ORIGIN OF VOLUMINOUS MID-TERTIARY IGNIMBRITES OF THE BATOPILAS REGION, CHIHUAHUA: IMPLICATIONS FOR THE FORMATION OF CONTINENTAL CRUST BENEATH THE SIERRA MADRE OCCIDENTAL

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RESUMEN

Las ignimbritas riolíticas de la región de Batopilas, del norte de la Sierra Madre Occidental, están interestratifica-das con un número menor de lavas andesíticas y dacíticas. Varias líneas de evidencia indican que esta serie an-desita - dacita - riolita es co-magmática. Por ejemplo, esta serie es distinta químicamente de rocas ígneas más jó-venes y más viejas de la misma región; no se observan variaciones sistemáticas en composición isotópica, y las va-riaciones en elementos-traza en la serie pueden ser modeladas por cálculos de fraccionación Rayleigh. Las varia-ciones en las concentraciones de Sr no concuerdan con un origen de fusión parcial para la serie y las riolitas pare-cen ser el producto de un sistema cerrado de cristalización fraccionada de magmas de una fuente subcortical.

Los resultados adicionales publicados sobre riolitas terciarias de otras cuatro áreas de la Sierra Madre Occiden-tal establecen que estas rocas son heterogéneas isotópicamente, al compararlas con las de Batopilas y que algunas de ellas contienen una componente cortical. La fuente sub-cortical debajo de la Sierra Madre Occidental tiene cocientes de $^{87}Sr/^{86}Sr$ entre 0.7042 y 0.7050 y ϵ_{Nd} cercanos a cero. La mayoría de las riolitas analizadas tienen razones iniciales de Sr menores de 0.7070 y sus composiciones isotópicas pueden explicarse por un modelo de asimilación y cristalización fraccionada que abarca menos del 25% de componente cortical. La extrusión de la secuencia Volcánica Superior y el emplazamiento del batolito marcaron un evento mayor de formación de corte-za en el occidente de México.

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ABSTRACT

The voluminous rhyolitic ignimbrites of the Batopilas region of the northern Sierra Madre Occidental are inter-layered with minor amounts of andesitic and dacitic lava flows. Several lines of evidence indicate that this andesite - dacite - rhyolite series is comagmatic. For example, the series is chemically distinct from older and younger igneous rocks found in the same geographical region; it lacks systematic variations in isotopic compositions; and trace element variations within the series can be modeled by Rayleigh fractionation calculations. Variations in Sr concentrations are inconsistent with a partial melting origin for the series, and the voluminous rhyolites of the Batopilas region appear to be the product of essentially closed-system fractional crystallization of magmas from a subcrustal source.

Additional published data on mid-Tertiary rhyolites from four other areas of the Sierra Madre Occidental establish that these rocks are isotopically heterogeneous compared to those from Batopilas and that some of them clearly contain a crustal component. The subcrustal source region beneath the Sierra Madre Occidental is believed to have $^{87}Sr/^{86}Sr$ between about 0.7042 and 0.7050, and ϵ_{Nd} near 0. Most analyzed rhyolites have initial $^{87}Sr/^{86}Sr < 0.7070$ and their isotopic compositions can be explained by an assimilation - fractional crystallization model that involves less than 25% of a crustal component. The extrusion of the Upper Volcanic sequence and the emplacement of the underlying batholith marked a major crust forming event in western Mexico.

INTRODUCTION

In their field aspects, the rhyolitic tuffs of the Batopilas region (Fig. 1) of western Chihuahua appear typical of the vast ignimbrite plateau that caps the Sierra Madre Occidental. The Upper Volcanic Sequence, the unit in which the ignimbrites occur, is about 1 km thick here, and it is composed of 80-90% rhyolitic tuff with relatively minor amounts of interlayered intermediate and silicic lavas (Bagby, 1979). The origin of the ignimbrites and associated intermediate lavas of the Batopilas region is addressed in a number of papers. M. Cameron *et al.* (1980) presented major and trace element (Sr, Rb, Y, Th, Zr, and Nb) analyses on about 60 rocks, and Lanphere *et al.* (1980) reported $^{87}Sr/^{86}Sr$ data on 13 of these samples. This suite was further characterized by analyses of the rare earth element (REE) concentrations of 16 samples (K. Cameron and Hanson, 1982) and of the Pb isotopic compositions of 11 rocks (Barreiro *et al.*, 1982). Bagby *et al.* (1981) compared the geochemistry of the Upper Volcanic sequence to that of late Cretaceous to Tertiary plutonic rocks from the same geographical region. Finally, the geochemistry of the Batopilas rocks is discussed in the broader context of spatial geochemical trends across the mid-Cenozoic magmatic arc in K. Cameron *et al.* (1980), M. Cameron *et al.* (1983), and Cameron and Cameron (1985).

The major conclusion drawn from this collection of studies is that the Batopilas andesite - dacite - rhyolitic ignimbrite series is coherent chemically and that it lacks

systematic variations in isotopic compositions. The geochemical data are consistent with the series being related by closed - system crystal fractionation of magmas of a subcrustal origin with little or no crustal interaction. Isotopic studies of rocks from elsewhere in the Sierra Madre Occidental are quite limited in number, and except for Verma (1984), they were published only in the form of abstracts or notes (McDowell *et al.*, 1978; Duex, 1983; Ruiz *et al.*, 1983). Nevertheless, these studies establish that rocks from other areas in the Sierra Madre Occidental are more heterogeneous isotopically than those from Batopilas, and some rocks clearly show isotopic evidence of a significant crustal component.
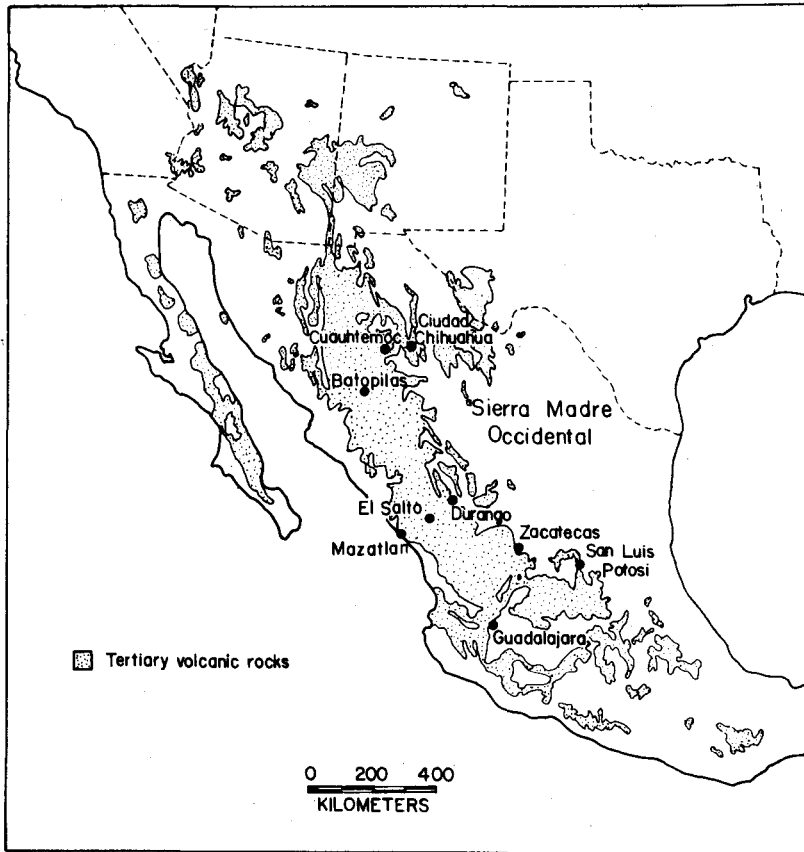

Fig. 1. Location map.

Petrogenetic models for the origin of the Upper Volcanic sequence must consider at least two end - member sources, one subcrustal and the other crustal. A fundamental objective of petrogenetic studies is assessment of the relative contributions of these sources. For example, is the silicic nature of the Upper Volcanic sequence a direct reflection of a large contribution of the crustal component, or is the crustal component of second order importance? Was a large amount of new material added to the crust of western Mexico during the mid-Tertiary, or was prexisting crust simply reworked? The quantitative evaluation of the relative contributions of the crustal and subcrustal sources requires characterization of their major and trace element and isotopic compositions. It is understood that each of these end - member sources was probably exceedingly complex and heterogeneous, and was probably zoned both horizontally and vertically. Nevertheless, some compositional constraints can be put on the sources from geologic and geochemical data (e.g. Nimz *et al.*, this volume).

Although the Batopilas samples are not geochemically representative of rocks from the entire Sierra Madre Occidental, they do appear typical in their field aspects. Their special importance is that they may have evolved by an end-member, nearly closed-system process. If this is true, then they provide important information regarding the trace element and isotopic composition of the subcrustal source, and they demonstrate that large volumes of rhyolite can be produced without a major crustal component. The purpose of this paper is to summarize the pertinent geochemical arguments related to the origin of the Batopilas rocks. We then estimate, using assimilation - fractional crystallization calculations, the amount of crustal contamination needed to produce deviations from the Batopilas data of the magnitude found elsewhere in the Sierra Madre Occidental (Verma, 1984). Finally, we briefly consider the implications of these calculations regarding the origin of the continental crust beneath western Mexico.

GEOLOGY OF THE BATOPILAS REGION

The oldest rocks exposed in the Batopilas region comprise a late Mesozoic to Tertiary volcanic - plutonic complex. The extrusive rocks of this complex are referred to as the Lower Volcanic sequence, and they are largely lahars and lavas of intermediate composition. These rocks are extensively altered, and little geochemical data exist on them. The plutonic rocks form a bimodal population of quartz diorites and granodiorites, approximately equal in abundance. One granodiorite yielded biotite

and hornblende K-Ar ages of about 83 m.y., but plutonic activity probably extended into the Cenozoic (Bagby, 1979). This 83 m.y. old pluton intruded and metamorphosed rocks of the Lower Volcanic sequence, but in other areas rocks of the Lower Volcanic sequence are believed to unconformably overlie plutons (Bagby, 1979). The time span represented by this volcanic-plutonic complex is not well constrained, but is believed to encompass tens of millions of years.

The older complex is overlain unconformably by the Upper Volcanic sequence. Although stratigraphic sections in this sequence were measured, the internal stratigraphy in the Batopilas region has not been mapped in detail. Three K-Ar ages of rhyolites lie in the range 30 to 26 m.y. (Bagby, 1979), which is similar to ages reported on the Upper Volcanic sequence elsewhere in the Sierra Madre Occidental (McDowell and Clabaugh, 1979; Clark *et al.*, 1982). Likewise, the aggregate thickness of the ignimbrites and the ratio of rhyolite to intermediate rocks in the Upper Volcanic sequence in the Batopilas region appears typical of the ignimbrite plateau of the Sierra Madre Occidental. The stratigraphic section is about 1 000 m thick, and is $\geqslant 80\%$ rhyolite. No basalts and only one basaltic andesite were found within this sequence. Andesites and dacites occur locally as lava flows interlayered with the ignimbrites. In overall geochemical characteristics the Upper Volcanic sequence is calc-alkalic.

Overlying the Upper Volcanic sequence are rocks of the mildly alkalic basaltic suite (K. Cameron *et al.*, 1980). One of these basalts from Batopilas was dated at 21 m.y., and another from a large field about 70 km to the west gave an age of 24 m.y. McDowell and Clabaugh (1979) reported ages of about 28 m.y. on basalts north of the Batopilas region.

CONSANGUINITY OF THE UPPER VOLCANIC SEQUENCE

In this section we establish the consanguinity, that is genetic relationship, of the andesite - dacite - rhyolite series of the Upper Volcanic Sequence by showing that it is geochemically coherent and distinct from igneous rocks of other ages from the Batopilas region. Volcanic rock names used throughout this paper are based on SiO_2 content: basalt $< 53\%$ SiO_2, basaltic andesite 53-56% SiO_2, andesite 56-63% SiO_2, dacite 63-70% SiO_2, and rhyolite $\geqslant 70\%$ SiO_2. The plutonic rocks are classified on modal mineralogy, but the quartz diorites generally contain 57-63% SiO_2 and the granodiorites 66-68% SiO_2 (Bagby *et al.*, 1981).

Rocks from the Upper Volcanic sequence of the Batopilas region vary from 54 to 78% SiO_2, and they define continuous trends on major and trace element silica variation diagrams (M. Cameron *et al.*, 1980). The voluminous ignimbrites generally contain between 71 and 75% SiO_2, whereas most rocks containing more than 75% SiO_2 are rhyolitic lavas. The plutonic rocks have, compared to rocks of the Upper Volcanic sequence at similar SiO_2 contents, slightly higher Al_2O_3 and slightly lower TiO_2, P_2O_5, and total Fe (Bagby *et al.*, 1981). Furthermore, the granodiorites have noticeably lower Y and Zr, and higher Sr than the dacites. The mildly alkalic basaltic suite is enriched in most alkali and high-field-strength elements (e.g., K, Ti, P, Zr, Y, Nb and REE) relative to the Upper Volcanic sequence (K. Cameron *et al.*, 1980).
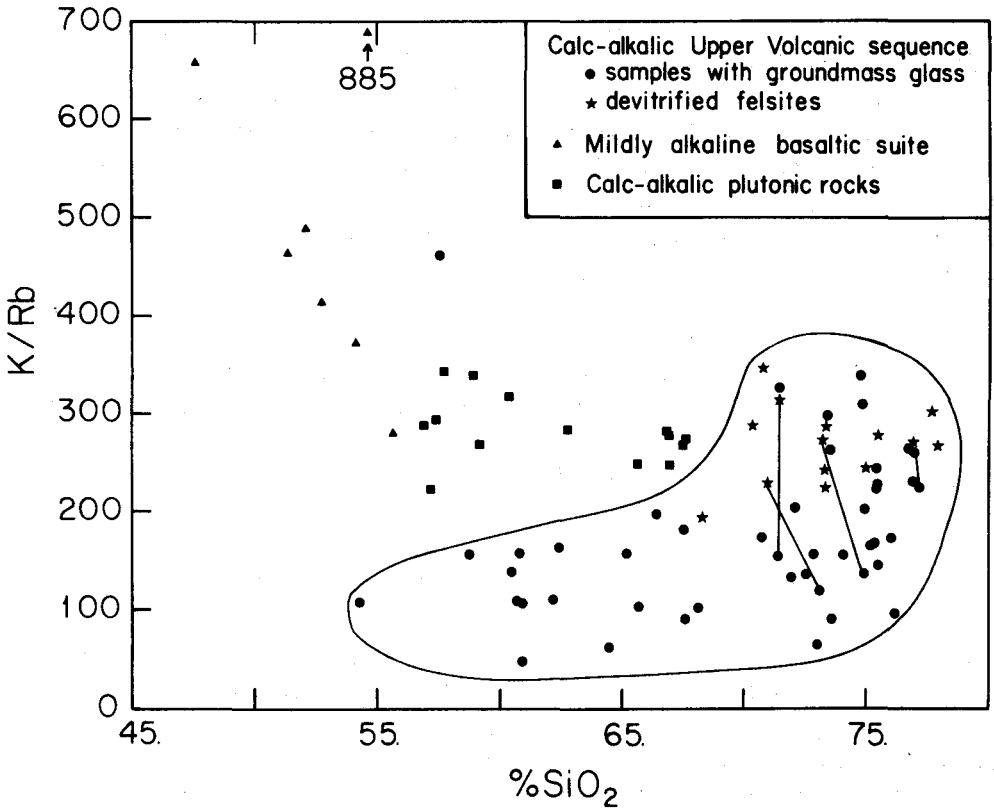

Fig. 2. Variation of K/Rb with SiO_2 of rocks from the Upper Volcanic Sequence, the older plutons, and the mildly alkaline basaltic suite. Lines connect vitrophyre - devitrified samples from the same outcrop. Figure from M. Cameron *et al.* (1980).

The distinctiveness of the Upper Volcanic sequence is shown even more clearly by interelement ratios. The K/Rb ratios of all intermediate rocks but one from the Upper Volcanic sequence are ≤ 200, and they are significantly lower than those of the plutonic and basaltic rocks (Fig. 2). The K/Rb ratios of the rhyolites show considerable scatter, which in part is related to crystallinity. In the four felsite (devitrified) - vitrophyre pairs, the felsites invariably have higher K/Rb than the vitrophyres (Fig. 2). Aboult half of the rhyolites have K/Rb ratios similar to the intermediate rocks (≤ 200), and these rhyolites are vitrophyres with one exception. Most felsites and some vitrophyres have K/Rb > 200. Thus the scatter in the K/Rb may reflect differing mobilities of K and Rb during post-solidification processes.
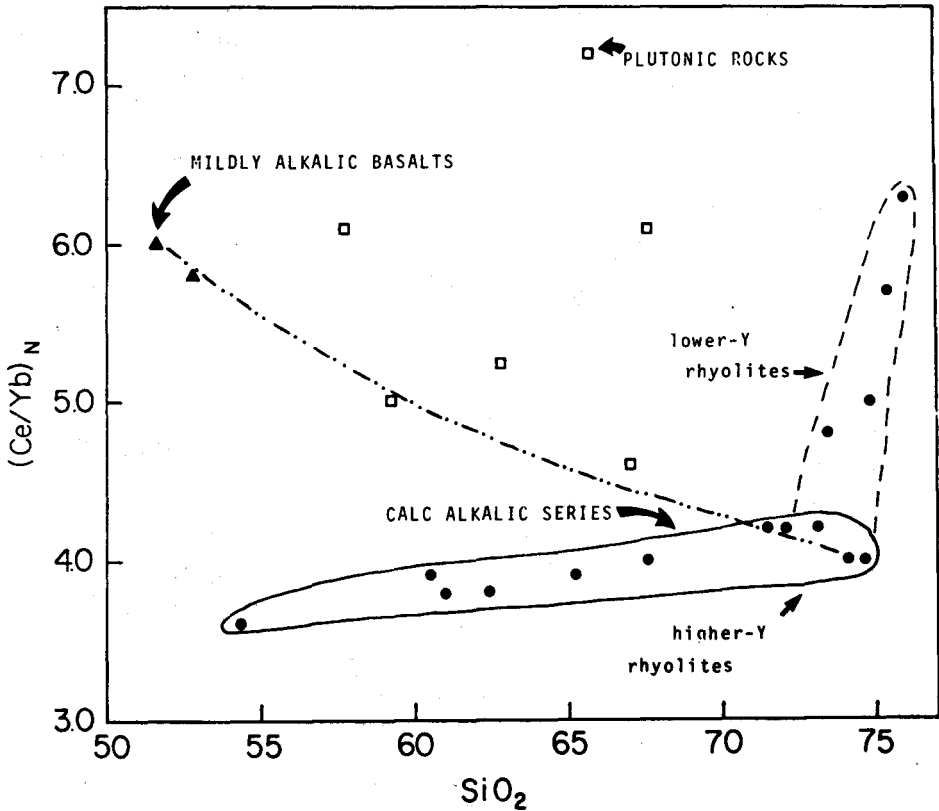

Fig. 3. Chondrite - normalized Ce/Yb vs. SiO_2. Triangles: mildly alkaline basaltic suite. Squares: plutonic rocks. Solid circles: Upper Volcanic Sequence. Data from K. Cameron and Hanson (1982) and Bagby *et al.* (1981). A calculated mixing curve between the mildly alkaline basalts and the average ignimbrite is shown.

M. Cameron *et al.* (1980) and K. Cameron and Hanson (1982) divided the rhyo-
lites into two groups based on their yttrium (Y) content. Pyroxene is believed to be
the principal mafic silicate involved in the evolution of rhyolites containing greater
than 32 ppm Y, whereas hornblende fractionation was important in those contain-
ing less than 32 ppm Y. Most ignimbrites are the *higher*-Y variety. Figure 3 shows
that the basaltic andesite, andesites, dacites, and *higher*-Y ignimbrites define a regul-
ar trend of slightly increasing (Ce/Yb)n, that is the chondrite normalized ratio of Ce
to Yb, with increasing SiO_2. This series has much lower (Ce/Yb)n than the mildly
alkalic basalts and plutonic rocks of similar SiO_2 content.

The geochemical distinctiveness discussed above argues that the Upper Volcanic
sequence is consanguineous, but even more convincing evidence is provided by the
results of Rayleigh fractionation calculations. These calculations closely model
changes in the REE patterns and other trace element concentrations throughout the
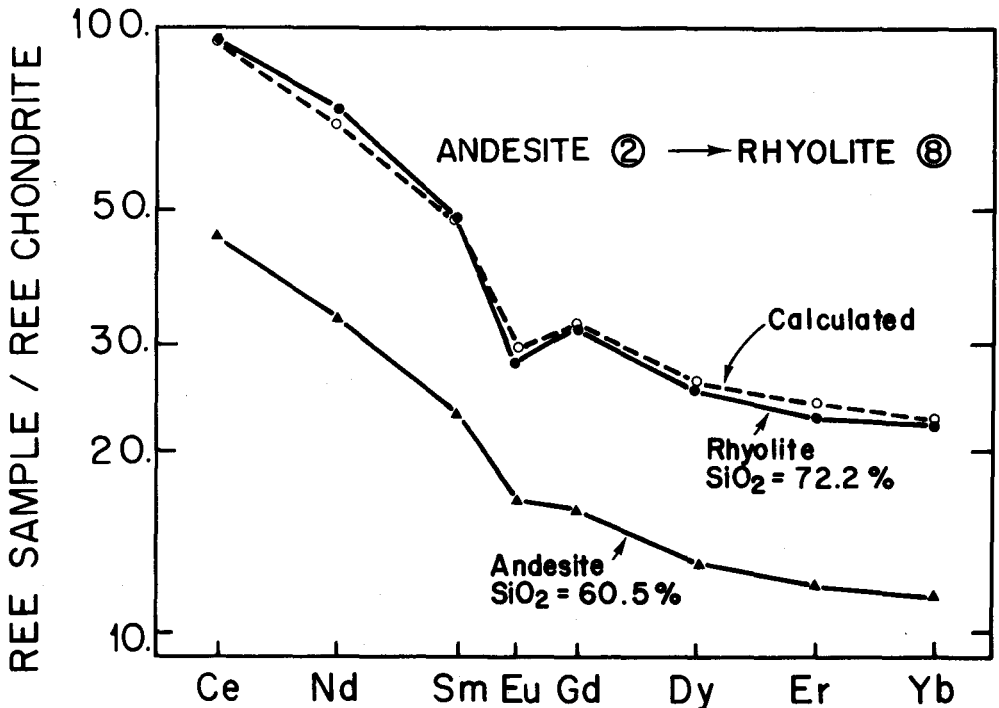andesite to rhyolite series of the Upper Volcanic sequence (Fig. 4; K. Cameron and

Fig. 4. Model REE pattern of a rhyolitic ignimbrite. Dotted line was calculated with the Rayleigh fractionation
equation by removal of 57 wt.% crystals (plagioclase, orthopyroxene, clinopyroxene, and Fe-Ti oxides in the
wt. proportions 63:11:17:9) from the andesite. See K. Cameron and Hanson (1981) for discussion of the cal-
culations.

Hanson, 1982, M. Cameron *et al.* 1980). However, the REE patterns of rocks within the Upper Volcanic sequence can *not* be modeled satisfactorily using either plutonic or mildly alkalic basalts as parents. The "goodness-of-fit" of these calculations is striking because the ignimbrites of the Batopilas region undoubtedly came from a number of different eruptive centers. The analyzed ignimbrites are believed to represent 16 different ash-flow sheets (M. Cameron *et al.*, 1980). As discussed below these calculations do not prove that the rocks of the Upper Volcanic sequence were produced by crystal fractionation, but they are a stringent test of the hypothesis that the rocks are comagmatic.

Two other lines of evidence support the hypothesis of consanguinity. One is the small but systematic changes in mineral chemistry found in the andesite to rhyolite series (M. Cameron *et al.*, 1980). The second is the relative uniformity of Sr, Pb, and Nd isotopic compositions, which is discussed in following sections. In summary, the rocks have passed every test of consanguinity. Obviously the rhyolites did not differentiate from the andesites along one line of liquid descent. Rather they represent a number of magmas that evolved by similar mechanisms from similar parents or source areas.

PETROGENETIC MODELS

The origin of the Batopilas andesite to rhyolite series, and indeed the entire Upper Volcanic sequence of the Sierra Madre Occidental, must be evaluated in terms of at least five petrogenetic models that are enumerated below:

(1) Closed-system fractional crystallization of mafic or intermediate composition magmas of subcrustal origin. In this case isotopic compositions should be compatible with a subcrustal source, and they should remain uniform throughout the rock series. Trace element concentrations can be modeled by the Rayleigh or "batch extraction" equations (e.g. Arth, 1976).

(2) Closed-system fractional crystallization of an intermediate composition magma of crustal origin. Presumably the isotopic compositions of these magmas should differ from those above, but if the crust is young, it may prove difficult to distinguish this case from (1).

(3) Generation of the rhyolites by direct crustal anatexis, perhaps· followed by some crystal fractionation. This model seems applicable for the origin of rhyolites

from Yellowstone National Park, U. S. A. (Doe *et al.*, 1982). Such rhyolites would be recognized geochemically by the isotopic signature of their crustal source. It is difficult to test the anatexis origin for the rhyolites *alone* using trace element data. However, an anatexis origin for a *series* of rocks (e.g., rhyolite to andesite) can be tested by trace element modeling. Trace elements with small bulk distribution behave similarly during fractional crystallization and partial melting, but the two processes can be distinguished using elements with relatively large bulk distribution coefficients (e.g., Hanson, 1978).

(4) Mixing of a rhyolitic magma of crustal origin with a more mafic magma, usually considered to have a subcrustal origin. Eichelberger (1978) and Kuo and Kirkpatrick (1982) described textural and mineralogical criteria for the recognition of rocks that have crystallized from hybrid magmas formed by mixing. Trace element and isotopic trends produced by mixing can be modeled by equations presented by Vollmer (1976), Langmuir *et al.* (1978), and DePaolo and Wasserburg (1979).

(5) Combined wallrock assimilation and fractional crystallization. Such models were discussed qualitatively for the San Juan volcanic field of Colorado, U. S. A. (Lipman *et al.*, 1978) and quantitatively for plutonic rocks of the western U. S. A. (DePaolo, 1981b; Farmer and DePaolo, 1983), volcanic rocks of the Andes (James, 1982), and dacitic rocks from Mexico (Cameron and Cameron, 1985). Equations to model trace element and isotopic variations resulting from assimilation and fractional crystallization were presented by DePaolo (1981a) and James (1981).

ORIGIN AND EVOLUTION OF THE BATOPILAS UPPER VOLCANIC SEQUENCE

In the following sub-sections we discuss data available for the Batopilas Upper Volcanic Sequence that allow us to distinguish among the various petrogenetic models outlined above.

Trace element data

The basaltic andesite (54% SiO_2) is the only sample from the Upper Volcanic Sequence that shows textural and mineralogical evidence of mixing (M. Cameron *et al.*, 1980). The basalt end-member involved in the mixing was not a mildly alkalic basalt because mixing curves between these basalts and silicic rocks lie well above the calc-alkalic basaltic andesite on Figure 3. The basaltic parent must lie along the

same trend as the calc-alkalic basaltic andesite, andesites and dacites on Figure 3, but at lower values of SiO_2 and $(Ce/Yb)n$. Although calc-alkalic basalts have not yet been found in the Batopilas region, the mixed nature of the basaltic andesite provides evidence for the existence of such magmas.

The Rayleigh fractionation calculations relating andesites and rhyolites (Fig. 4) are a strong argument for consanguinity, but they do not favor an origin by fractional crystallization over one by partial melting. The reason for this, as previously mentioned, is that trace elements with small bulk distribution coefficients behave similarly in rock series formed by crystal fractionation and partial melting. Thus Rayleigh calculations involving Th, Y, Rb, Zr, Nb and the REE are also consistent with the hypothesis that the rhyolite to andesite series formed by direct partial fusion of similar, plagioclase-bearing crustal sources. The voluminous ignimbrites would be produced by relatively small amounts of melting, whereas rocks of intermediate composition would represent local pockets of more extensive melting. The two petrogenetic processes can be distinguished by examining trace elements with bulk distribution coefficients greater than one, because they behave quite differently during fractional crystallization and partial melting. For a feldspar-bearing residue, Sr would have a bulk distribution greater than 1. M. Cameron *et al.* (1980) discussed in detail the behavior of Sr in the andesite to rhyolite series, and they showed that its behavior is inconsistent with partial melting. Thus the Sr data present an important argument against the andesite to rhyolite series having formed by partial melting.

The behavior of Sr and the other trace elements is compatible with and indeed strongly support the fractional crystallization hypothesis. On the basis of this model, the voluminous ignimbrites represent about 40% residual liquid from the andesites. The data are also consistent with the andesites being derived in turn from calc-alkalic basalts with low $(Ce/Yb)n$, and in this scenario the ignimbrites would represent about 20% residual liquid. However, no samples of these basalts have yet been found, and the evidence for their existence is indirect, i.e. the mixed nature of the basaltic andesite.

Bagby *et al.* (1981) discussed the origin of the plutonic rocks of the Batopilas region, and they concluded that the quartz diorites had an evolutionary history much like that of the andesites from the Upper Volcanic sequence. The granodiorites, in contrast, are believed to have originated by partial melting of a crustal source leaving a residue of amphibolite or garnet granulite.

Isotopic compositions of the Batopilas rocks

Lanphere *et al.* (1980) reported Sr isotopic compositions of 13 samples ranging in SiO_2 from 60.5% to 76.3%. Their data showed considerable dispersion of initial $^{87}Sr/^{86}Sr$, from 0.7042 to 0.7050, with an average value of about 0.7047. The initial ratios exhibited no systematic variation with rock composition and.

Three mildly alkalic basaltic rocks that were described in the REE paper by K. Cameron and Hanson (1982) have initial $^{87}Sr/^{86}Sr$ in the range 0.7049 to 0.7050 (K. Cameron unpub. data). These basaltic rocks have fairly high Sr contents (about 600 ppm), are aphanitic, and are xenocryst-free; thus, their Sr isotopic compositions should reflect that of their subcrustal source region. We call attention to the fact that the rocks from the Upper Volcanic Sequence have initial ratios similar to these basaltic rocks.

The plutonic rocks of the Batopilas region have Sr isotopic compositions that largely overlap with those of the Upper Volcanic sequence. Six quartz diorites have initial $^{87}Sr/^{86}Sr$ in the range 0.7045 to 0.7052, and two granodiorites have values of 0.7047 (Bagby *et al.*, 1981). A sample from a third granodiorite pluton has an initial ratio of 0.7053 (MX7539; Bagby *et al.*, 1981), and a second sample from this same pluton has an initial ratio of 0.7054 (MXB7703; Lanpheree unpub. data). This pluton, which was dated at 83 m.y. (Bagby, 1979), clearly originated from a more radiogenic source than the Upper Volcanic sequence. Thirty million years ago this pluton had $^{87}Sr/^{86}Sr$ of about 0.7056. Thus, isotopic contrast existed 30 m.y. ago between the magmas of the Upper Volcanic sequence and at least one of the granodiorite plutons and its source region.

Eleven samples from the Upper Volcanic sequence ranging from 60 to 76% SiO_2 are remarkably uniform in Pb isotopic compositions with $^{206}Pb/^{204}Pb = 18.86$, $^{207}Pb/^{204}Pb = 15.60$, and $^{208}Pb/^{204}Pb = 38.57$ (Barreiro *et al.*, 1982). They do not show the systematic and large variation found by Lipman *et al.* (1978) in the San Juan Mountains of Colorado (Fig. 5) or by Doe *et al.* (1982) in the Yellowstone region of Wyoming.

Barreiro (unpub. data) determined $^{143}Nd/^{144}Nd$ ratios of five samples. One ande-

site, one dacite, and two rhyolites have ratios that fall between 0.51274 (ϵ_{Nd} = +2.3)[1] and 0.51269 (ϵ_{Nd} = +1.3). A third rhyolite has a slightly lower ratio of 0.51262 (ϵ_{Nd} = −0.1). K. Cameron has determined the ratio of a second dacite to be 0.51264 (ϵ_{Nd} = +3). Granodiorite MX7539 contrasts with the Upper Volcanic sequence with respect to Nd as well as Sr isotopic composition. It has $^{143}Nd/^{144}Nd$ = 0.51252, which corresponds to ϵ_{Nd} = −1.9 at 30 m.y. ago and ϵ_{Nd} = −1.3 at 83 m. y. ago.
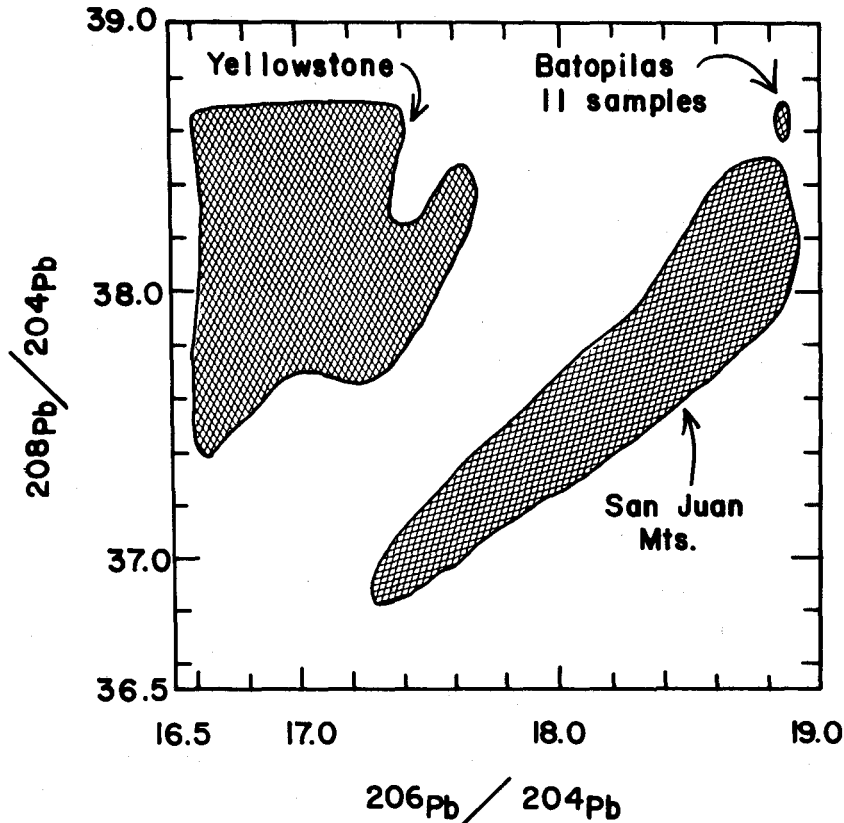

Fig. 5. Pb isotopic compositions of the Batopilas Upper Volcanic Sequence (from Barreiro *et al.*, 1982) compared to compositions of volcanic rocks from Yellowstone (Doe *et al.*, 1982) and the San Juan Mts., USA (Lipman *et al.*, 1978).

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[1] ϵ_{Nd} is the deviation in parts 10^4 of a rock's initial $^{143}Nd/^{144}Nd$ ratio from the ratio of $^{143}Nd/^{144}Nd$ in a model chondritic reservoir, CHUR (e.g. De Paolo and Wasserburg, 1979). All ϵ_{Nd} values are normalized to $^{146}Nd/^{144}Nd$ = 0.72190, and ϵ_{Nd} is based on $^{143}Nd/^{144}Nd$ CHUR = 0.512636, and Sm/Nd CHUR = 0.1967. Unless otherwise stated, ϵ_{Nd} is calculated for 30 m.y., and typical analytical uncertainties in ϵ_{Nd} are ±0.6.

Origin of the Batopilas Upper Volcanic sequence

The lack of systematic change of the isotopic data with increasing SiO_2 indicates that either the magmas behaved as closed systems, or that there was no isotopic contrast between the magmas and wall rock. The latter can not be ruled out, but it seems doubtful to us for two reasons. First, the magmas had to pass through the source region that produced the granodiorites, and at least part of this region had $^{87}Sr/^{86}Sr$ between 0.7054 and 0.7056, 30 m.y. ago. Assimilation - fractional crystallization calculations indicate that if the magmas assimilated about 20% wall rock with 250 ppm Sr and $^{87}Sr/^{86}Sr = 0.7056$, then the initial ratios of the rhyolites would be greater than 0.7050. The initial ratios of the rhyolites are < 0.7050, thus there is no evidence of substantial assimilation of crust even with relatively low $^{87}Sr/^{86}Sr$. Second, rhyolitic lavas from about 50 to 70 km north of Batopilas have initial $^{87}Sr/^{86}Sr$ ranging from 0.7055 to 0.7074 (Lanphere *et al.*, 1980). Thus, some radiogenic crust must exist beneath the Sierra Madre Occidental of western Chihuahua. The presence of radiogenic crust is also clearly shown by isotopic data from other areas in the Sierra Madre Occidental as discussed in the following section. Based on the present data we favor the hypothesis that the Upper Volcanic sequence of the Batopilas region evolved essentially as a closed system because there is no geochemical evidence for open system behavior. The isotopic compositions of the rocks, therefore, reflect those of the source region.

Although the Sr, Pb and Nd isotopic data are quite uniform for the Upper Volcanic sequence, they do not uniquely identify the source region. For example, the Pb isotopic compositions of the rocks are in the range of values delineated by Doe and Zartman (1979) for primitive and mature island arcs, pelagic sediments, and non-cratonized continental crust. The Sr and Nd data rule out the possibility that the rocks originated by anatexis of Precambrian craton. The isotopic data are consistent with the magmas originating from either a subcrustal or a "young" crustal source. We favor a subcrustal source for two reasons. First, the mantle beneath Batopilas is relatively radiogenic with respect to Sr isotopes, as shown by the data from the mildly alkalic basalts. Second, calc-alkalic dacites from Baja California, Batopilas, eastern Chihuahua, and the Chinati Mountains of west Texas cluster at initial $^{87}Sr/^{86}Sr$ = 0.7046 (± 0.0004) and ϵ_{Nd} = 0.0 (± 1.0) (Cameron and Cameron, 1985). These dacites are separated by more than 600 km and are from areas underlain by North American craton as well as areas lacking such crust. The regional uniformity of isotopic compositions suggests a subcrustal source.

lite from San Luis Potosi. $^{143}Nd/^{144}Nd$ data were presented for the andesite, six rhyolites from Zacatecas, and the rhyolite from San Luis Potosi. The andesite has an initial Sr isotopic ratio of about 0.7051 and $\epsilon_{Nd} = +1.4$. The rhyolites from Zacatecas range widely in initial $^{87}Sr/^{86}Sr$, from 0.7051 to 0.7105, but all have ϵ_{Nd} restricted to the range $+1.4$ and -1.4. The rhyolite from San Luis Potosi has an initial Sr isotopic composition of 0.7149 and $\epsilon_{Nd} = -2.3$. Verma presented a binary mixing model in which magmas from a slightly depleted mantle ($\epsilon_{Nd} = +7$, $^{87}Sr/^{86}Sr = 0.7038$) mix with an upper/middle crustal source with $\epsilon_{Nd} = -5$ and $^{87}Sr/^{86}Sr$ between about 0.7090 and 0.7200. Verma's mixing model requires from 30 to 80% of the crustal component to explain the range of variation observed in the samples. Textures indicative of mixing are not discussed.

Several important points emerge from this brief review of the available isotopic data from the Sierra Madre Occidental. First, the Sr isotopic compositions of the Batopilas Upper Volcanic sequence are extremely homogeneous compared to other areas studied thus far in the Sierra Madre Occidental. Second, initial $^{87}Sr/^{86}Sr$ ratios less than about 0.7042 are rare in the mid-Tertiary rocks, even basalts. Probably no more than two or three such ratios have been found (McDowell *et al.*, 1978; Duex, 1983), and it is not known if those analyses have been replicated. Third, many of the silicic rocks from the Sierra Madre Occidental clearly contain a crustal component, but such a component is not necessarily required in rocks with initial $^{87}Sr/^{86}Sr$ less than about 0.7050. Fourth, the Nd isotopic compositions of mid-Tertiary calc-alkalic rocks from Batopilas, Zacatecas, Baja California, eastern Chihuahua, and west Texas group rather tightly (this study; Verma, 1984; Cameron and Cameron, 1985). All samples with initial $^{87}Sr/^{86}Sr$ less than 0.7050 (total of 11) have ϵ_{Nd} between $+2.3$ and -0.8. It should be pointed out that these were analyzed in three different laboratories. Nine of these eleven cluster at $\epsilon_{Nd} = +0.7 \pm 1.0$.

All workers agree that there is a significant crustal component in some, perhaps most, silicic rocks of the Sierra Madre Occidental (Duex, 1983; Ruiz *et al.*, 1983; McDowell and Henry, 1983; Verma, 1984; Cameron and Cameron, 1985). There is, however, disagreement on the following points: (1) the character of the subcrustal and crustal source regions, especially the former; (2) the mechanism of crustal interaction, i.e. magma mixing vs. assimilation - fractional crystallization; and (3) the overall volume or mass significance of the crustal component.

Based on the very limited data available at present from the Sierra Madre Occiden-

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Based on the very limited data available at present from the Sierra Madre Occiden-

tal, we favor a model where many, perhaps most, magmas evolve by assimilation - fractional crystallization, but some (e.g., Batopilas) differentiate as essentially closed systems. The source region which produced the parental magmas was not "depleted" like the source regions of most arcs, and it had a time integrated history with Rb/Sr and Sm/Nd near that of the bulk earth. Rocks from the Sierra Madre Occidental with ϵ_{Nd} more negative than about -1.0 and initial $^{87}Sr/^{86}Sr$ greater than about 0.7050 probably contain a significant crustal component. Nevertheless, crustal interaction is not required to produce voluminous rhyolites, and the silicic nature of the ignimbrites does not necessarily indicate a major crustal component. Thick continental crust may just provide the room needed for large magma chambers to form and the conditions necessary for extensive fractionation to occur.

The "slightly-depleted", arc-like source favored by Verma does not explain the clustering of many ϵ_{Nd} values near zero and the lack of ϵ_{Nd} values more positive than $+2.3$. However, we agree with his conclusion that the magmas have interacted with the crust. Cameron and Cameron (1985) and Gunderson *et al.* (in press) have modeled the isotopic compositions of dacites and rhyolites from eastern Chihuahua by assimilation - fractional crystallization of parental basalts with ϵ_{Nd} about 0 and $^{87}Sr/^{86}Sr$ about 0.7042. Silicic rocks with initial $^{87}Sr/^{86}Sr$ as high as 0.7070 can be modeled with low assimilation rates (r less than 0.2) and Ma/Mo (mass of assimilated wall rock/mass of original magma) less than 0.25. (See DePaolo, 1981a, and Farmer and DePaolo, 1983 for the method of calculations.) We reinterpret Verma's data as a group of three nearly uncontaminated rocks with ϵ_{Nd} near zero ($+1.4$ to -0.8) and initial $^{87}Sr/^{86}Sr$ of 0.7051. From this cluster, five contaminated rocks extend to higher $^{87}Sr/^{86}Sr$ (range 0.7077 to 0.7149) and slightly lower ϵ_{Nd} (-1.0 to -2.3). All of Verma's rhyolites contain less than 100 ppm Sr and only one has initial $^{87}Sr/^{86}Sr$ greater than 0.7105. Assimilation - fractional crystallization calculations demonstrate that those rhyolites with initial $^{87}Sr/^{86}Sr \leqslant 0.7100$ could represent about 40% residual liquid from a parental andesite, similar to those from Batopilas (400 ppm Sr; $^{87}Sr/^{86}Sr = 0.7048$), that was contaminated by crust with 250 ppm Sr and $^{87}Sr/^{86}Sr = 0.7200$. The assimilation rate in the model is low (r = 0.2), and the Ma/Mo of the rhyolites is less than 0.25. Varying the composition of the crustal component within reasonable limits is unlikely to change these calculations by as much as a factor of two.

The quantitative evaluation of the mass fraction of the crustal component in the rhyolites of the Sierra Madre Occidental requires much more data on the nature of

the subcrustal source, on the composition of the crust, and on the Upper Volcanic sequence. As a first, very rough approximation, we estimate that those silicic rocks with initial $^{87}Sr/^{86}Sr \leqslant 0.7060$ contain Ma/Mo less than 0.1 and those with $^{87}Sr/^{86}Sr \leqslant 0.7070$ have Ma/Mo less than 0.25. If this is the case, then the generation of the Upper Volcanic sequence marked a major crust - forming event. Several kilometers of new crust formed in western Mexico in the period of a few million years during the eruption of the Upper Volcanic sequence and the emplacement of the underlying batholith.

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