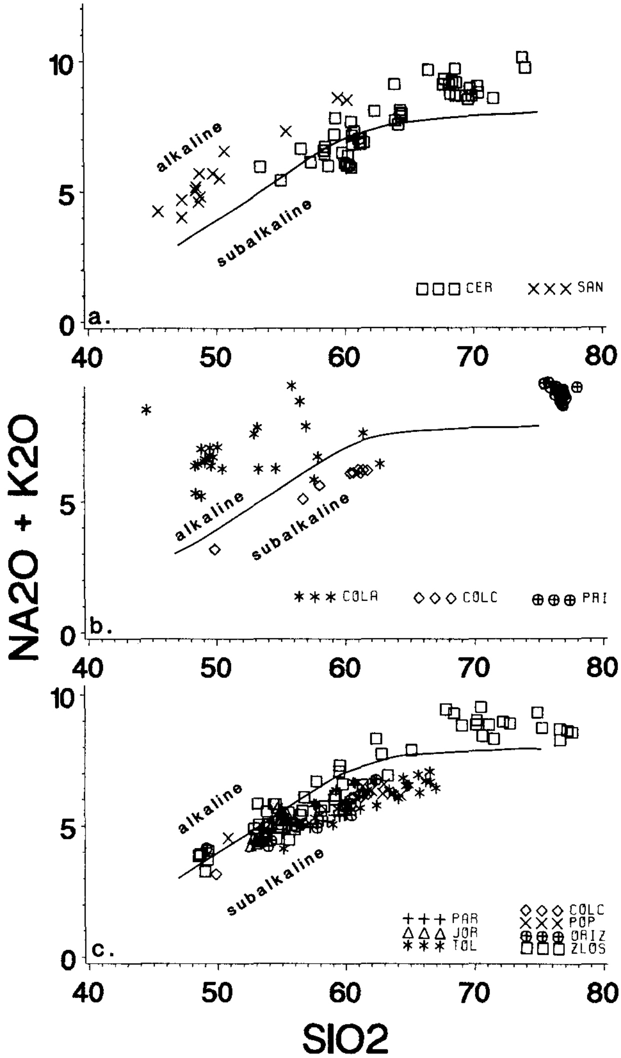


Fig. 4

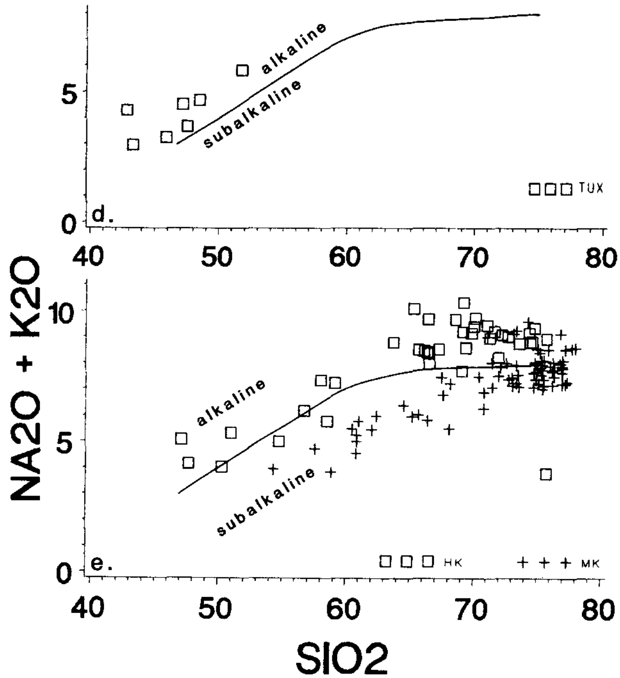
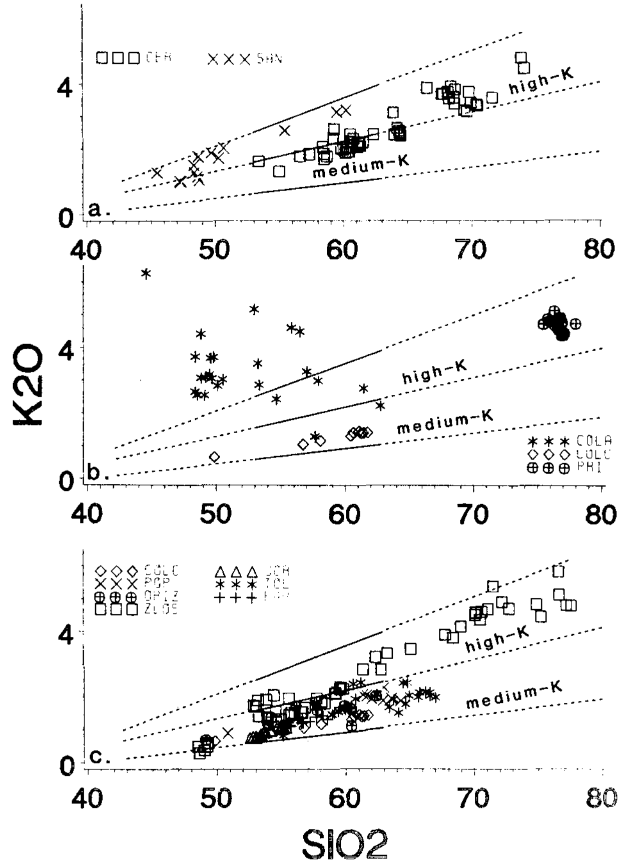


Fig. 4. Total alkalies (% Na_2O + %K_2O) vs %SiO_2 for SMO-SEC and MVB volcanic rocks. Line separating alkaline from subalkaline fields is from Miyashiro (1978). Key to abbreviations and sources of data are presented in Table 1. (A) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB ; (B) alkaline (COLA and PRI) and calc-alkalic (COLC) rocks of the Colima graben; (C) calc-alkalic rocks of the central MVB; (D) alkaline rocks of the eastern MVB (= eastern alkaline province) ; and (E) moderate-K (MK) and high-K (HK) calc-alkalic rocks of the SMO and SEC areas.

peni *et al.,* 1984) either lie in the subalkaline field or straddle the subalkaline-alkaline boundary whereas the high-K calc-alkalic rocks studied by Capps (1981) lie within the alkaline field. The MVB volcanic rocks plot in both the alkaline and subalkaline fields (Figs. 4a-d). Calc-alkalic andesites of the central MVB lie almost entirely within the subalkaline field except for samples from Los Humeros (open squares in Fig. 4c), which is located in the back arc area. Most analyses for the alkali-rich pyroxene andesites and dacitas of Ceboruco, in the western segment, plot in the alkaline field. Again, these rocks and probably most from Los Humeros appear to have calc-alkalic affinities on the basis of their mineralogy and trace element chemistry. Volcanics that plot in the alkaline field, and appear to have true alkaline affinities, include those from: *(1)* cinder cones associated with Sangangüey (western MVB; Fig. 4a), *(2)* lavas or cinder cones either in the Colima graben or associated with V. Colima, which is located at the southern end of the Colima graben (Fig. 4b), *(3)* the volcanic complex at La Primavera (north end of Colima graben; Fig. 4b), *(4)* the lava and cinder cones at Cerro La Pilita (not plotted), 3 km south of Jorullo (central MVB), and *(5)* the Tuxtla area (eastern MVB: Fig. 4d).

Variations in selected major elements in rocks of the SMO-SEC and MVB areas are shown in Harker diagrams in Figures 5 to 7. The K_2O data (Fig. 5) for calc-alkalic volcanics from each locality define regular trends, with rocks of intermediate composition (53 - 63 % SiO_2) plotting either in the medium-K or high-K fields of Gill (1981). Intermediate rocks from the SMO proper (Batopilas area) lie mostly in the medium-K field whereas those from SEC either lie within or above the high-K field (Fig. 5e). Both data sets cut diagonally across extensions of the boundaries of Gill such that the felsic rocks of each suite plot in successively higher K_2O fields. Da-



. Fig. 5

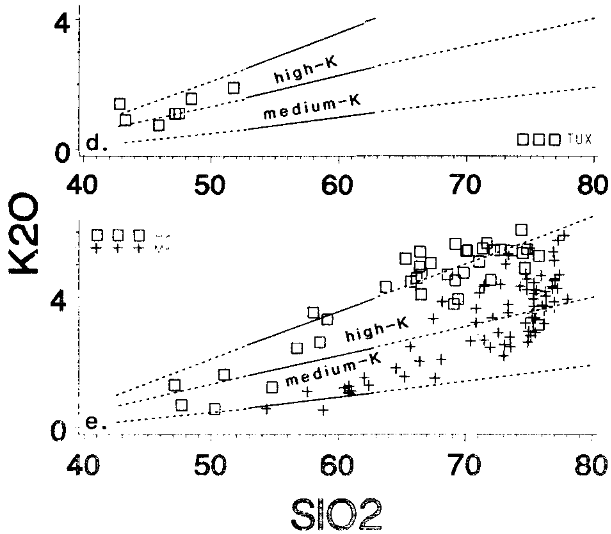


Fig. 5. Variation of %K_2O with %SiO_2 for SMO-SEC and MVB volcanic rocks. Solid lines separating medium-K and high-K fields are from Gill (1981). Key to abbreviations and sources of data are presented in Table 1. (A) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB; (B) alkaline (COLA and PRI) and calc-alkalic (COLC) rocks of the Colima graben; (C) calc-alkalic rocks of the central MVB; (D) alkaline rocks of the eastern MVB (= eastern alkaline province); and (E) moderate-K (MK) and high-K (HK) calc-alkalic rocks of the SMO and SEC areas.

ta for Ceboruco, in the western MVB segment, straddle the boundary between Gill's high-K and medium-K fields (Fig. 5a). Calc-alkalic rocks from the central MVB segment, except Los Humeros, have similar K_2O concentrations, with intermediate rocks plotting mostly in the moderate-K field (Fig. 5c). Samples from Los Humeros lie in both the medium- and high-K fields. K-concentrations in andesites of the SMO and central MVB zone are significantly lower than those reported by Ewart (1982) for andesites of the western U. S. (~2.60 %), but are comparable to values for andesites from the Aleutians-Alaska-Cascades region (~1.33 %). Ceboruco, with its higher K_2O, is more similar to the western U. S. or Andean andesites (~2.47 %). Some of the mafic alkaline rocks in the Colima graben (Fig. 5b) and at Jorullo (not shown) are significantly enriched in K_2O.

CaO decreases regularly with increasing SiO_2 for volcanics of both the SMO-SEC and MVB (Fig. 6). Moderate-K SMO volcanics are systematically higher in CaO than are rocks of the high-K SEC series. Concentrations of CaO in calc-alkalic andesites of the central MVB zone overlap those of both the SMO and SEC suites, with the Los Humeros volcanics generally having the lowest CaO contents. Volcanics from Ceboruco, in the western MVB segment, have CaO contents that are similar to Los Humeros and lower than central MVB volcanics.

FeO* data (not shown) for calc-alkalic rocks of the SMO-SEC and MVB define a single linear trend that decreases from ~8 % at 55 % SiO_2 to ~3 % at 70 % SiO_2. There are no significant differences in FeO* between the medium and high-K facies of the SMO and SEC, nor are there pronounced differences between andesites in the western and central MVB segments.

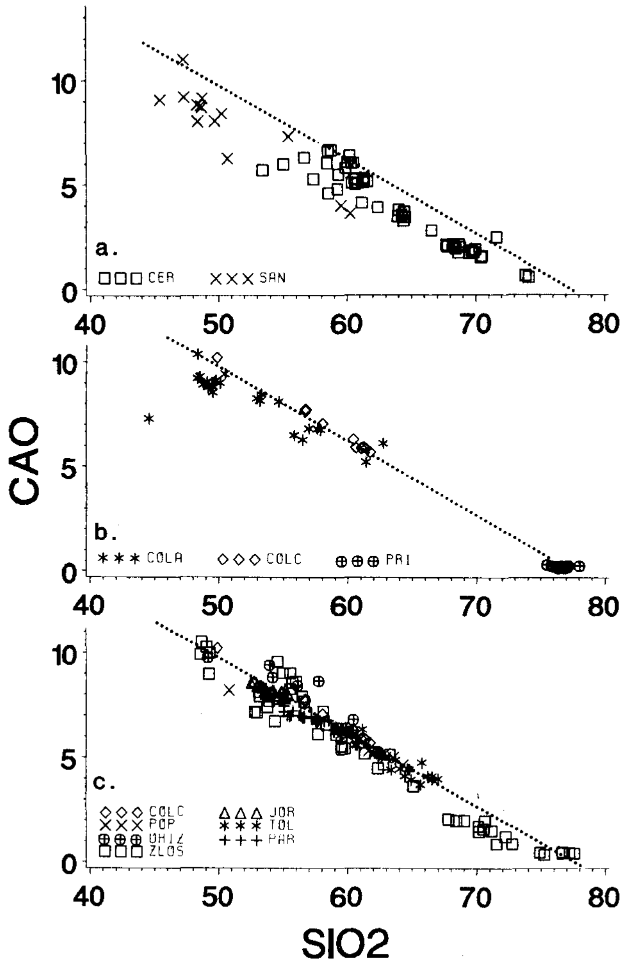


Fig. 6

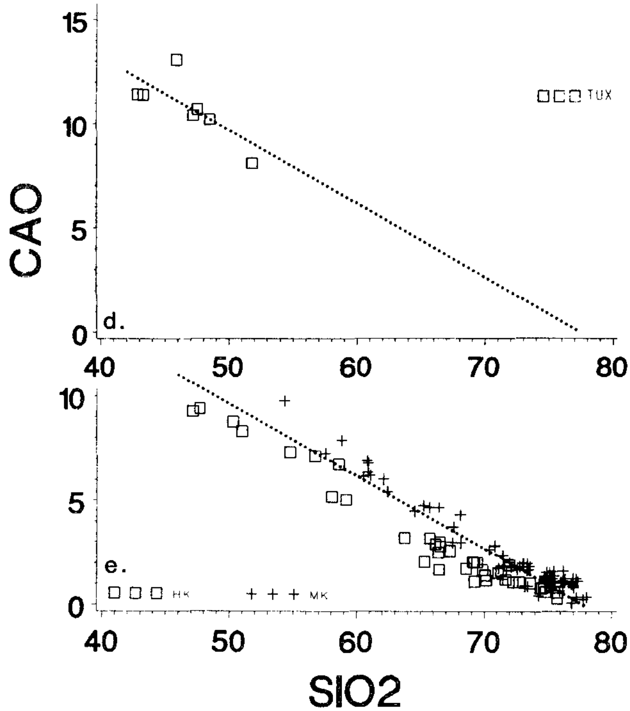


Fig. 6. Variation of %CaO vs %SiO_2 for SMO-SEC and MVB volcanic rocks. Arbitrary dotted lines are included to enable comparison among regions. Key to abbreviations and sources of data are presented in Table 1. (A) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB; (B) alkaline (COLA and PRI) and calc-alkalic (COLC) rocks of the Colima graben; (C) calc-alkalic rocks of the central MVB; (D) alkaline rocks of the eastern MVB (= eastern alkaline province); and (E) moderate-K (MK) and high-K (HK) calc-alkalic rocks of the SMO and SEC areas.

Al_2O_3 concentrations (not shown) in the calc-alkalic rocks of the SMO-SEC and the central MVB zone are nearly constant at about 17 % in the basaltic andesite/andesite compositional range, but at approximately 63 % SiO_2, Al_2O_3 begins to decrease with increasing SiO_2. The Al_2O_3 content of rocks from Ceboruco and Los Humeros decreases linearly from ~19 % in basaltic andesites to ~13 % in rhyolites. Los Humeros volcanics with <53 % SiO_2, and alkaline mafic rocks at Tuxtla and Colima define trends that generally increase with increasing SiO_2.

TiO_2 contents (Fig. 7) of calc-alkalic rocks of the SMO-SEC and MVB decrease with increasing SiO_2. Concentrations in felsic rocks of the high-K and moderate-K facies of the SMO-SEC are indistinguishable; however, in the intermediate compositional range two trends may be present, with the high-K rocks having higher TiO_2 concentrations at a given SiO_2 content. Rocks of the central MVB (with the exception of Los Humeros) seem to have slightly lower TiO_2 compared to SMO-SEC rocks. Los Humeros and Ceboruco have concentrations that are similar to the high-K SEC rocks. TiO_2 contents in mafic alkaline rocks of the Tuxtla area and V. Colima are similar, and both are lower than those from Sangangüey.

P_2O_5 concentrations (not shown) in the moderate-K SMO samples of the Batopilas area are approximately constant at 0.3% in the intermediate compositional range, but at SiO_2 greater than ~63% P_2O_5 decreases regularly. Intermediate volcanics from the central MVB (with the exception of Los Humeros) have relatively constant concentrations at ~0.2 - 0.5% P_2O_5. Rocks from Los Humeros, in the back arc area

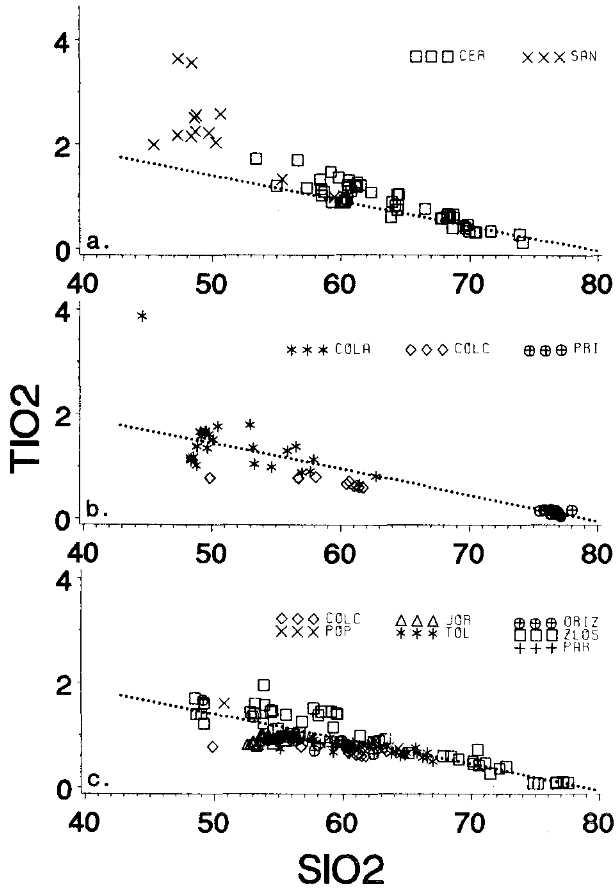


Fig. 7

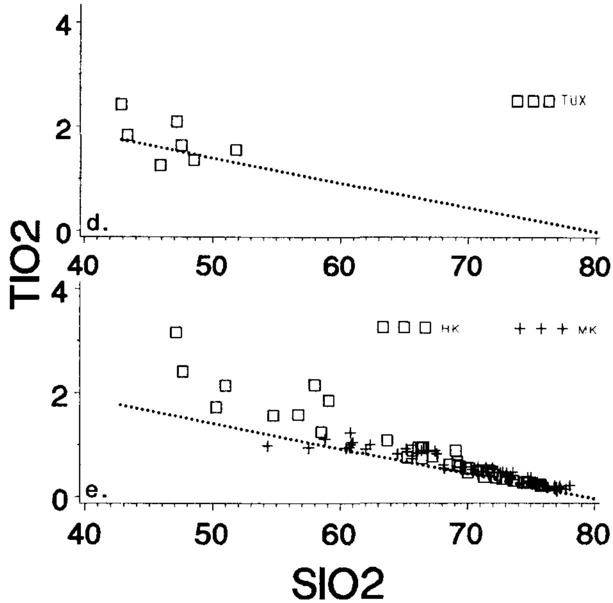


Fig. 7. Variation of %TiO_2 vs %SiO_2 for SMO-SEC and MVB volcanic rocks. Arbitrary dotted lines are included to enable comparison among regions. Key to abbreviations and sources of data are presented in Table 1. (A) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB; (B) alkaline (COLA and PRI) and calc-alkalic (COLC) rocks of the Colima graben; (C) calc-alkalic rocks of the central MVB ;(D) alkaline rocks of the eastern MVB (= eastern alkaline province); and (E) moderate-K (MK) and high-K (HK) calc-alkalic rocks of the SMO and SEC areas.

of the central MVB, define a trend that increases from mafic compositions to a maximum of 0.5% P_2O_5 at ~53% SiO_2 and then decreases linearly with increasingly higher SiO_2. (The intermediate-felsic high-K calc-alkalic rocks of SEC show a similar decreasing trend.) P_2O_5 in volcanics from Ceboruco exhibit considerable scatter, but in general the data define a decreasing trend with increasing SiO_2. Mafic alkaline rocks of the Tuxtla area have P_2O_5 concentrations that cluster around 0.5%, whereas those from V. Colima and Sangangüey show larger ranges and larger absolute concentrations.

Trace elements

Sr behavior is significantly different among the various geographic areas (Fig. 8). Sr contents of the SMO-SEC volcanics (Fig. 8d) decrease linearly with increasing SiO_2, with the high-K facies generally containing lower concentrations than the moderate-K facies throughout the entire compositional range. Trends for intermediate and felsic rocks from Ceboruco (Fig. 8b) and Los Humeros (Fig. 8c) are very similar to the SMO-SEC. In contrast, Sr concentrations in most calc-alkalic rocks of the Central

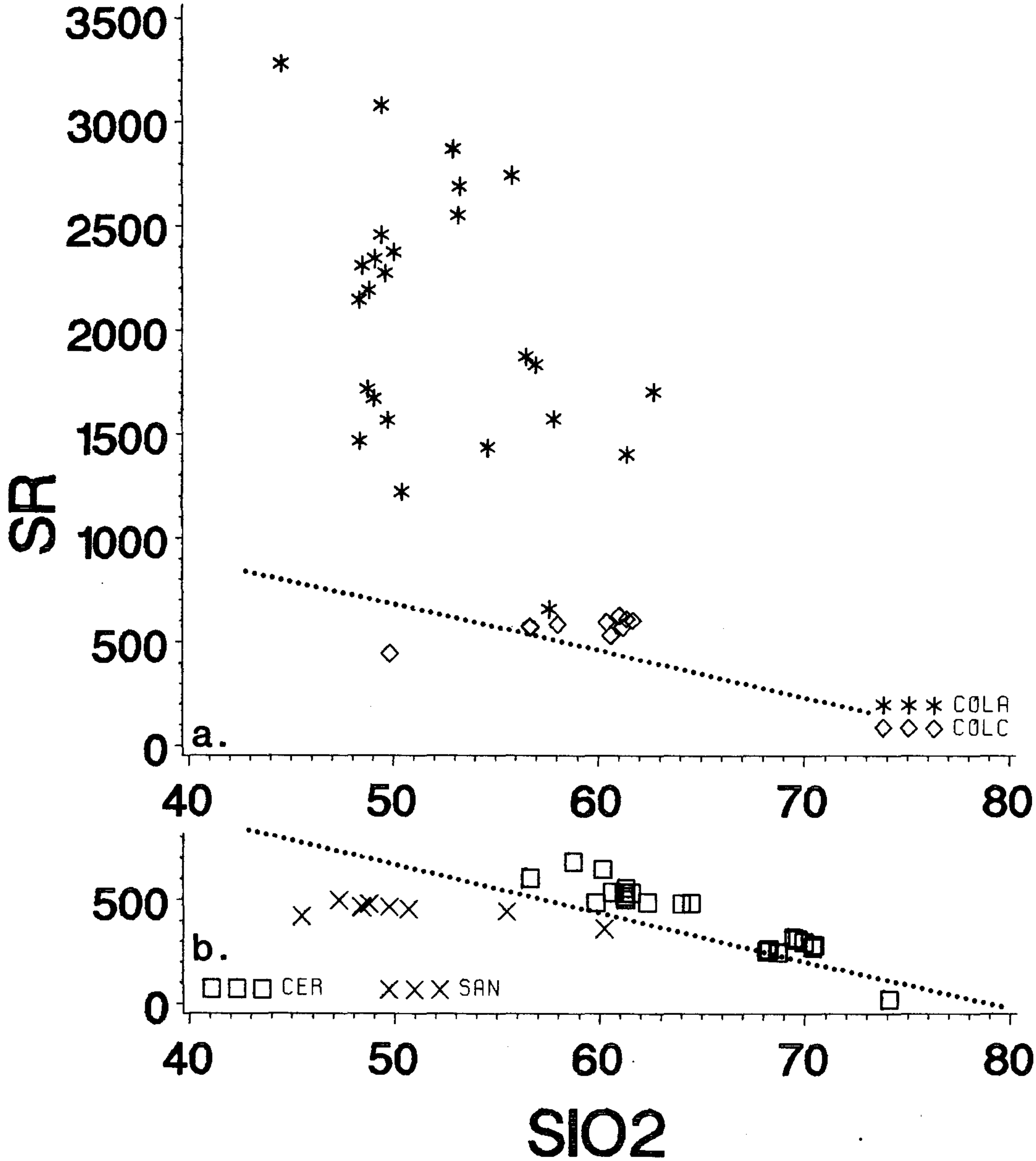


Fig. 8

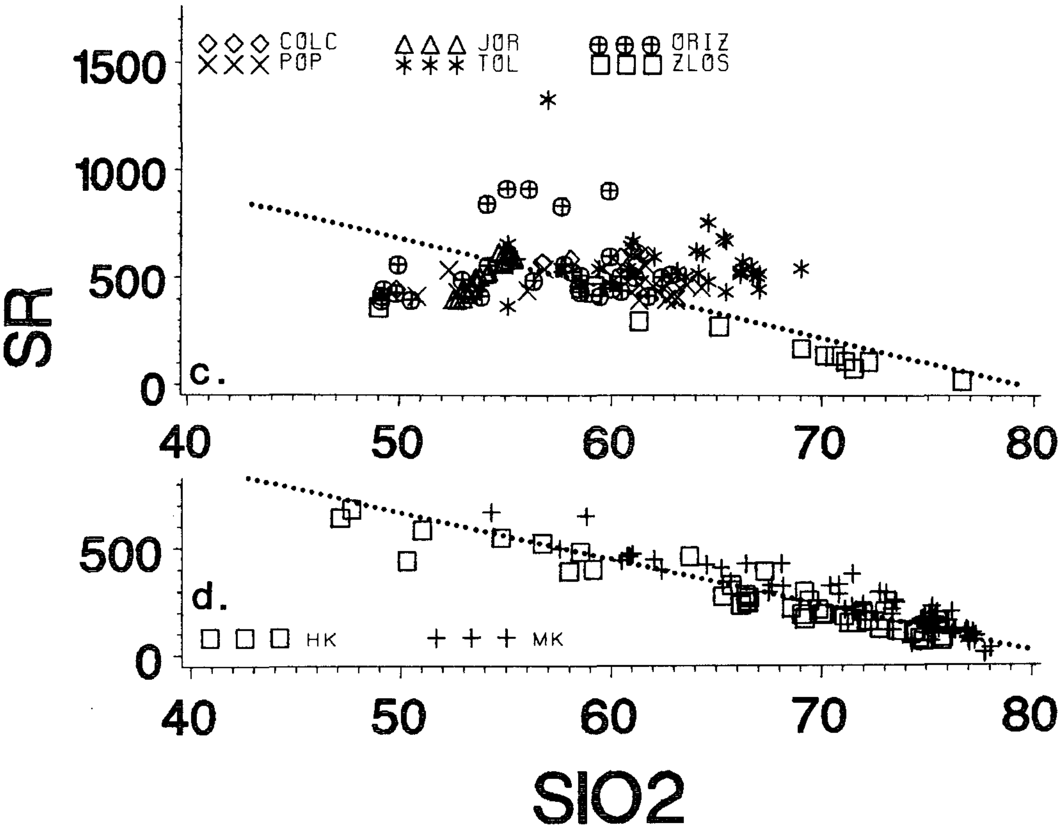


Fig. 8. Variation of Sr(ppm) with %SiO_2 for SMO-SEC and MVB volcanic rocks. Arbitrary dotted lines are included to enable comparison among regions. Key to abbreviations and sources of data are presented in Table 1. (A) alkaline (COLA) and calc-alkaline (COLC) rocks of the Colima graben; (B) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB; (c) calc-alkalic rocks of the central MVB; and (D) moderate-K (MK) and high-K (HK) calc-alkalic rocks from the SMO and SEC areas.

MVB either increase slightly or remain approximately constant over the silica ranges examined. Sr contents of 60% SiO_2 andesites from both the SMO-SEC and MVB volcanics are significantly lower than the average (~1118 ppm) reported by Ewart (1982) for the western U. S., but are similar to those reported for the southwest Pacific (~516 ppm), Aleutians-Alaska-Cascades (~673 ppm), and the Andes (~648 ppm). The mafic alkaline rocks at Sangangüey have Sr concentrations similar to, or slightly lower than, calc-alkalic volcanics whereas those at V. Colima have much higher Sr.

Rb contents (not shown) of the SMO-SEC volcanics increase with increasing SiO_2, and in general rocks of the moderate-K facies have lower Rb concentrations than the high-K rocks. Calc-alkalic rocks of the MVB comprise a broad trend, with concentrations on the average being lower than those in the moderate-K SMO rocks (~45 ppm vs ~75 ppm at 60% SiO_2). Rb contents of the MVB andesites are similar to those reported by Ewart (1982) for Aleutians-Alaska-Cascades (~36.2 ppm) and southwest Pacific andesites (~41 ppm), but are significantly lower than the average for andesites from the western U. S. (~79 ppm) and Andes (~75 ppm). K/Rb (not shown) of the SMO moderate-K calc-alkalic rocks ranges from 50 - 350 and high-K rocks from 200 - 500. Calc-alkalic rocks of the central MVB have ratios mostly in the range 250 - 700, and those in the western segment have K/Rb in the range 400 - 700. Mafic alkaline rocks from V. Colima exhibit large variations (~300 - 1 400) in K/Rb whereas those from Sangangüey define a smaller range (~550 - 1 000).

Ba data are not available for moderate-K rocks from axial portions (e.g., Batopilas area) of the SMO. However, analyses were published for one area in the eastern SMO (Durango: Fig. 1) and for southeastern Chihuahua. Ba data reported by Huspeni *et al.* (1984) for rhyolites from the Durango area are highly variable (38 -125 ppm for rhyolites hosting tin deposits and 117 - 706 ppm for cap ignimbrites and associated andesites). Analyses included in Gunderson *et al.* (1986) for intermediate to silicic high-K calc-alkalic rocks of SEC show a trend that decreases from ~1 300 ppm Ba at 64% SiO_2 to 400 ppm at 76% SiO_2. Ba concentrations in calc-alkalic volcanics of the MVB increase with increasing SiO_2. Trends for the western and central MVB zones are subparallel with the western zone displaced toward slightly higher Ba values (~800 ppm vs ~500 ppm at 60% SiO_2). Two 74-78 % rhyolites at Ceboruco and Los Humeros contain ~200 ppm Ba, which may reflect crystallization of K-spar at a late stage in the evolutionary history of the volcanic system. Ba concentrations in the MVB and SEC andesites are significantly less than the average value reported by Ewart (1982) for andesites of the western U. S. (~1 528 ppm). The central MVB andesites have Ba contents similar to those that Ewart (1982) presented for the southwest Pacific (~479 ppm), whereas Ceboruco andesites in the western MVB have Ba that is similar to Andean andesites.

Ba/La ratios (Fig. 9) of calc-alkalic rocks of Ceboruco and the central MVB eruptive centers are similar. The ratios for Los Humeros volcanics (back arc region of the central MVB) are lower than ratios for other volcanics of the central MVB. Such differences are consistent with geochemical variations reported for other volcanic arc/back arc assemblages (see tabulations by Gill, 1981). Ba/La ratios for volcanics from Orizaba and Los Humeros (central MVB) increase with increasing SiO_2 as observed for other orogenic rock suites (Gill, 1981). Alkaline rocks from Colima have Ba/La ratios similar to associated calc-alkalic rocks, whereas those at Sangangüey (western MVB) have distinctly lower ratios. High-K calc-alkalic volcanics from SEC have Ba/La ~ 15, which is comparable to Los Humeros volcanics.

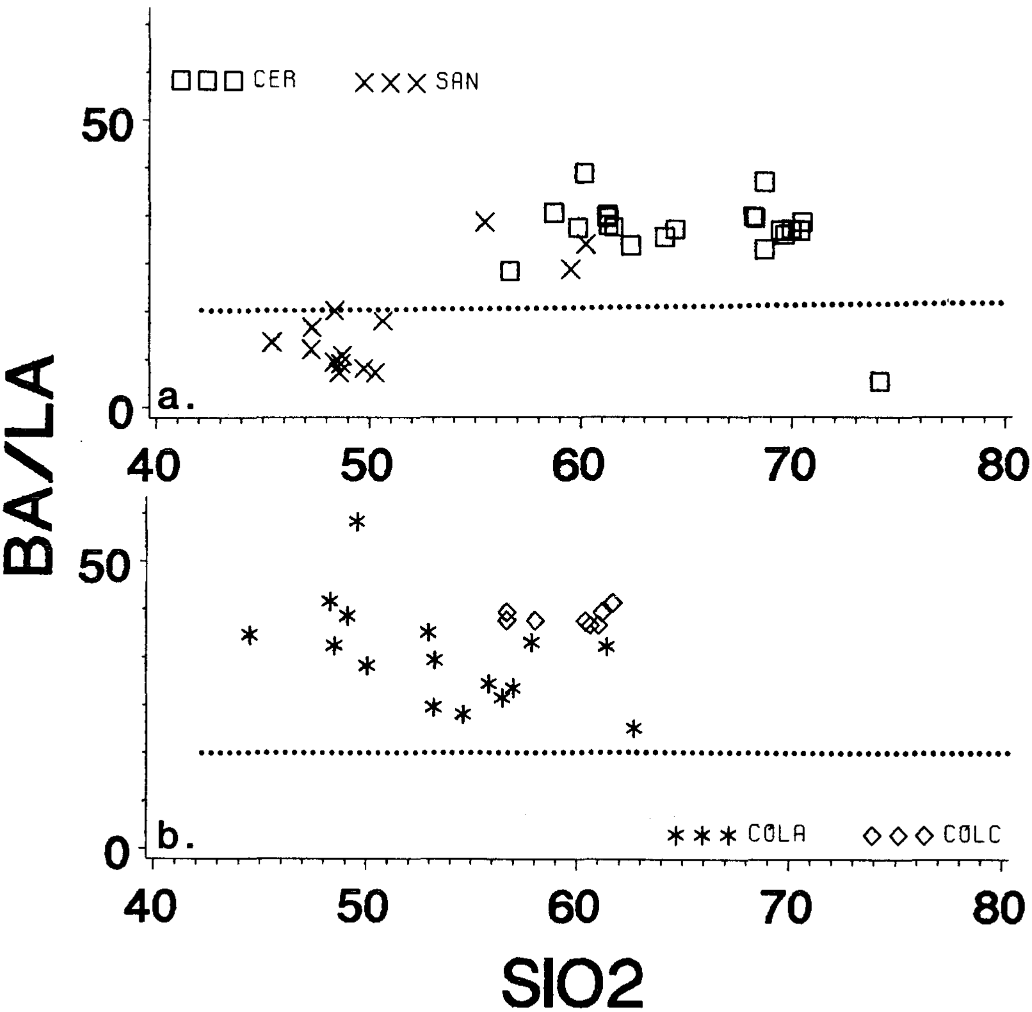


Fig. 9

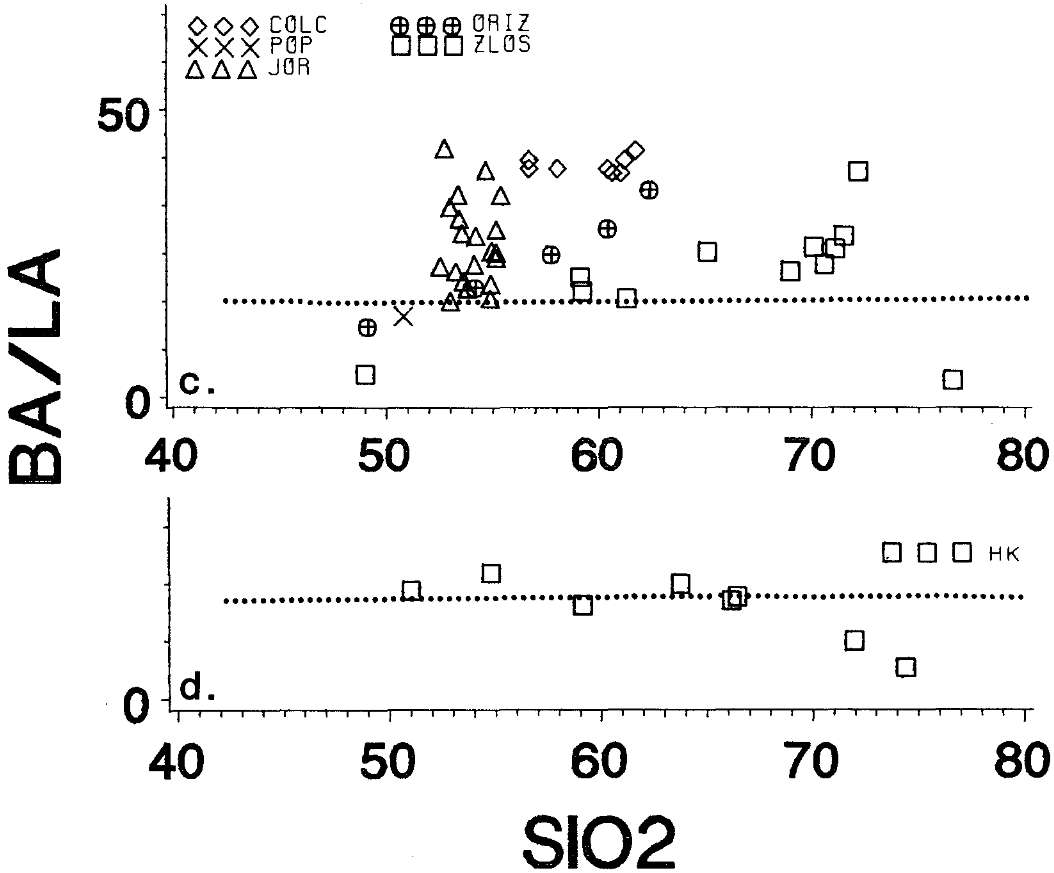


Fig. 9. Variation of Ba/La vs %SiO_2 for rocks from the MVB and SEC areas. Arbitrary dotted lines are included to enable comparison among regions. Key to abbreviations and sources of data are presented in Table 1. (A) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB; (B) alkaline (COLA) and calc-alkalic (COLC) rocks of the Colima graben; (C) calc-alkalic rocks of the central MVB; and (D) high-K calc-alkalic rocks of SEC.

Zr (Fig. 10) is usually incompatible in mafic rocks and compatible in felsic rocks of both the SMO-SEC and MVB. In the moderate-K calc-alkalic series of the SMO, Zr contents increase over the range ~55% to ~69-70 % SiO_2, at which point the concentrations begin to decrease regularly. Zr behavior in the high-K calc-alkalic rocks of SEC is similar, except the trends are more exaggerated. Additionally, the change in Zr behavior seems to occur at lower SiO_2, *i.e.* the change from incompatible to compatible behavior occurs at 66 - 67% rather than 69 - 70% SiO_2. In calc-alkalic rocks of the central MVB, Zr generally behaves as an incompatible element in rocks with <68% SiO_2 and as a compatible element in rocks with >68% SiO_2. Volcanics from Ceboruco (western MVB) and Los Humeros (back arc region of the central MVB) have slightly higher Zr concentrations than suites from the volcanoes comprising the frontal portion of the central MVB arc. Zr contents of moderate-K calc-alkalic andesites from the SMO and the central MVB are slightly lower than those reported by Ewart (1982) for the western U. S. (~222 ppm), but they are comparable to values for andesites of the Aleutians-Alaska-Cascades (~151 ppm) and southwest Pacific (~138 ppm) areas. Peralkaline rhyolites of La Primavera and mafic alkaline rocks at V. Colima and Sangangüey have Zr contents that lie above the overall calc-alkalic trend.

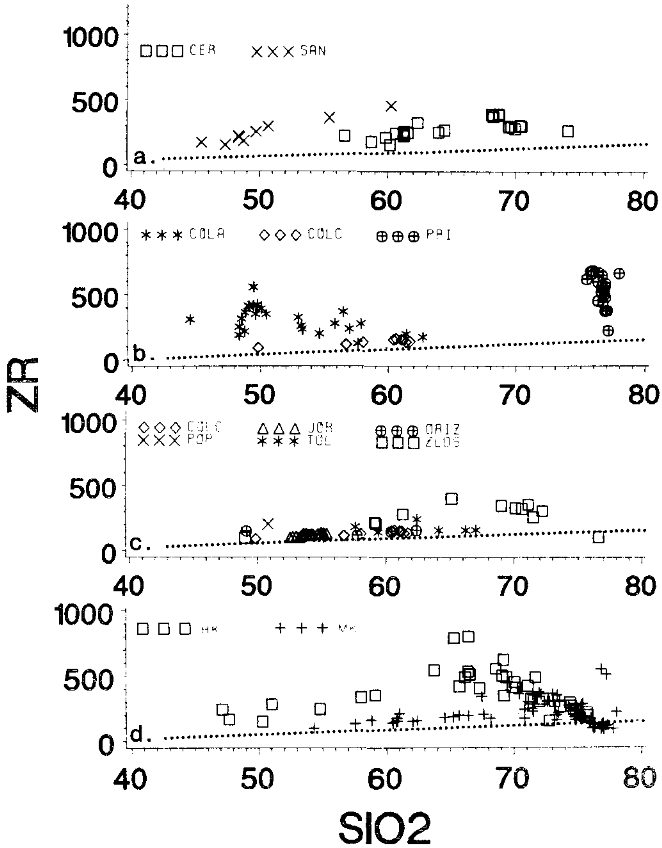


Fig. 10. Variation of Zr(ppm) with $\%SiO_2$ for SMO-SEC and MVB volcanic rocks. Arbitrary dotted lines are included to enable comparison among regions. Key to abbreviations and sources of data are presented in Table 1. (A) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB; (B) alkaline (COLA and PRI) and calc-alkalic (COLC) rocks of the Colima graben; (C) calc-alkalic rocks of the central MVB; and (D) moderate-K (MK) and high-K (HK) calc-alkalic rocks from the SMO and SEC areas.

Zr/Nb ratios (not shown) for mafic alkaline rocks at Sangangüey lie mostly in the range 6 - 9 whereas Zr/Nb for mafic alkaline rocks at Colima are extremely variable (9 to 42). Zr/Nb ratios of calc-alkalic basalts and basaltic andesites of Jorullo lie mostly in the range 7 - 11. Medium-K andesitic rocks of the northern SMO have ratios in the range 13 - 16, but at higher silica contents two weakly defined trends are present. From 60 to 75% SiO_2 one Zr/Nb trend increases from 13 - 16 to 24 whereas the other trend decreases from 13 - 16 to 6. Zr/Nb ratios of the high-K series from SEC exhibit considerable scatter, with intermediate rocks having Zr/Nb ~12 - 14 and both mafic and felsic rocks having lower Zr/Nb.

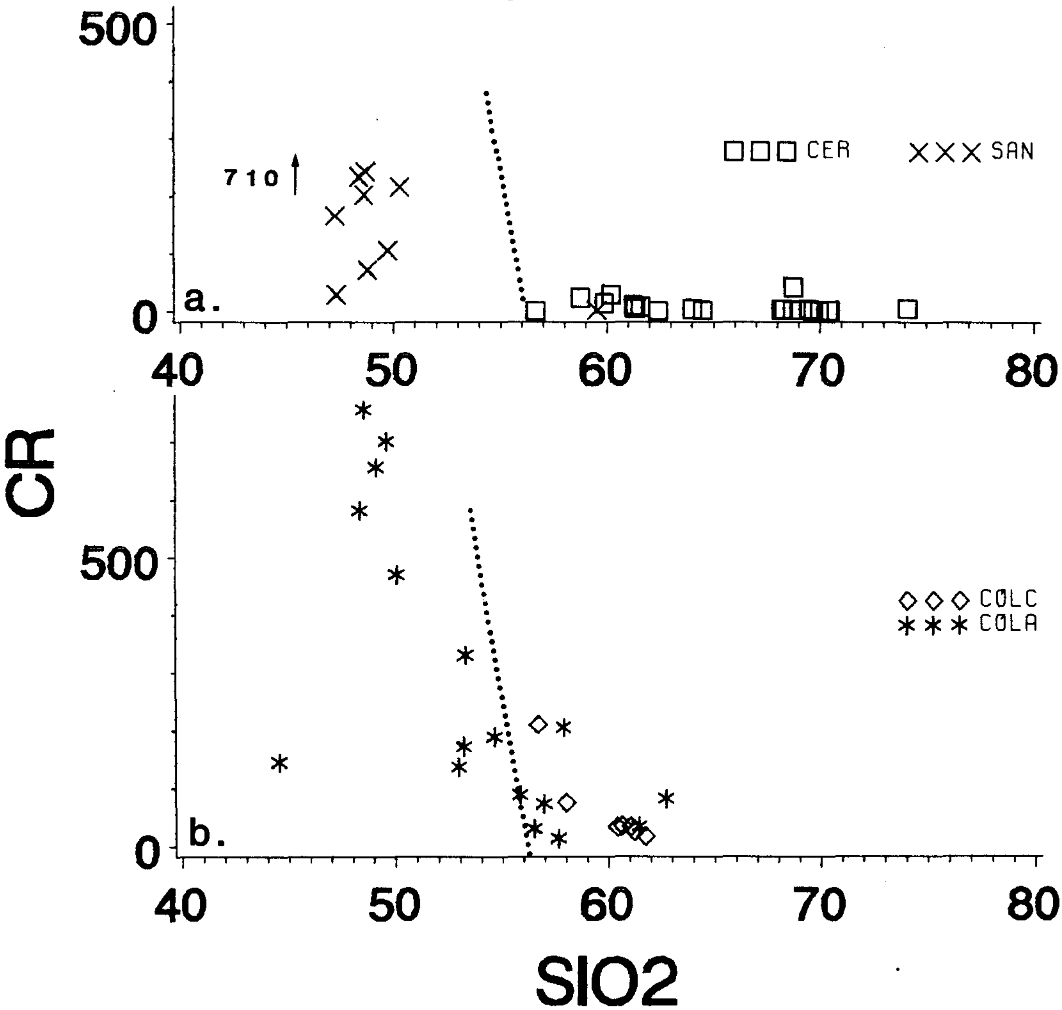


Fig. 11

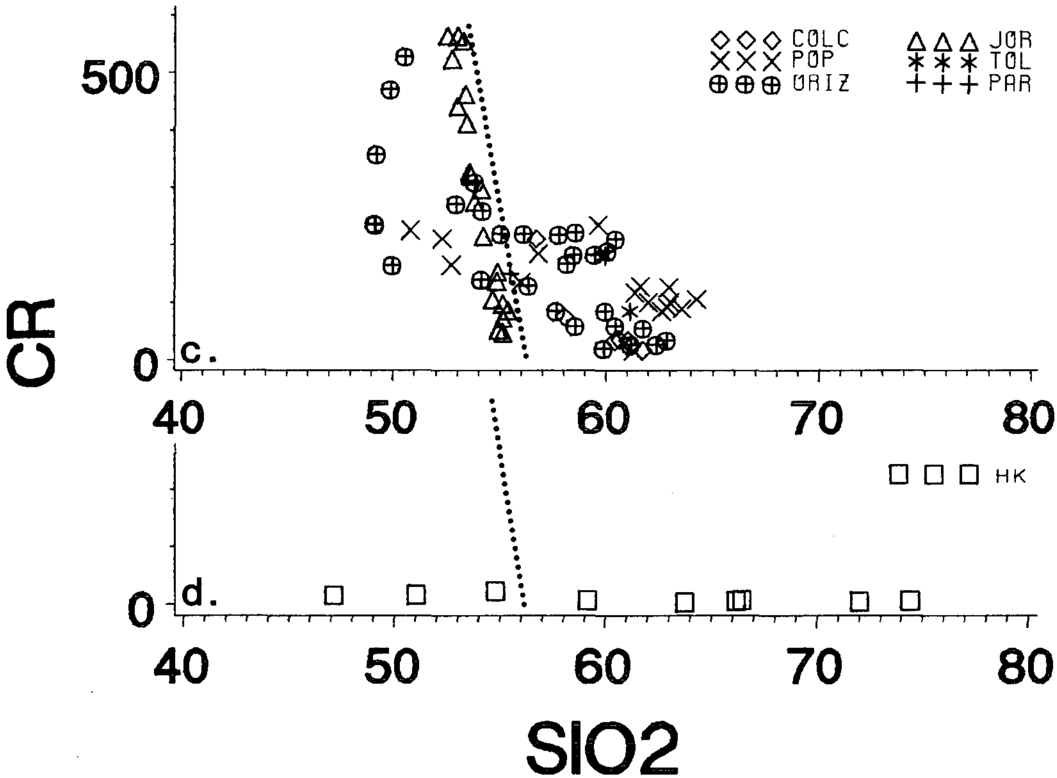


Fig. 11. Variation of Cr (ppm) with $\%SiO_2$ for MVB volcanic rocks. Arbitrary dotted lines are included to enable comparison among areas. Key to abbreviations and sources of data are presented in Table 1. (A) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB; (B) alkaline (COLA) and calc-alkalic (COLC) rocks of the Colima graben; and (C) calc-alkalic rocks of the central MVB; and (D) high-K calc-alkalic rocks of SEC.

Cr behaves differently in calc-alkalic volcanics of the central and western MVB (Fig. 11). In the central MVB Cr data show considerable scatter, but in general analyses from individual eruptive centers define decreasing trends with increasing silica content. The decrease in Cr content is especially regular in the basalts/basaltic andesites of Jorullo (data from Luhr and Carmichael, 1985). Intermediate and silicic volcanics from Ceboruco (western MVB) define an essentially flat trend over the intermediate-felsic compositional range studied. The Cr contents of andesites from the central MVB are comparable to those reported by Ewart (1982) for the western U. S. (~102 ppm), southwest Pacific (~87 ppm), the Aleutians-Alaska-Cascades (~52 ppm), and the Andes (~48 ppm).

La contents (not shown) of moderate-K calc-alkalic volcanics of the SMO increase regularly from ~20 ppm at 60% SiO_2 to ~30 ppm at 75% SiO_2. The high-K series of SEC has significantly higher La than moderate-K rocks with similar SiO_2. Compared to SMO volcanics calc-alkalic rocks from Ceboruco (western MVB) and Los Humeros (back arc region of the central MVB) have higher concentrations of REE

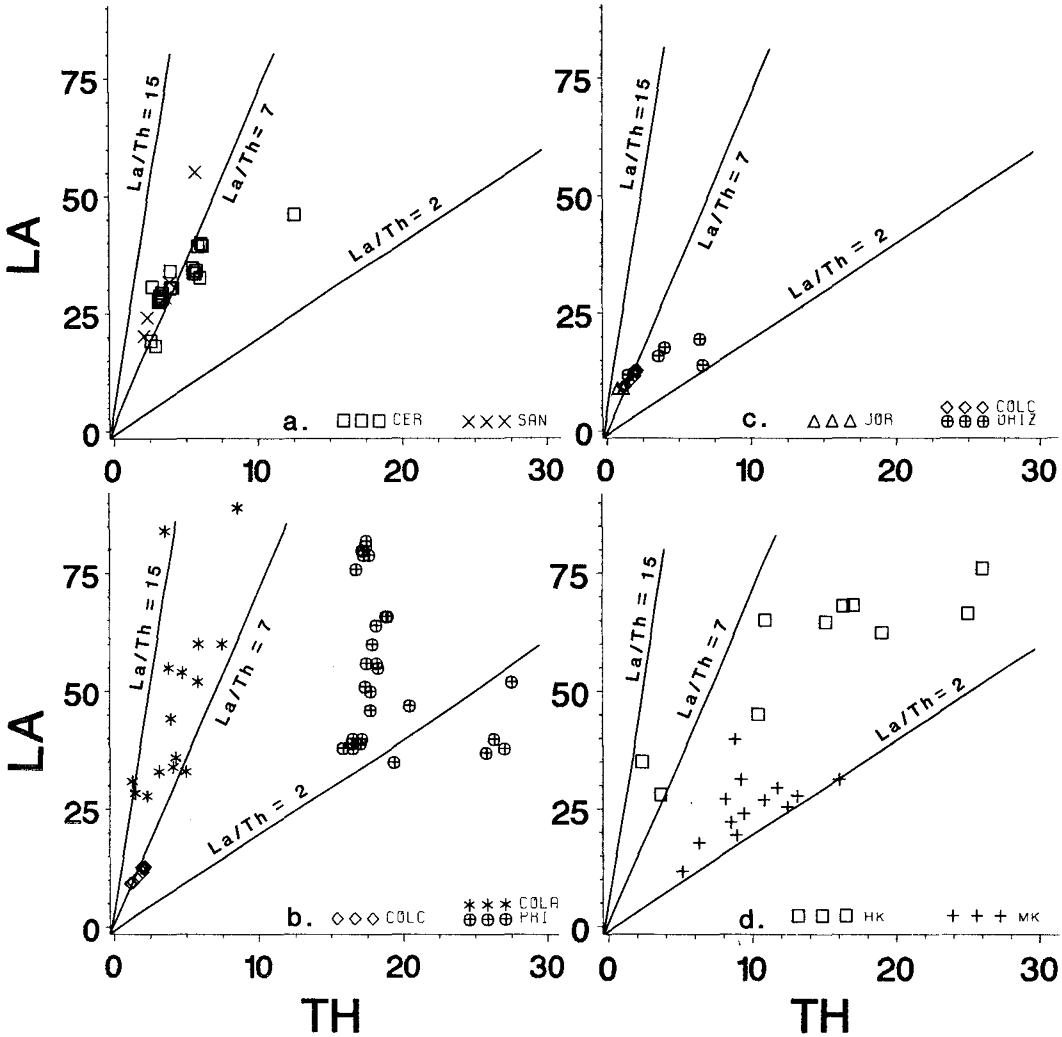


Fig. 12. La (ppm) vs Th (ppm) for MVB and SMO-SEC volcanic rocks. Key to abbreviations and sources of data are presented in Table 1. La/Th = 7-15 represents E-MORB field of Gill (1981). (A) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB; (B) alkaline (COLA and PRI) and calc-alkalic (COLC) rocks of the Colima graben; (C) calc-alkalic rocks of the central MVB; and (D) moderate-K (MK) and high-K (HK) calc-alkalic rocks from the SMO and SEC areas.

whereas rocks from the frontal arc of the central MVB generally have lower concentrations. The alkaline rocks of Primavera, Colima, and Sangangüey show large ranges in La, with concentrations in the Colima rocks well above the associated calc-alkalic suite. La contents of the MVB and SMO andesites are significantly lower than the averages reported by Ewart (1982) for andesites of the western U. S. (~78 ppm), but are generally similar to those of andesites from the southwest Pacific (~25 ppm) and the Aleutians-Alaska-Cascades (~19 ppm). Both Los Humeros, in the central MVB, and Ceboruco, in the western MVB, have La similar to the Andean andesites (~38 ppm).

La/Th ratios for calc-alkalic and alkaline rocks are significantly different. On La vs Th diagrams (Fig. 12) mafic alkaline rocks of Colima and Sangangüey lie in the E-MORB field (La/Th ~7-15) delineated by Gill (1981). The calc-alkalic rocks of Ceboruco have ratios similar to Bulk Earth (~7), and calc-alkalic rocks of the SMO-SEC areas have even lower ratios.

The behavior of Y (Fig. 13) is significantly different among the various volcanic centers. In the moderate-K calc-alkalic facies of the SMO it increases slightly over andesitic and dacitic compositional ranges, but in the rhyolitic range several trends develop. Rhyolites containing amphibole generally have Y values less than ~32 ppm whereas those lacking amphibole have higher Y contents. The high-K rocks have Y contents higher than the moderate-K volcanics, and the concentrations appear to increase slightly with increasing SiO_2. Y concentrations in rocks from Ceboruco (western MVB) are in general similar to those of intermediate moderate-K volcanics from the northern SMO. Rocks from the central MVB (except Los Humeros) have lower Y contents, and define trends that are approximately flat or decrease with increasing SiO_2. The Y contents of volcanics from Los Humeros are approximately constant or they increase slightly with increasing SiO_2, which is similar to trends of the Ceboruco (western MVB) and SMO-SEC volcanics. Mafic alkaline rocks of V. Colima have Y concentrations that cluster around 20 ± 5 ppm, which is similar to associated calc-alkalic rocks.

Chondrite-normalized REE patterns of representative andesites and dacites from the SMO-SEC and MVB areas are shown in Figure 14. $(Ce/Yb)_N$ of moderate-K volcanics of the Batopilas area of the SMO increases regularly from andesites through dacites to rhyolites. Eu anomalies are generally small, and Eu/Eu* varies from ~0.85 in andesites to ~0.6 - 0.7 in rhyolites. The high-K SEC rocks are more enriched in LREE and MREE, and their patterns are generally more fractionated than those of the moderate-K SMO suite ($Ce_N/Yb_N \sim 3.8$ vs 6.2 at 60% SiO_2). Calc-alkalic andesites of Ceboruco have REE patterns that are slightly more fractionated than those of moderate-K SMO andesites ($(Ce/Yb)_N \sim 5.5$) whereas andesites of V. Colima have $(Ce/Yb)_N$ of 3.7, which is similar to the SMO andesites. Eu/Eu* of the Ceboruco andesites is close to 1.0, although some of the felsic rocks exhibit small negative Eu anomalies. REE in the mafic alkaline rocks of V. Colima are more strongly fractionated than those in the associated calc-alkalic rocks. $(Ce/Yb)_N$ is >8 and Eu/Eu* is typically about 1.0. Mafic alkaline rocks from Sangangüey have patterns that are not significantly different from those for MVB calc-alkalic rocks.

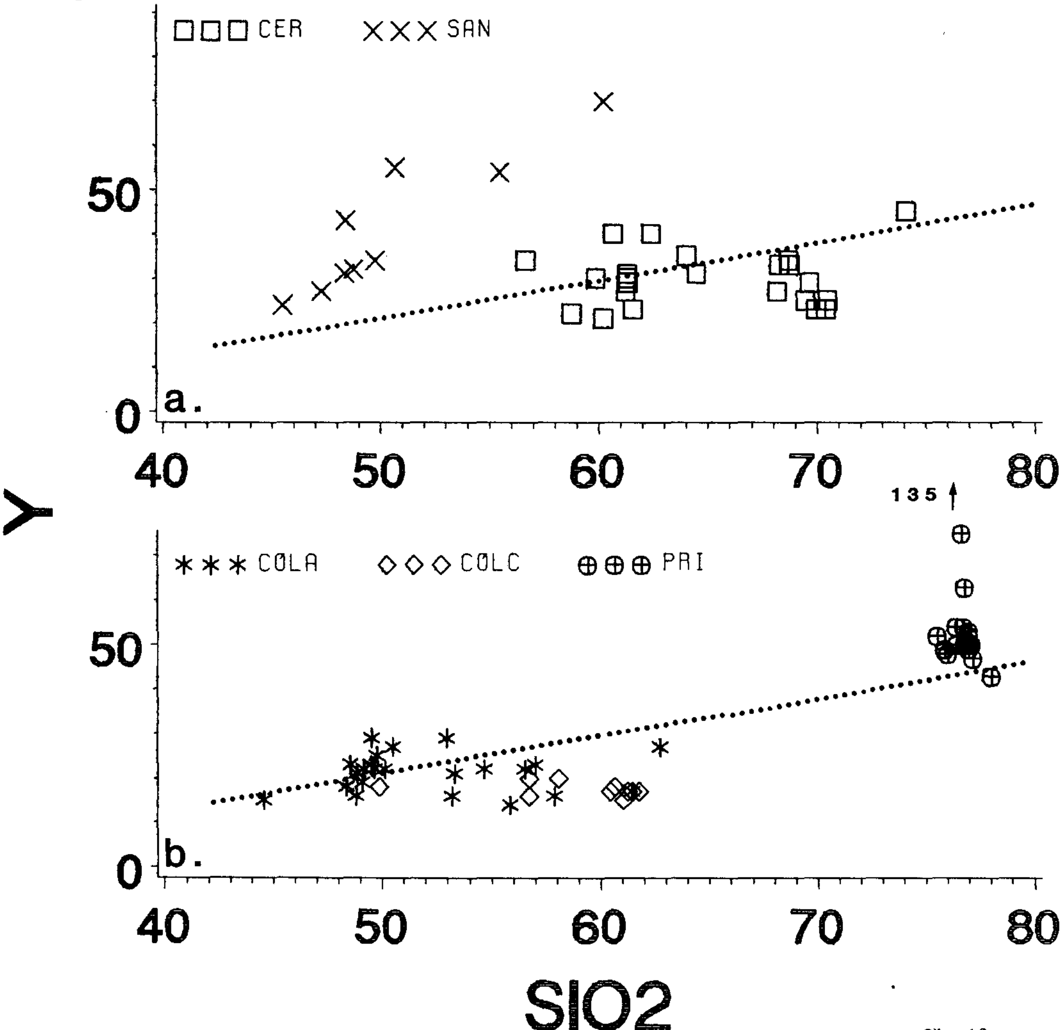


Fig. 13.

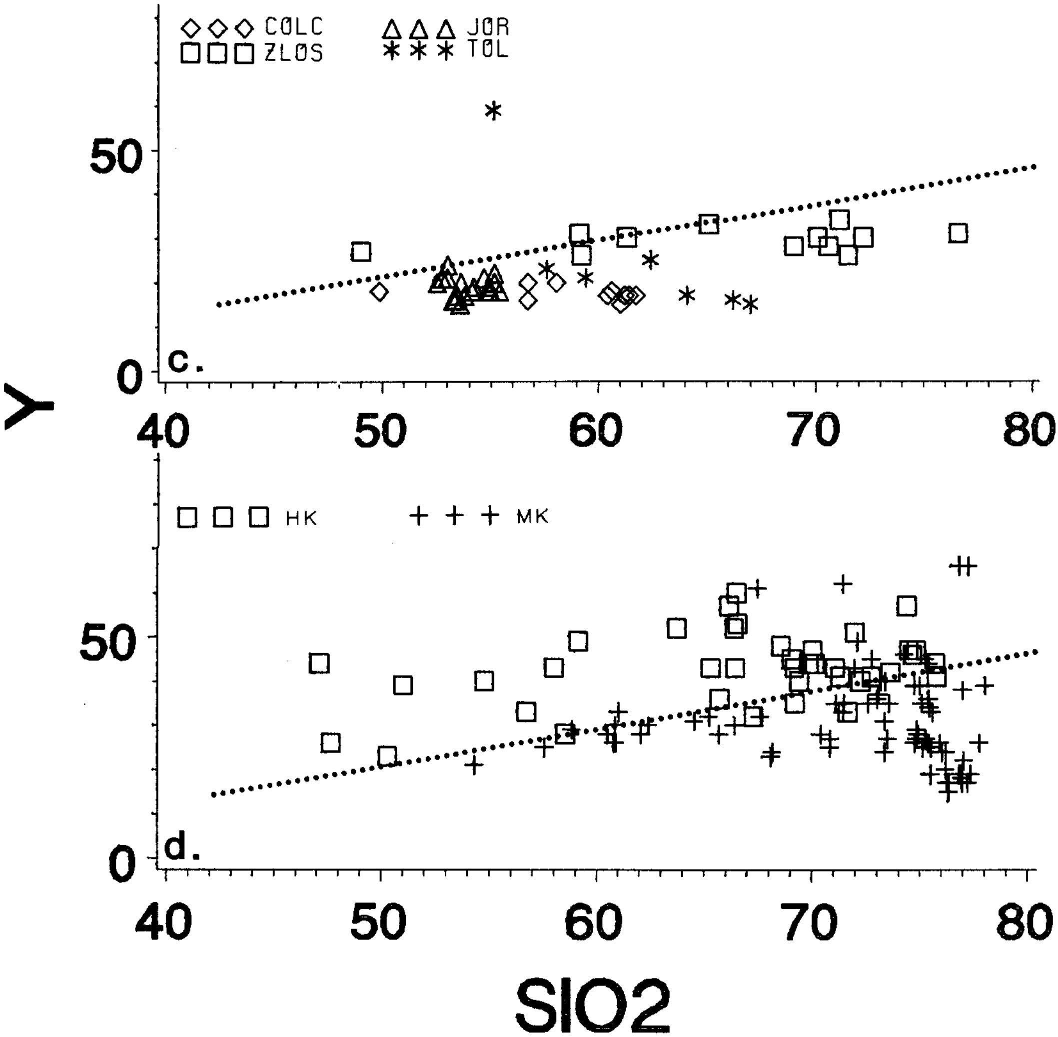


Fig. 13. Variation of Y(ppm) with %SiO_2 for SMO-SEC and MVB volcanic rocks. Arbitrary dotted lines are included to enable comparison among regions. Key to abbreviations and sources of data are presented in Table 1. (A) calc-alkalic (CER) and alkaline (SAN) rocks of the western MVB; (B) alkaline (COLA and PRI) and calc-alkalic (COLC) rocks of the Colima graben; (C) calc-alkalic rocks of the central MVB; and (D) moderate-K (MK) and high-K (HK) calc-alkalic rocks from the SMO and SEC areas.

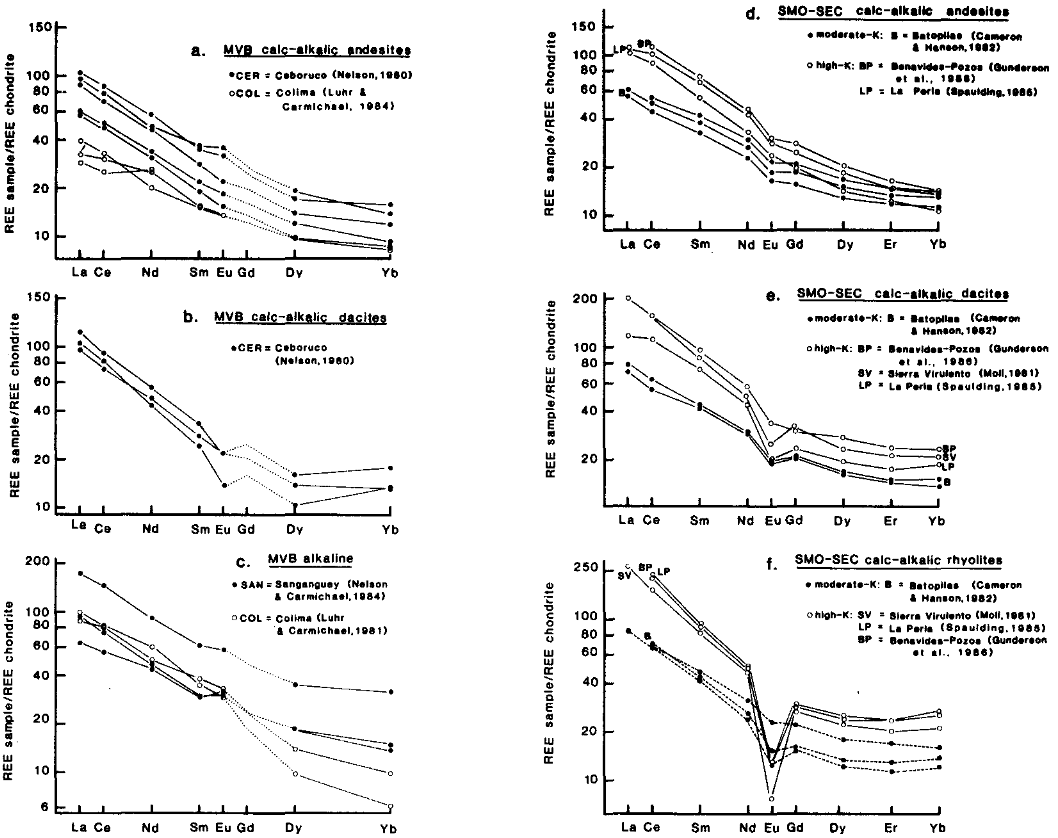


Fig. 14. Chondrite-normalized REE patterns of: (A) MVB calc-alkalic andesites; (B) MVB calc-alkalic dacites; (C) MVB alkaline rocks; (D) SMO-SEC calc-alkalic andesites; (E) SMO-SEC calc-alkalic dacites; and (F) SMO-SEC calc-alkalic rhyolites. Key to abbreviations is presented in Table 1, and sources of data are given in figure.

Isotopic variations

Sr isotopic ratios of volcanics from the MVB and SMO-SEC areas are shown in Figure 15. Sources of data plotted are given in Table 1. MVB ratios have a very restricted range from ~0.7035 to 0.7047. Volcanics from the central MVB have a median value near 0.7040 ± 0.002, and those from Ceboruco, in the western MVB, have ratios of 0.7042 - 0.7043. Mafic alkaline rocks from Tuxtla and basanites and minettes from V. Colima have median values near 0.7038 ± 0.0002. None of these ratios indicate significant involvement of sialic or old radiogenic crustal material, a conclusion reached by other researchers (e.g., Moorbath *et al.*, 1978; Verma, 1983;

Verma and M. P. Verma, 1986). The ratios probably reflect values of mantle source regions, as suggested by Whitford and Bloomfield (1976). Ratios for calc-alkalic andesites of the central MVB lie in the upper part of the range reported by Gill (1981; p.146) for orogenic andesites at modern convergent plate boundaries. They are higher than N-type MORB, but are similar to ratios in oceanic crust modified by seawater alteration (Gill, 1981, p.147). In contrast to the MVB rocks, Sr isotopic ratios of volcanics in the SMO-SEC areas are extremely variable. Published initial ratios for calc-alkalic rocks vary from 0.7033 to 0.7614. With the exception of the Batopilas area in the northern SMO, the range in ratios reported at any one geographic lo-

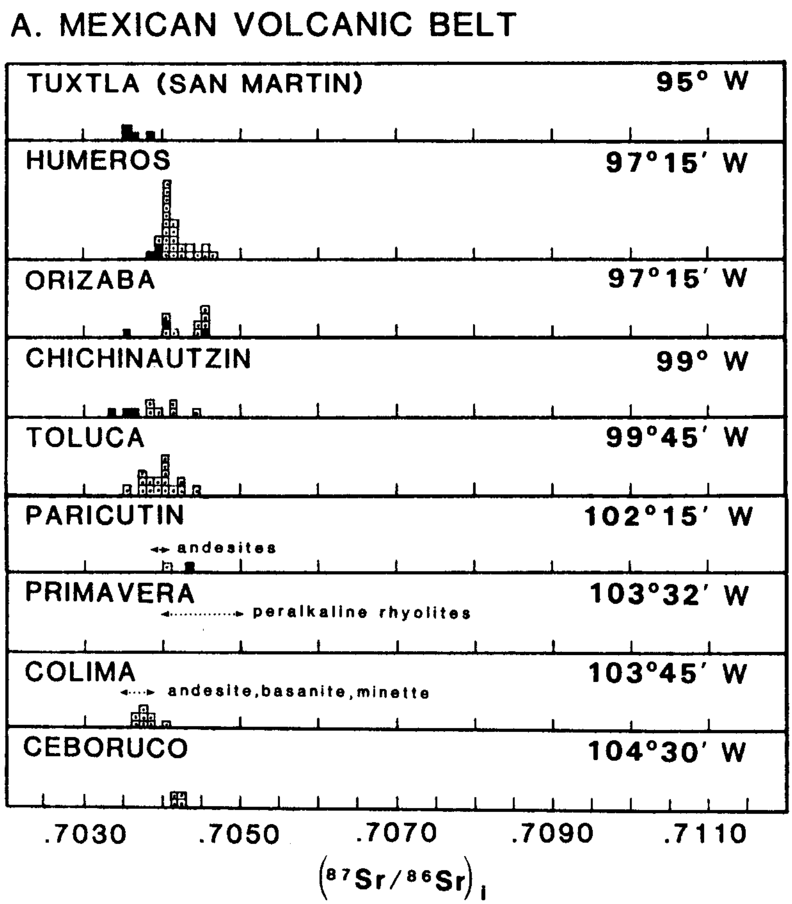


Fig. 15. Initial Sr isotopic ratios of volcanics from: (A) the Mexican Volcanic Belt and (B) the Sierra Madre Occidental and adjacent areas in southeastern Chihuahua. Sources of data are listed in Table 1. Solid symbols indicate basalts; open symbols indicate rhyolites; symbols with dots represent rocks of intermediate composition.

cality can be large and values for silicic rocks commonly indicate significant involvement of radiogenic crust. Ratios for seven basalts from various areas lie between 0.7035 and 0.7051, and values as low as 0.7025 were reported for basalts in the Cuauhtémoc-La Junta and Durango-Mazatlán areas (see Fig. 15 and references in Table 1). If all of these basalts have high Sr contents and are aphyric, such variations may indicate the presence of considerable inhomogeneities in the mantle source region from which the primary basaltic magmas originated. Rocks from the Upper Volcanic sequence of the Batopilas area exhibit the most restricted range of Sr isotopes of any area studied in detail. Ratios for basalts to high-silica rhyolites from this area cluster at 0.7048 ± 0.0002, and indicate no significant interaction with old radiogenic crustal material. This is consistent with the fact that the Batopilas region is not believed to be underlain by Precambrian crust. The younger, mildly-alkaline basalts that overlie the mid-Tertiary Upper Volcanic sequence in the Batopilas area have ratios of 0.7050 - 0.7051.

Pb isotopic data (Fig. 16) on volcanic rocks are published only for 11 samples from the Upper Volcanic sequence of the Batopilas area of the northern SMO (Barreiro *et al.*, 1982). The ratios are remarkably uniform, and rocks ranging in composition from andesite to dacite to rhyolite have $^{206}Pb/^{204}Pb$ = 18.847 - 18.889, $^{207}Pb/^{204}Pb$ = 15.590 - 15.648, and $^{208}Pb/^{204}Pb$ = 38.535 - 38.691. These ratios place

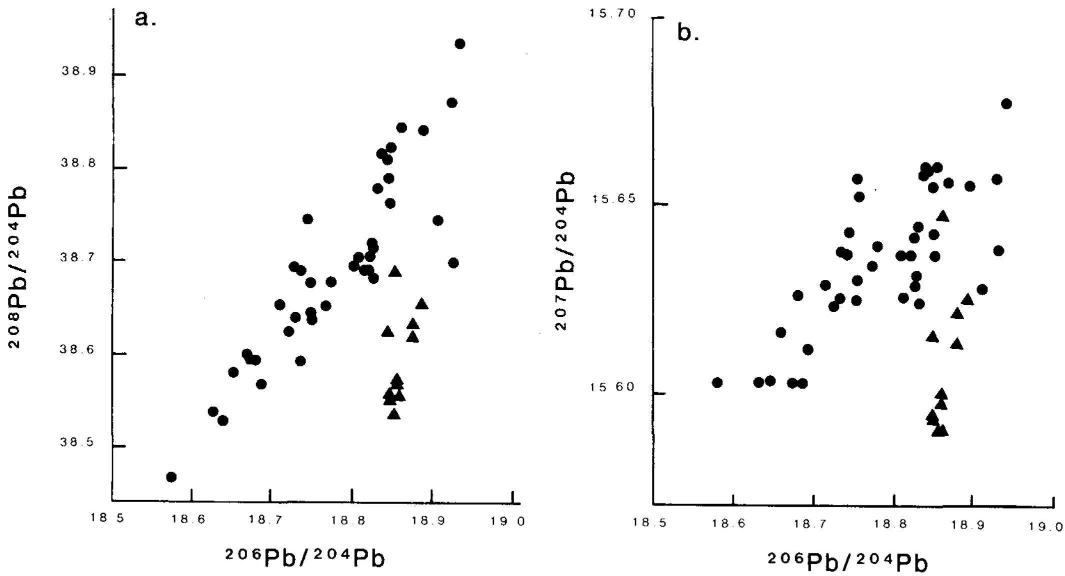


Fig. 16. Pb isotopic data on mid-Tertiary Upper Volcanic rocks and Cenozoic mineral deposits from Mexico. Cenozoic ore leads (stages 1 and 2; Cumming *et al.*, 1979) are shown as filled circles whereas Pb data on volcanic rocks from Batopilas area of the northern SMO (Barreiro *et al.*, 1982) are shown as filled triangles. (A) $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$, and (B) $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$.

few constraints on the source of parental magmas because the values lie within ranges compiled by Doe and Zartman (1979) for primitive and mature island arcs, pelagic sediments, and non-cratonized continental crust. The range in ratios is much smaller than those reported by Lipman *et al.* (1978) for the San Juan Mountains of Colorado or by Doe *et al.* (1982) for the Yellowstone region of Wyoming. $^{207}Pb/^{204}Pb$ ratios are higher than most MORBs, but $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ are within observed MORB ranges. The Pb isotopic data published on ore lead (also shown in Fig. 16) from 34 Mesozoic and Cenozoic mineral deposits of northern Mexico also have a relatively restricted range. Cumming *et al.* (1979) reported $^{206}Pb/^{204}Pb$ = 18.4 - 19.0 and $^{207}Pb/^{204}Pb$ values that extend from Doe and Zartman's (1979) field for mature arcs to more radiogenic values characteristic of pelagic sediments and non-cratonized continental crust.

Nd isotopic data on rocks of the SMO-SEC and MVB areas are also limited. Published data (mostly in abstracts) on the MVB are available for calc-alkalic and alkaline rocks of V. Colima (Carmichael and DePaolo, 1980), for peralkaline rocks of La Primavera (Halliday *et al.*, 1985), and for calc-alkalic rocks of Los Humeros (Verma, 1983), Chichinautzin (Verma and Armienta-H., 1985), and Paricutín (Reid, 1983, 1984). The calc-alkalic andesites of Colima have ϵ_{Nd} between +5 and +6, which is within the MORB range, whereas associated alkaline minettes and basanites have ϵ_{Nd} as low as +3 (Carmichael and DePaolo, 1980). Halliday *et al.* (1985) reported relatively primitive ϵ_{Nd} values of approximately +5.3 for high-silica rhyolites from La Primavera. Sr and Nd isotopic data on a range of volcanics (54 to 67% SiO_2) from Los Humeros plot within the mantle array (Verma, 1983). Andesitic, dacitic and rhyolitic volcanics from the Batopilas area of the northern SMO have ϵ_{Nd} values at or slightly above Bulk Earth (Cameron *et al.*, 1985). The data are similar to those of ocean island basalts and indicate little involvement of old sialic or continental material. In contrast, dacites from SEC (Cameron and Cameron, 1985) and rhyolites from Zacatecas (Verma, 1984a) exhibit slightly to moderately negative ϵ_{Nd}, which indicates some contamination or involvement of radiogenic crust.

PETROGENESIS

The discussion of petrogenesis that follows emphasizes results of published isotopic and trace element research. The conclusions reported are largely those of researchers whose papers are referenced, and the reader should consult cited papers for additional details.

Sierra Madre Occidental-Southeastern Chihuahua

The silicic nature of many continental arc rocks, such as those in the SMO-SEC areas, is often interpreted to reflect involvement of crustal materials in the generation and evolution of parental melts. Volcanics from the SMO-SEC do indeed display large variations in initial Sr ratios, with some ratios indicating little or no crustal involvement (e.g., McDowell *et al.*, 1978; Lanphere *et al.*, 1980) and others, especially those for silicic rocks, indicating a significant crustal component (e.g., Damon *et al.*, 1983; Duex, 1983; Ruiz *et al.*, 1983; McDowell and Henry, 1983; Verma, 1984a; Cameron and Cameron, 1985; Verma and Verma, 1986). Accordingly, petrogenetic studies on the SMO-SEC volcanics have attempted to elucidate the nature of crustal involvement (magma mixing vs assimilation/fractional crystallization vs partial melting), the overall volume or mass of crustal component involved, and the geochemical characteristics of the subcrustal and crustal source regions.

Batopilas (axial portion of the northern SMO). Major and trace element data and Sr, Pb, and Nd isotopic ratios were used to constrain the generation and evolution of the dominantly rhyolitic Upper Volcanic sequence of the Batopilas area (M. Cameron *et al.*, 1980; K. Cameron and Hanson, 1982; Barreiro *et al.*, 1982; Cameron *et al.*, 1985). The data presently available are consistent with the andesite to high-silica rhyolite series in that area being produced by fractional crystallization of plagioclase + pyroxene + amphibole + FeTi oxides. The voluminous 71 - 75% SiO_2 ignimbrites represent no more than the final 40% of an andesitic parent chemically similar to intermediate flows present in the sequence. Isotopic data are consistent with the fractionation occurring essentially in a closed magmatic system or in an environment where there was no isotopic contrast between the magma and wall rock (Cameron *et al.*, 1984; Cameron *et al.*, 1985). Parental magmas for calc-alkalic dacitic rocks from the SMO (and SEC) appear to have had a subcrustal source, with average Rb/Sr and Sm/Nd near that of Bulk Earth (Cameron and Cameron, 1985).

Durango-Mazatlán area (east-west transect across the middle SMO). The Upper Volcanic supergroup in the Durango-Mazatlán area is dominantly calc-alkalic rhyolitic ignimbrite, although minor amounts of other rock types are present. The 32-28 m.y. rhyolites near Durango City, in the eastern SMO, have a different phenocryst assemblage and are more K-rich compared to the ~23 m.y. volcanics further to the west (McDowell and Keizer, 1977; Swanson *et al.*, 1978). There are no published petrogenetic studies involving trace element/isotopic modelling of these rocks, but based on the observed range in initial Sr isotopic ratios (0.7033 to 0.7062) McDowell *et al.* (1978; p.290) concluded that "little or no radiogenic crustal material was involved in generating magmas that produced the upper volcanic supergroup".

Huspeni *et al.* (1984) examined the geochemistry of rhyolites in six tin districts in the general vicinity of Durango. Sr isotopic data collected by these authors showed that the host rhyolites and cap ignimbrites in all districts fall on the same Sr isotopic isochron, and thus appear to be "comagmatic products of a differentiated magma chamber" (p. 96). They further state that the "relatively radiogenic nature of the tin rhyolites . . . suggests that their magmas were contaminated or are partial melts of the Mexican crust". Because these rocks form good isochrons, the authors conclude that "the bulk of the crustal contamination of the tin-rich magmas must have occurred before they homogenized isotopically in magma chambers . . . and supports an origin by partial melting of the lower crust" (p.101).

Chihuahua (eastern portion of the northern SMO). The high-K calc-alkalic rocks of southeastern Chihuahua range in composition from basalt to rhyolite. Felsic rocks are volumetrically important, but volcanics of intermediate composition are more prominent than they are in the SMO. A recent isotopic and trace element study by Gunderson *et al.* (1986) provided evidence that both magma mixing and crustal interaction were important in generating some of the andesitic and dacitic lavas in SEC. AFC (assimilation-fractional crystallization) modelling of Sr isotopic data indicates that the most contaminated andesites and dacites contain about 25% crustal component. In a Sr and Nd isotopic study of high-K calc-alkalic dacites from three areas in southeastern Chihuahua (SEC), Cameron and Cameron (1985) concluded that the source region for these rocks was isotopically similar to that which produced the Batopilas lavas of the SMO, but it was enriched in LIL (large ion lithophile) and HFS (high field strength) elements. They proposed that the source region had $^{87}Sr/^{86}Sr = 0.7042$ to 0.7050 and $\epsilon_{Nd} = +3$ to -2.

Duex (1983) published Sr isotopic data on volcanics from the eastern SMO near the towns of Cuauhtémoc-La Junta in the state of Chihuahua. Basalts he analyzed have initial Sr ratios (Fig. 15) in the range 0.7025 - 0.7071, which he interpreted to reflect a heterogeneous source area. Rhyolites from the same area have initial ratios between 0.7045 and 0.7083, which he explains in terms of zoned magma chambers whose upper portions were contaminated with radiogenic crustal materials.

San Luis Potosí-Zacatecas (eastern portion of the southern SMO). Sr and Nd isotopic data were used by Verma (1984a) to constrain the petrogenesis of rhyolitic lavas and tuffs from San Luis Potosí and Zacatecas (Fig. 1). The isotopic variations in these rocks were interpreted in terms of "a binary mixing model in which magmas derived from a slightly-depleted mantle fractionate and mix with varying proportions of the overlying middle/upper continental crust and undergo further shallow level fractional crystallization before eruption" (Verma, 1984a, p.37). His slightly-depleted mantle has ϵ_{Nd} = +7 and $^{87}Sr/^{86}Sr$ = 0.7038, and his mixing model requires ~30 - 80% involvement of a crustal component.

Ruiz *et al.* (1983) also determined Sr isotopic ratios on two mid-Tertiary suites from the La Salitrera area in San Luis Potosí. One 32 m.y. suite of andesites/dacites/rhyolites has an initial ratio of 0.70603, whereas a second genetically-unrelated suite comprised only of dacites has Sr_i of 0.7054 - 0.7072. The latter were interpreted to have formed as a result of mixing, with one hypothetical end member being a mildly alkalic basalt with Sr_i~0.7040 and the other end member being a high-K calc-alkalic rhyolite with Sr_i~0.7085.

Mexican Volcanic Belt

Generation of the MVB volcanics is commonly related to subduction of the Cocos (and ?Rivera) plate beneath the North American plate (e.g., Thorpe and Francis, 1975; Molnar and Sykes, 1969; Nixon, 1982; Luhr *et al.*, 1985). Sr isotopic ratios of andesites of the MVB are low (Fig. 15), and indicate minimal (?no) involvement of radiogenic crust with parental magmas (e.g., Moorbath *et al.*, 1978; Verma and Verma, 1986). The limited amount of Nd data, available for calc-alkalic rocks of Colima, Paricutín, Sierra Chichinautzin, and Los Humeros and for mildly-peralkaline rhyolites of La Primavera, lie within or the right of the mantle array.

Ceboruco (western MVB). The most detailed geochemical study addressing the petrogenesis of Ceboruco volcanics is that of Nelson (1980), who used crystal fractionation models to explain major and trace element variations. Nelson (1980) recognized the following five distinct groups of calc-alkalic lavas erupted from the central volcanic complex: precaldera andesites, postcaldera andesites, the Jala pumice group, second-stage dacites, and 1870 dacites. Modelling showed that crystal fractionation of the postcaldera andesites could generate both the Jala pumice and the 1970 dacites, although the latter relationship is the only feasible choice based on eruptive sequences and other considerations. The fractionating assemblages included various proportions of orthopyroxene, clinopyroxene, plagioclase, magnetite, and apatite.

After examining and modelling trace element concentrations, Nelson (1980) concluded that generation of the andesites was a complex process "involving partial melting, fractional crystallization, magma mixing, and, perhaps, crustal assimilation" (p.2291).

The distinctive alkali-rich characteristics of the Ceboruco volcanics, and their higher $^{87}Sr/^{86}Sr$, K_2O, TiO_2, P_2O_5, Rb, Y, Zr, Ba, La, and Yb relative to volcanics of the central MVB has been recognized by many researchers (e.g., Thorpe and Francis, 1975; Moorbath *et al.*, 1978; Luhr and Nelson, 1980). Moorbath *et al.* (1978) concluded that the slightly higher Sr isotope ratios of the Ceboruco rocks might reflect the Sr isotope composition of the mantle beneath the volcano, thus implying some degree of mantle heterogeneity in the MVB.

Sangangüey (western MVB). Contemporaneous calc-alkalic and alkaline volcanics are present in the region around Sangangüey. The calc-alkalic magmatism has been related indirectly to subduction processes and the alkaline magmatism to extensional tectonics (Nelson and Carmichael, 1984). The calc-alkalic rocks include basalts, andesites and dacites erupted from the main volcanic center. The alkaline rocks include alkali basalts, hawaiites, mugearites, and benmoreites erupted from cinder cones associated with the main volcano (Nelson and Carmichael, 1984). Presently available data (e.g., Livieres and Nelson, 1983) provide no evidence of interaction between Sangangüey's calc-alkalic and alkaline magmas. Additional studies show that some of the calc-alkalic basalts cannot be related to the alkaline suite, and that the alkali basalts were not parental (at least by simple closed system crystal fractionation) to the hawaiites (Nelson and Carmichael, 1984). None of the alkali basalts analyzed in the latter study appear to be unmodified primary magma produced by direct partial melting of the mantle, and they may represent mixtures of primitive magma with more evolved compositions in the suite. Nelson and Carmichael (1984) also showed that major and trace element variations in the hawaiite to benmoreite series can be explained by fractionation of olivine + plagioclase + augite + magnetite, and sometimes apatite.

Colima (Colima graben and central MVB). Contemporaneous calc-alkalic and alkaline volcanics also occur in the area around the Colima volcanic complex. Post-caldera calc-alkalic hornblende and olivine andesites were studied by Luhr and Carmichael (1980); basic alkaline rocks (potassic basanites/leucite basanites/minettes) from associated cinder cones by Luhr and Carmichael (1981); and alkaline scoria and ash-fall deposits at V. Colima by Luhr and Carmichael (1982). Additionally, Allen and Carmichael (1984) examined the geochemistry of lamprophyric lavas (phlogopite- and hornblende-bearing lamprophyres and ankaratrites) in the Colima graben north of V. Colima. Major element variations in the post-caldera suite at Colima can be produced by crystal fractionation involving various combinations of plagioclase, olivine, orthopyroxene, clinopyroxene, hornblende, and titanomagnetite (Luhr and Carmichael, 1980). However, enrichment of the transition metals Cr, Ni, and Zn could not be modelled successfully by either crystal fractionation or magma mixing, and Luhr and Carmichael (1980) concluded that these anomalous enrichments resulted from simultaneous crystal fractionation and mixing of primitive magma injected periodically into the subvolcanic system. The basanites, leucite basanites and minettes that occur in cinder cones northwest and northeast of V. Colima represent primitive, high temperature magmas that are greatly enriched in incompatible trace elements (Luhr and Carmichael, 1981). The same study showed that the alkaline basanites and minettes and calc-alkaline suite cannot be related by fractionation of any reasonable mineral assemblage. Luhr and Carmichael (1982), however, concluded that the minette and calc-alkalic magmas may have mixed in the subvolcanic system of V. Colima to produce alkaline scoria observed at the eruptive center. Variations in Nd isotopic data available for Colima calc-alkalic and alkaline rocks (Carmichael and DePaolo, 1980) were interpreted in terms of two scenarios: *(1)* the lavas could represent magmas contaminated by continental crust, with successively lower ϵ_{Nd} values indicating more contamination (although the effects of such contamination are not obvious in the rock chemistry), or *(2)* the crust in this area is "underlain by some amount of low Sm/Nd (high K, Rb, Ce . . .) mantle that formed concomitantly with the crust".

Primavera (Colima graben and central MVB). Eruptive units of the volcanic center at La Primavera are high-silica rhyolites. Detailed studies of these rocks by Mahood (1981a, b) resulted in the following conclusions: *(1)* Most of the volcanic units are mildly-peralkaline, with major element variations among the various rocks being small and minor/trace element variations being more pronounced; *(2)* there is strong evidence that the post-caldera lavas erupted from a single unified magma chamber, although the chemical trends do not reflect tapping of a static zoned magma chamber that is more differentiated near the top; *(3)* the temporal/chemical variations within the post-caldera lavas/Tala Tuff were not produced by crystal settling or incremental partial melting alone. Other processes such as transport of trace metals as volatile complexes and emigration of trace elements within melts may also have been very important (Mahood, 1981b).

The presence of alkaline rocks at La Primavera and in other areas of the Colima-Chapala-Zacoalco grabens provides evidence for a major episode of continental rifting in the northwestern portion of the Trans-Mexican Volcanic Belt (Luhr *et al.*, (1985). Alkaline magmas have erupted since the Pleistocene, and Luhr *et al.* (1985) suggested that extension began in the Pliocene during the initial stage of an eastward jump of the East Pacific Rise spreading center. In a recent paper Mahood *et al.* (1985) suggested that the extensional regime may have been present for at least 3.3 m.y. Her evidence is the peralkaline nature of the 3.3 m.y. Guadalajara ignimbrite that crops out north, northeast, and east of Sierra La Primavera.

Jorullo (Central MVB). The eruptive products of Jorullo Volcano and associated cinder cones range from early, hypersthene-normative primitive basalts to late-stage quartz-normative, basaltic andesites (Luhr and Carmichael, 1985). The presence of such primitive calc-alkaline basalts is significant because they represent a compositional range that is rarely erupted in mature arcs and stratovolcanoes, and thus they may provide some insight into the early stages of evolution of calc-alkalic arc magmas (Luhr and Carmichael, 1985). Compositional variations within the calc-alkalic suite at Jorullo are "most consistent with simple crystal fractionation of olivine + augite + plagioclase + minor spinel at lower crustal to upper mantle pressures. Early formed augite and plagioclase were effectively removed from the Jorullo lavas prior to eruption; the actual minerals in the lavas appear to have crystallized at low pressure" (Luhr and Carmichael, 1985, p.157). The authors stated that bulk crustal assimilation was insignificant, but that anomalous enrichments of the LREE and other incompatible trace elements indicate that other processes were operative concomitant with crystal fractionation. Luhr and Carmichael also reported primitive, nepheline-normative trachybasalts in a cinder and lava cone 3 km south of Jorullo. These alkaline rocks and the calc-alkalic ones at Jorullo cannot be related to one another by simple crystal fractionation and bulk assimilation processes, and the authors concluded that they "must represent fundamentally different partial melting events in the mantle" (p.142).

Paricutín (central MVB). The chemistry of volcanic rocks at Paricutín varies regularly with time from early (1943) calc-alkalic basaltic andesite to late (1952) hypersthene andesites (Wilcox, 1954). Wilcox showed by graphical methods that geochemical variations in associated rocks could not be explained by fractionation of phenocryst phases alone. A combination of processes—fractional crystallization of olivine + plagioclase and assimilation of salic country rock—provided a satisfactory solution, which was later quantified by Bryan (1969). Two Sr isotopic analyses presented by Tilley *et al.* (1968) seemed to limit or preclude contamination by old crustal sialic material, but recent isotopic and trace element research by Reid (1983, 1984) indicates some contamination is probable. Reid (1984, p.133) concludes that "Three phases of crustal contamination ± fractional crystallization are recognized. Preliminary U-series nuclide data indicate that assimilation may have occurred within decades of eruption." and "mass balance considerations taken together with the trace element data show that the silicic component was most likely not older sialic crust."

Los Humeros (back arc area in central MVB). Volcanics comprising the Los Humeros eruptive center range from basalt to high-silica rhyolite (Verma and López, 1982; Ferriz and Mahood, 1984). The rock series shows a general trend through time toward increasingly mafic compositions, which Ferriz and Mahood (1984, p.8511) attributed to "an increasing volumetric rate of eruption that exceeded the rate of regeneration of differentiated magma." Verma and López (1982) and Verma (1984b) concluded that the dominant petrogenetic process which produced chemical variations within the rock series was crystal fractionation of plagioclase, olivine and clinopyroxene, and perhaps biotite and titanomagnetite in later stages of differentiation. Sr and Nd isotopic data of the Los Humeros volcanics (Verma, 1983) lie on the mantle array, and indicate very little contribution from altered and subducted oceanic crust, sediment, or continental crust. The initial $^{87}Sr/^{86}Sr$ ratios of the more differentiated rocks overlap with those of the less differentiated, which also supports a comagmatic origin for the Los Humeros volcanics (Verma, 1984b, p.36).

Tuxtla (eastern MVB and eastern alkaline province). Volcanics from the Tuxtla area comprise an alkaline picrite basalt-basanitoid-alkali basalt-hawaiite association (Thorpe, 1977). Pichler and Weyl (1975) suggested that "two volcanic groups are present; an undersaturated alkaline suite and a 'mugearitic' group, the latter possibly derived from 'tholeiitic or olivine tholeiitic basaltic parent magmas' " (Thorpe, 1977, p.T22). However, Thorpe (1977) showed that available analyses from the area lie within the alkali basalt field on a total alkalies vs SiO_2 plot, and he concluded that none of the chemical data examined provide evidence for a tholeiitic basalt parent. Sr isotopic ratios for San Martin basanites and alkali basalts lie in the range reported for other alkali basalts (Moorbath *et al.*, 1978).

Numerous researchers (e.g., Thorpe, 1977; Robin and Tournon, 1978; Cantagrel and Robin, 1979) have concluded that the alkaline Tuxtla province is petrologically distinct from the calc-alkalic MVB, and Robin and Tournon (1978) suggested that it could be a southward extension of the alkaline volcanism in Trans-Pecos, Texas. Volcanics from the both of these areas are generally sodic in nature, especially in comparison to the relatively K-rich alkaline rocks in the Colima-Chapala-Zacoalco grabens in the western MVB.

CONCLUSIONS

1. *Major and Trace Element Characteristics of Volcanic Rocks of the SMO and contiguous areas to the northeast.* The volumetrically-dominant mid-Tertiary rocks of the Sierra Madre Occidental (SMO) are calc-alkalic rhyolitic ignimbrites. Interlayered lava flows of intermediate-felsic composition are relatively minor. Dacitic and andesitic rocks are common in SEC northeast of the SMO ignimbritic plateau. A moderate-K calc-alkalic facies is recognized within axial portions of the SMO whereas a high-K facies is recognized along the eastern margins of the SMO and especially in southeastern Chihuahua. The geographic extent of each facies and the nature of the boundary between the two facies are not known. Additional mid-Tertiary rock types reported in the literature for the SMO-SEC areas include mildly alkaline basalts in the SMO and mildly alkaline basalts and ferroaugite rhyolites (including peralkaline varieties) in Chihuahua.

Comparison of the moderate-K facies from the Batopilas area of the northern SMO and the high-K facies from SEC (SV, LP, BP areas) shows that the latter is enriched in total alkalies, K_2O, Rb, Nb, Zr, Th, La, and Y and is depleted in CaO and Sr relative to the moderate-K facies. The high-K facies also has higher K/Rb, $(La/Yb)_N$, and Nb/Y than the moderate-K facies.

2. *Major and Trace Element Characteristics of Neovolcanics of the MVB.* Neovolcanic centers of the MVB are comprised dominantly of calc-alkalic basaltic andesite and andesite. Calc-alkalic volcanics of the western MVB (e.g., Ceboruco) are chemically distinguishable from those of the central MVB volcanoes (Colima, Popocatepetl, Orizaba, Toluca, Paricutín). Andesites of Ceboruco have higher total alkalies, K_2O, Na_2O, TiO_2, P_2O_5, Ba, La, and $(Ce/Yb)_N$ and lower CaO, MgO, Cr and Ba/La compared to volcanics of the central MVB. Los Humeros, which occupies a back-arc position in the central MVB, contains more evolved rocks whose geochemical characteristics are distinct from those of the calc-alkalic centers along the frontal portion of the arc. When rocks of similar silica content are compared, samples from Los Humeros have higher total alkalies, K_2O, TiO_2, Zr, La, and Y and commonly lower CaO, MgO, Sr, and Ba/La.

Alkaline rocks are present in the western, central, and eastern MVB segments–with those in the eastern and western MVB associated with areas of known crustal extension or rifting. Alkaline volcanics in the western MVB include both felsic and mafic varieties, the latter having erupted contemporaneously with calc-alkalic volcanics at some localities. Eruptive centers in the extreme eastern portion of the MVB are comprised of mafic alkaline rocks, but are considered by many researchers to be distinct from the MVB volcanic belt. The alkaline rocks seem to vary in chemistry, with those that occur in the Colima graben (peralkaline rhyolites at Primavera and mafic alkaline rocks at Colima) generally being more K_2O-rich than rocks either from Sangangüey in the western MVB or from Tuxtla in the eastern MVB.

3. *Comparison of Major and Trace Element Variations in Calc-Alkalic Andesites of the SMO and MVB.* Calc-alkalic andesites from the Batopilas area of the northern SMO and from the central MVB zone (except Los Humeros) have similar total alkalies, K_2O, Na_2O, CaO, Sr, Zr, and $(Ce/Yb)_N$. The SMO andesites have lower MgO and K/Rb and higher FeO*, TiO_2, Rb, Th, La, and Y than calc-alkalic volcanics of the central MVB.

4. *Comparison of Major and Trace Elements of SMO-SEC and MVB Andesites with Andesites of Other Areas.* Chemical analyses of the Mexican andesites were compared to Ewart's (1982) averaged mean compositions of andesites from the Andes, the western U. S. (western zone), the Aleutians-Alaska-Cascades, and the southwestern Pacific. In general, the central MVB and northern SMO (Batopilas) andesites are more similar to andesites from the southwestern Pacific and the Aleutians-Alaska-Cascades whereas andesites from Ceboruco are more similar to Andean andesites.

The K_2O, Rb, Sr, Ba, Zr, and La contents of the Ceboruco rocks are especially similar to those of Andean andesites.

5. *Mineralogical Variations.* Clino- and orthopyroxenes in andesites from the northern SMO (Batopilas area) and from the central MVB (Colima and Jorullo) are very Mg-rich and show limited compositional variations. Pyroxenes in the alkali-rich calc-alkalic andesites from the western MVB (Ceboruco) and from SEC (LP-SV-BP areas) show greater variability, with their compositions ranging to more Fe-rich values. Plagioclase in calc-alkalic andesites of the central MVB and moderate-K andesites of the SMO typically have compositions in the range An_{73} to An_{45}, but those in the more alkali-rich andesites at Ceboruco and SEC are as sodic as An_{20}. Fe-Ti oxide data on volcanics from five centers in the MVB and two in the SMO-SEC indicate a

range in oxygen fugacities and equilibration temperatures. Oxygen fugacities for the SMO-SEC volcanics plot midway between the H-M and Ni-NiO buffer curves. Volcanics from the central MVB (Colima and Jorullo) have similar values whereas alkali-rich volcanics in the back arc area of the central MVB (Los Humeros) and the western MVB (Ceboruco) appear to have significantly lower values.

6. *Isotopic Variations.* $^{87}Sr/^{86}Sr$ ratios in the MVB volcanics are restricted to the range 0.7035 to 0.7047, and thus show little evidence for significant interaction with old radiogenic crust. In contrast, calc-alkalic volcanics from the SMO-SEC areas exhibit variations from 0.7033 to 0.7614. The range in ratios reported at any specific locality can be large, and the values for silicic rocks in many areas indicate significant involvement of radiogenic crust.

Pb isotopic data on 11 volcanic rocks from the Batopilas area of the northern SMO are remarkably homogeneous. The ratios lie within the ranges compiled by Doe and Zartman (1979) for primitive and mature island arcs, pelagic sediments, and non-cratonized continental crust. The $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios are lower than those reported for ore leads in a variety of Cenozoic mineral deposits of northern Mexico.

ϵ_{Nd} values of calc-alkalic MVB volcanics are generally greater than bulk earth (up to = +6.0), and on ϵ_{Nd} vs ϵ_{Sr} diagrams the calc-alkalic rocks plot near or slightly to the right of the mantle array. ϵ_{Nd} for the mafic alkaline rocks of Colima range as low as $\epsilon_{Nd} = +3$ whereas ϵ_{Nd} of +5.3 were reported for peralkaline rhyolites at Primavera. ϵ_{Nd} for andesitic, dacitic and rhyolitic volcanics from the northern SMO (Batopilas area) are near or slightly above Bulk Earth, and are consistent with little involvement of old sialic or continental crustal material. ϵ_{Nd} for dacites from SEC and rhyolites from Zacatecas exhibit slightly to moderately negative ϵ_{Nd} values, which is consistent with some contamination or involvement of radiogenic continental crust.

7. *Petrogenesis of the SMO-SEC Volcanics.* Detailed petrogenetic studies on volcanics of the SMO and adjacent areas to the northeast are limited. The petrogenetic scenarios envisioned for various areas differ principally in the nature of crustal involvement (magma mixing vs partial melting vs assimilation-fractional crystallization) and also in the overall volume or mass of crustal component involved. The voluminous rhyolites of the Batopilas area (northern SMO) are perhaps atypical in that they may be the end product of essentially closed-system fractional crystallization

of magma derived from a subcrustal source. Isotopic data available on most other areas of the SMO indicate some contamination by radiogenic crust. The chemical variations are interpreted by various researchers as indicating partial melting, magma contamination, or magma mixing followed by shallow level fractional crystallization. Many of the variations can be explained by an assimilation-fractional crystallization model involving less than 25% of a crustal component. Modelling of Nd isotopic data on samples from SEC indicates that the parental magmas were contaminated by <25% crustal component.

8. *Petrogenesis of the MVB Volcanics.* The nature of the source region and the mechanism for generation of magmas parental to the MVB volcanics has not been examined in a comprehensive manner by means of combined trace element/isotopic studies. Presently available data indicate that parental magmas for the MVB volcanics were not contaminated significantly by radiogenic crustal materials. The dominant process responsible for intrasuite variations at the various andesitic volcanic centers is fractional crystallization, although minor assimilation and magma mixing may also have been important.

ACKNOWLEDGEMENTS

This study was supported by N.S.F. grant EAR 81-22046. We acknowledge the thorough and constructive reviews of Dr. S. Verma and three anonymous referees. Diana Diez de Medina helped with computer work and drafting.

BIBLIOGRAPHY

ALLAN, J. F. and I. S. E. CARMICHAEL, 1984. Lamprophyric lavas in the Colima graben, SW Mexico. *Contrib. Mineral. Petrol.*, *88*, 203-216.

BAGBY, W.C., 1979. Geology, geochemistry, and geochronology of the Batopilas region, Sierra Madre Occidental, Chihuahua, Mexico. Unpubl. Ph. D. dissertation, Univ. of California at Santa Cruz, Santa Cruz, California, 271 pp.

BAGBY, W. C., K. L. CAMERON and M. CAMERON, 1981. Contrasting evolution of calc-alkalic volcanic and plutonic rocks of western Chihuahua, Mexico. *J. Geophys. Res.*, *86*, 10402-10410.

BARREIRO, B., M. CAMERON, K. CAMERON and A. GRUNDER, 1982. A lead isotope study of silicic and intermediate volcanic rocks from south-central Chile and the Sierra Madre Occidental, Mexico. *Carnegie Inst. Wash. Year Book*, *81*, 494-498.

BLOOMFIELD, K. and L. CEPEDA-DAVILA, 1973. Oligocene alkaline igneous activity in NE Mexico. *Geol. Mag., 110,* 551-555.

BRYAN, W. B., 1969. Materials balance in igneous rock suites. *Carnegie Inst. Wash. Year Book, 67,* 241-243.

CAMERON, K. L. and M. CAMERON, 1985. Rare-earth element, $^{87}Sr/^{86}Sr$, and $^{143}Nd/^{144}Nd$ compositions of Cenozoic orogenic dacites from Baja California, northwestern Mexico, and adjacent west Texas: Evidence for the predominance of a subcrustal component. *Contrib. Mineral. Petrol., 91,* 1-11.

CAMERON, K. L. and G. N. HANSON, 1982. Rare earth element evidence concerning the origin of voluminous mid-Tertiary rhyolitic ignimbrites and related volcanic rocks. Sierra Madre Occidental, Chihuahua, Mexico. *Geochim. Cosmochim. Acta, 46,* 1489-1503.

CAMERON, M., W. C. BAGBY and K. L. CAMERON, 1980. Petrogenesis of voluminous mid-Tertiary ignimbrites of the Sierra Madre Occidental, Chihuahua, Mexico. *Contrib. Mineral. Petrol., 74,* 271-284.

CAMERON, M., K. L. CAMERON and B. BARREIRO, 1984. ?Closed system evolution of the voluminous mid-Tertiary ignimbrites of the Batopilas region, Sierra Madre Occidental, Mexico. *Proceed. of Conf. on Open Magmatic Systems,* ISEM Southern Methodist University, Dallas, Texas, 21-22.

CAMERON, K. L., M. CAMERON, W. C. BAGBY, E. J. MOLL and R. E. DRAKE, 1980. Petrologic characteristics of mid-Tertiary volcanic suites, Chihuahua, Mexico. *Geology, 8,* 87-91.

CAMERON, K. L., M. CAMERON and B. BARREIRO, 1985. Origin of voluminous mid-Tertiary ignimbrites of the Batopilas region, Chihuahua: Implications for the formation of continental crust beneath the Sierra Madre Occidental. *Geofís. Int., 25*-1, 39-59.

CAMPBELL, A. R., 1977. Volcanic rocks of the La Perla area, Chihuahua, Mexico. Unpubl. M. A. thesis, Univ. of Texas at Austin, Austin, Texas, 110 pp.

CANTAGREL, J. M. and C. ROBIN, 1978. Géochimie isotopique du strontium dans quelques séries types du volcanisme de l'Est mexicain. *Bull. Soc. Géol. France, XX,* 935-939.

CANTAGREL, J. M. and C. ROBIN, 1979. K-Ar dating in eastern Mexican volcanic rocks–relations between the andesitic and the alkaline provinces. *J. Volcanol. Geotherm. Res., 5,* 99-114.

CANTAGREL, J. M., C. ROBIN and P. VINCENT, 1981. Les grandes étapes d'évolution d'un volcan andésitique composite: exemple du Nevado de Toluca (Mexique). *Bull. Volcanol., 44,* 177-188.

CAPPS, R. C., 1981. Geology of the Rancho El Papalote area, Chihuahua, Mexico. In *Uranium in Volcanic and Volcaniclastic Rocks* (Eds. P. C. Goodell and A. C. Waters), *Amer. Assoc. Petrol. Geol. Studies in Geol., 13,* 243-264.

CARMICHAEL, I. S. E. and D. J. DePAOLO, 1980. Nd and Sr isotopes in the lavas of Colima, Mexico. *Geol. Soc. Am. Abst. with Progr., 12,* 398.

CUMMING, G. L., S. E. KESLER and D. KRSTIC, 1979. Isotopic composition of lead in Mexican mineral deposits. *Econ. Geol., 74,* 1395-1407.

DAMON, P. E., M. SHAFIQULLAH and K. F. CLARK, 1983. Geochronology of the porphyry copper deposits and related mineralization of Mexico. *Can. J. Earth Sci., 20,* 1052-1071.

DEMANT, A., 1978. Características del eje neovolcánico Transmexicano y sus problemas de interpretación. *UNAM, Inst. Geol. Revista, 2,* 172-187.

DEMANT, A., 1979. Vulcanología y petrografía del sector occidental del eje neovolcánico. *UNAM, Inst. Geol. Revista, 3,* 39-57.

DEMANT, A. and J. J. COCHEME, 1983. Le volcanisme basaltique mio-pliocène de la frontière Sonora-Chihuahua, Sierra Madre Occidental, Mexique. *C. R. Acad. Sc. Paris, 296,* 1253-1258.

DEMANT, A. and C. ROBIN, 1975. Las fases del volcanismo en México: una síntesis en relación con la evolución geodinámica desde el Cretácico. *UNAM, Inst. Geol. Revista, 1,* 70-82.

DOE, B. R. and R. E. ZARTMAN, 1979. Plumbotectonics, the Phanerozoic in *Geochemistry of Hydrothermal Ore Deposits* (Ed. H. L. Barnes), 2nd Edition: 22-70, John Wiley, New York.

DOE, B. R., W. P. LEEMAN, R. L. CHRISTIANSEN and C. E. HEDGE, 1982. Lead and strontium isotopes and related trace elements as genetic tracers in the Upper Cenozoic rhyolite-basalt associations of the Yellowstone Plateau volcanic field, U. S. A., *J. Geophys. Res., 87,* 4785-4806.

DUEX, T. W., 1983. The role of crustal contamination in the evolution of mid-Tertiary rhyolites, Sierra Madre Occidental, Mexico. *Geol. Soc. Am. Abst. with Progr., 15,* 13-14.

EWART, A., 1979. A review of the mineralogy and chemistry of Tertiary-Recent dacitic, latitic, rhyolitic, and related salic volcanic rocks: *in* Trondhjemites, Dacites and Related Rocks (Ed. F. Barker) Elsevier, Amsterdam, 13-121.

EWART, A., 1982. The mineralogy and petrology of Tertiary-Recent orogenic volcanic rocks, with special reference to the andesitic-basaltic compositional range *in* Andesites (Ed. R. S. Thorpe), John Wiley and Sons, 25-95.

FERRIZ, H. and G. A. MAHOOD, 1984. Eruption rates and compositional trends at Los Humeros volcanic center, Puebla, Mexico. *J. Geophys. Res., 89,* 8511-8524.

GILL, J., 1981. Orogenic Andesites and Plate Tectonics. Springer-Verlag, New York, 390 pp.

GUNDERSON, R. P., 1983. Geology and geochemistry of the Benavides-Pozos area, eastern Chihuahua, Mexico. M. S. thesis, Univ. California, Santa Cruz, 135 pp.

GUNDERSON, R. P., K. L. CAMERON and M. CAMERON, 1986. Mid-Cenozoic high-K calc-alkalic and alkalic volcanism in eastern Chihuahua, Mexico: geology and geochemistry of the Benavides-Pozos area. *Bull. Geol. Soc. Am., 97,* 737-753.

GUNN, B. M. and F. MOOSER, 1971. Geochemistry of the volcanics of central Mexico. *Bull. Volcanol., 34,* 577-616.

HALLIDAY, A., G. MAHOOD and W. HILDRETH, 1985. Mantle signature for high-silica rhyolites with < 1 ppm Sr: Sierra La Primavera, Mexican Volcanic Belt (MVB). *EOS, 66,* 1136.

HUSPENI, J. R., S. E. KESLER, J. RUIZ, Z. TUTA, J. F. SUTTER and L. M. JONES, 1984. Petrology and geochemistry of rhyolites associated with tin mineralization in northern Mexico. *Econ. Geol., 79,* 87-105.

KELLER, P. C., N. T. BOCKOVEN and F. W. McDOWELL, 1982. Tertiary volcanic history of the Sierra del Gallego area, Chihuahua, Mexico. *Geol. Soc. Am. Bull., 93,* 303-314.

LANPHERE, M. A., K. L. CAMERON and M. CAMERON, 1980. Sr isotopic geochemistry of voluminous rhyolitic ignimbrites and related rocks, Batopilas area, western Mexico. *Nature, 286,* 594-596.

LIPMAN, P. W., B. R. DOE, C. E. HEDGE and T. A. STEVEN, 1978. Petrologic evolution of the San Juan volcanic field, southwestern Colorado: Pb and Sr isotope evidence. *Geol. Soc. Am. Bull., 89,* 59-81.

LIVIERES, R. A. and S. A. NELSON, 1983. The geology and petrology of volcán Sangangüey, Nayarit, México. *Geol. Soc. Am. Abst. Progr., 15,* 628-629.

LUHR, J. F. and I. S. E. CARMICHAEL, 1980. The Colima Volcanic Complex, Mexico I. Post-caldera andesites from volcán Colima. *Contrib. Mineral. Petrol., 71,* 343-372.

LUHR, J. F. and I. S. E. CARMICHAEL, 1981. The Colima Volcanic Complex, Mexico: Part II. Late-Quaternary cinder cones. *Contrib. Mineral. Petrol., 76,* 127-147.

LUHR, J. F. and I. S. E. CARMICHAEL, 1981. The Colima Volcanic Complex, Mexico: III. Ash- and scoria-fall deposits from the upper slopes of volcán Colima. *Contrib. Mineral. Petrol., 80,* 262-275.

LUHR, J. F. and I. S. E. CARMICHAEL, 1985. Jorullo volcano, Michoacan, Mexico (1759-1774): The earliest stages of fractionation in calc-alkalic magmas. *Contrib. Mineral. Petrol., 90,* 142-161.

LUHR, J. F. and S. A. NELSON, 1980. Volcanological and geochemical contrasts between two Mexican volcanoes: Colima and Ceboruco. *EOS, 61,* 69.

LUHR, J. F., S. A. NELSON, J. F. ALLAN and I. S. E. CARMICHAEL, 1985. Active rifting in southwestern Mexico: manifestations of an incipient eastward spreading-ridge jump. *Geology, 13,* 54-57.

MAHOOD, G. A., 1981a. A summary of the geology and petrology of the Sierra La Primavera, Jalisco, Mexico. *J. Geophys. Res., 86,* 10137-10152.

MAHOOD, G. A., 1981b. Chemical evolution of a Pleistocene rhyolitic center: Sierra La Primavera, Jalisco, Mexico. *Contrib. Mineral. Petrol., 77,* 129-149.

MAHOOD, G. A., C. M. GILBERT and I. S. E. CARMICHAEL, 1985. Peralkaline and metaluminous mixed-liquid ignimbrites of the Guadalajara region, Mexico, *J. Volcan. Geotherm. Res., 25,* 259-271.

MAUGER, R. L., 1981. Geology and petrology of the central part of the Calera del Nido block, Chihuahua, Mexico. *In* Uranium in Volcanic and Volcaniclastic Rocks (Eds. P. C. Goodell and A. C. Waters). *Am. Assoc. Petrol. Geol. Studies in Geol., 13,* 205-242.

McDOWELL, F. W. and S. E. CLABAUGH, 1979. Ignimbrites of the Sierra Madre Occidental and their relation to the tectonic history of western Mexico. *Geol. Soc. Am. Spec. Paper, 180,* 113-124.

McDOWELL, F. W. and C. D. HENRY, 1983. Late Cretaceous to Tertiary magmatic arcs in western Mexico and west Texas. *Geol. Soc. Am. Abst. Progr., 15,* 302.

McDOWELL, F. W. and R. P. KEIZER, 1977. Timing of mid-Tertiary volcanism in the Sierra Madre Occidental between Durango City and Mazatlán, México. *Geol. Soc. Am. Bull., 88,* 1479-1487.

McDOWELL, F. W., T. W. DUEX, C. D. HENRY and L. E. LONG, 1978. Age and strontium isotope chemistry of the Sierra Madre Occidental volcanic province, western Mexico *in:* Short Papers of the Fourth International Conference, Geochronology, Cosmochronology, Isotopes Geology (Ed. R. E. Zartman) U. S. Geological Survey Open-File Report 78-701, 289-291.

MIYASHIRO, A., 1978. Nature of alkalic volcanic rock series. *Contrib. Mineral. Petrol., 66,* 91-104.

MOLL, E. J., 1981. Geochemistry and petrology of mid-Tertiary ash flow tuffs from the Sierra El Virulento area, eastern Chihuahua, Mexico. *J. Geophys. Res., 86,* 10321-10334.

MOLNAR, P. and L. R. SYKES, 1969. Tectonics of the Caribbean and middle America region from focal mechanism and seismicity. *Geol. Soc. Amer. Bull., 80,* 1639-1684.

MOORBATH, S., R. S. THORPE and I. L. GIBSON, 1978. Strontium isotope evidence for petrogenesis of Mexico andesites. *Nature, 271,* 437-439.

NELSON, S. A., 1980. Geology and petrology of Volcán Ceboruco, Nayarit, Mexico: summary. *Geol. Soc. Am. Bull., Part 1, 91,* 639-643; *Part 2, 91,* 2290-2431.

NELSON, S. A. and I. S. E. CARMICHAEL, 1984. Pleistocene to recent alkalic volcanism in the region of Sangangüey volcano, Nayarit, Mexico. *Contrib. Mineral. Petrol., 85,* 321-335.

NIXON, G. T., 1982. The relationship between Quaternary volcanism in central Mexico and the seismicity and structure of subducted ocean lithosphere. *Geol. Soc. Amer. Bull., 93,* 514-523.

PAL, S. and J. URRUTIA-FUCUGAUCHI, 1977. Paleomagnetism, geochronology and geochemistry of some igneous rocks from Mexico and their tectonic implications. *IV Internat. Gondwana Symp., 1977,* 814-831.

PAL, S., M. LOPEZ-M., J. PEREZ-R. and D. J. TERRELL, 1978. Magma characterization of the Mexican Volcanic Belt. *Bull. Volcanol., 41,* 379-389.

PEACOCK, M. A., 1931. Classification of igneous rock series. *J. Geol., 39,* 54-67.

PICHLER, H. and R. WEYL, 1975. Magmatism and crustal evolution in Costa Rica and Central America. *Geol. Rundschau, 64,* 457-475.

REID, M. R., 1983. Paricutín Volcano revisited: Isotopic and trace element evidence for crustal assimilation. *EOS, 64,* 907.

REID, M. R., 1984. Isotopic and trace element geochemistry of Paricutín Volcano. *Proceed. Conf. on Open Magmatic System,* ISEM, Southern Methodist University, Dallas, Texas, 133-134.

ROBIN, C., 1982. Mexico *in* Andesites (Ed. R. S. Thorpe) John Wiley and Sons, 137-147.

ROBIN, C. and A. DEMANT, 1975. Les quatre provinces volcaniques du Mexique; relations avec l'évolution géodynamique depuis le Crétacé: synthèse Miocène-Quaternaire. *C. R. Acad. Sc. Paris, Serie D, 280,* 2437-2440.

ROBIN, C. and E. NICOLAS, 1978. Particularités géochimiques des suites andésitiques de la zone orientale de l'axe transmexicain, dans leur contexte tectonique. *Bull. Soc. Geol. France, XX,* 193-202.

ROBIN, C. and J. TOURNON, 1978. Spatial relations of andesitic and alkaline provinces in Mexico and Central America. *Can. J. Earth Sci., 15,* 1633-1641.

RUIZ, J., L. M. JONES and S. E. KESLER, 1983a. Strontium isotope evidence for crustal contamination during the evolution of mid-Tertiary ignimbrites from the Sierra Madre Occidental in central Mexico. *EOS, 64,* 326.

RUIZ, J., F. ORTEGA-G. and E. J. ESSENE, 1983b. Geochemical and petrographic characteristics of inclusions in Cenozoic alkalic basalts from central Mexico. *EOS, 64,* 343.

RUIZ, J., S. E. KESLER and L. M. JONES, 1985. Strontium isotope geochemistry of fluorite mineralization associated with fluorine-rich igneous rocks from the Sie-

965-C, U. S. Government Printing Office, Washington, 281-354.
WILLIAMS, H., 1950. Volcanoes of the Paricutín region, Mexico. *U. S. Geol. Surv. Bull., 965-B,* U. S. Government Printing Office, Washington, 165-279.

(Received: May 6, 1985)
(Accepted: March 10, 1986)

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

M. Cameron, K. Spaulding and K. L. Cameron, 1987. A synthesis and comparison of the geochemistry of volcanic rocks of the Sierra Madre Occidental and Mexican Volcanic Belt. *Geofís. Int.,* Special Volume on Mexican Volcanic Belt - Part 3A *(Ed. S. P. Verma),* Vol. 26-1, pp. 29-84.