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Nd – Sr isotope composition of lower crustal xenoliths – Evidence for the origin of mid-tertiary felsic volcanics in Mexico

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Abstract. Isotopic data were collected on lower crustal xenoliths to constrain the Mexican lower crust as source material for the mid-Tertiary Sierra Madre Occidental, which is one of the largest silicic volcanic piles known. The xenoliths are predominantly pelitic gneisses and mafic orthogneisses that were brought to the surface on the eastern edge of the Sierra Madre Occidental by recent alkalic basalts. The pelitic gneisses are uniform in mineral assemblage and contain garnet + quartz + plagioclase + sanidine + rutile + sillimanite/kyanite + graphite. The orthogneisses are plagioclase, garnet and/or spinel bearing two pyroxene granulites. Available geothermometric and geobarometric data show that the xenoliths equilibrated at temperatures and pressures consistent with those of the mantle/crust boundary in those areas.

The xenoliths range from 46.2 to 67.2 SiO_2. Paragneisses are in general more silicic than the orthogneisses. The xenoliths have Rb concentrations between 0.4 and 97 ppm but most samples are very low, with less than 3 ppm Rb. The Sr isotopic ratios of orthogneisses from the lowermost crust throughout most of northern Mexico are very similar and range from ca. 0.705 to 0.706. Previous studies indicate that these rocks have measured ε_{Nd} values between +2 and −5. Paragneiss xenoliths are generally more radiogenic in Sr isotopic ratio, up to 0.730, and have lower ε_{Nd} values of −11.

The Nd and Sr isotopic characteristics of the orthogneisses are similar to those of the voluminous mid-Tertiary ignimbrites of the Sierra Madre Occidental. The xenoliths cannot represent cumulate material produced during the mid-Tertiary volcanism because they are Paleozoic or older. Consequently, based on Sr and Nd isotopic data, the silicic ignimbrites could comprise up to 100% lower crustal material.

Introduction

The Sierra Madre Occidental volcanic pile is among the largest accumulation of felsic volcanic rocks known. The total volume of the volcanics may have approached 250000 km^3 (e.g. Cameron et al. 1980), which is greater than the Central Andes, North Island of New Zealand and central America. The bulk of the Sierra Madre Occidental was emplaced in a relatively short period of time between 34 and 27 Ma ago (McDowell and Clabaugh 1979) and is coincident in time with the subduction of the Farallon Plate of the west coast of North America (Atwater and Molnar 1973). The volcanism is thought to be related to subduction processes (McDowell and Clabaugh 1979; Cameron et al. 1980).

The source of the silicic melts is of critical importance for models of continental crustal genesis. If the ignimbrites are a product of fractional crystallization of mantle material (e.g. Cameron et al. 1980; Cameron and Cameron 1985), then the ca. 30 Ma old volcanic event produced considerable amounts of new continental crust. But if the volcanics were produced as partial melts of the crust, combined with some mantle-derived material, then the mid-Tertiary ignimbrite flare-up was a time of extensive reworking of old preexisting crust with possible variable addition of mantle material. Recent isotope (Lanphere et al. 1980; Cameron and Cameron 1985), trace element (Cameron and Hanson 1982), and major element studies (Cameron et al. 1980) of silicic volcanic rocks of the Sierra Madre Occidental, from a traverse from Baja California to Texas, have been interpreted to indicate that the silicic ignimbrites are almost wholly a product of fractional crystallization of mantle basalt. Verma (1984), however, based on Sr and Nd isotope data from the San Luis-Zacatecas areas, concludes that the ignimbrites contain a strong crustal component. Because northern Mexico is mostly covered by Mesozoic or younger rocks, all the petrologic studies have been hampered by an almost complete lack of knowledge of the isotopic and chemical character of the lower crust.

This study and those by Roberts et al. (1987) and Ruiz et al. (1988) are the first major attempts to determine the geochemical character of the Mexican lower crust. The data obtained here constrain the lower crust as a source of the melts that produced the silicic ignimbrites. The xenolith localities discussed occur in the northeastern and southeastern ends of the Sierra Madre Occidental where isotopic studies of the volcanic rocks have been done (Cameron and Cameron 1985; Verma 1984) (Fig. 1) and where the best comparisons can be made between the volcanic rock and xenolith geochemistry.

The lower crustal samples

Localities with large amounts of crustal and mantle xenoliths occur in La Olivina and Potrillo cinder cones in Chihuahua, El Toro cinder cone, Zacatecas and in 7 maars, known as the Ventura and Santo Domingo groups (Aranda-Gomez 1982), in the state of San Luis Potosi (Fig. 1).

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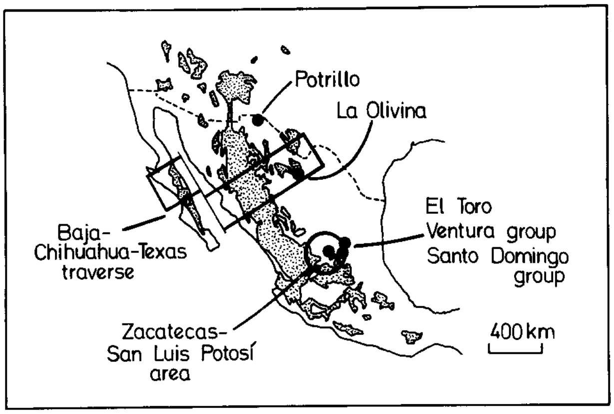

Fig. 1. Map of Mexico showing the Sierra Madre Occidental volcanic field (*stipple pattern*), and the relationship between areas where Nd and Sr isotopes have been studied and the xenolith localities discussed in this paper. Baja-Chihuahua-Texas traverse refers to work on volcanics by Cameron and Cameron (1985) and Zacatecas-San Luis Potosi area to work by Verma (1984)

All of these localities contain granulite facies metamorphic rocks and ultramafic nodules of lower crustal and upper mantle origin (Aranda-Gomez 1982; Nimz et al. 1986; Aranda-Gomez and Ortega-Gutierrez 1987). There are variations in the details of the xenolith assemblage from each locality, but generally there are similarities in the types of xenoliths found in each volcanic center. The mantle xenoliths, which are by far the most abundant at all localities, are mostly spinel lherzolites with lesser amounts of pyroxenite and websterite. Nimz et al. (1986) interpreted the spinel lherzolites to be primary mantle material and the pyroxenites to be veins formed by mineral plating or segregation caused by basaltic melts moving through the lherzolites.

The lower crustal xenoliths are predominantly two types: (1) sillimanite-garnet quartzofeldspathic paragneisses with graphite, and (2) various mafic to intermediate orthogneiss types, including two pyroxene granulites, pyroxene-plagioclase granulites, and garnet- and/or spinel-bearing granulites. Some of the pyroxene granulites contain amphibole or scapolite, which have been interpreted as secondary after plagioclase (Aranda-Gomez 1982; Ruiz et al. 1982; Nimz et al. 1986). Hornblendites and kaersutite megacrysts are common only in the Santo Domingo group maars. Generally, there is a 1:1 ratio between the pelitic gneisses and the pyroxene granulites. Roberts et al. (1987), based on trace element data, show that the orthogneisses are probably cumulates. Nevertheless, the numerous paragneiss xenoliths indicate that the lower crust cannot be composed simply of cumulates but that it represents a complex tectonic history with components that were once at the Earth's surface. Recently, Ruiz et al. (1988), based on Nd isotopic data, conclude that the lower crust in Chihuahua, represented by La Olivina xenoliths, is Precambrian in age. This date agrees with that obtained by Nimz et al. (1986). The lower crust in the southeastern part of the Sierra Madre Occidental in San Luis Potosi is Paleozoic and Precambrian (Ruiz et al., 1988).

An important characteristic of the xenolith suites is that few upper and middle crustal lithologies, such as amphibolite facies rocks, batholithic or volcanic rocks are present. Furthermore, available geothermometric and geobarometric studies of mantle and crustal xenoliths in San Luis Potosi indicate that the xenoliths equilibrated in the lowermost crust. Ruiz et al. (1983) obtained pressures of ca. 9 kb (32 km) for the pelitic gneisses of La Joya Honda using the geobarometer of Newton and Perkins (1982). Aranda-Gomez (1982), in a detailed study of xenoliths from San Luis Potosi, estimated slightly higher pressures of 13 ± 3 kb (45 ± 10 km) for all xenoliths. Pressures for the garnet and/or spinel bearing mafic xenoliths, similar to those studied here and by Ruiz et al. (1988), were calculated by Aranda-Gomez (1982) using the phase relations of gabbro, spinel gabbro and garnet pyroxenite (Herzberg 1978). Therometry and barometry for the spinel lherzolites from the same maars reported by Greene and Butler (1979) also range between 950 ± ° C and 13 ± 3 kb. Seismic (Fix 1975) and regional gravity data (Woolard et al. 1969) suggest that the crust in central Mexico is between 30 and 40 km. Consequently all of the xenoliths in the localities sampled for this study must have originated in a very restricted area close to the crust-mantle boundary. This is similar to the xenolith population of Engle Basin, New Mexico, where Warren et al. (1979), based on detailed geothermometric and geobarometric studies, conclude that spinel lherzolites and websterites are mantle derived and close to the crust-mantle boundary, while quartz-bearing granulites and pyroxene-plagioclase granulites represent samples from the lowermost crust.

No geobarometric or geothermometric studies have been reported on the crustal xenoliths from La Olivina or Potrillo in northern Mexico. No garnet-bearing mafic granulites have been reported from La Olivina, making geobarometry difficult but suggesting that the orthogneisses may have equilibrated at lower pressures than those in San Luis Potosi.

The Santo Domingo and Ventura group maars are located approximately 120 and 50 km, respectively, northeast of the city of San Luis Potosi. The Santo Domingo group consists of the La Joya Prieta, El Banco, Joya de Los Contreras and Xalapasco de Santo Domingo maars. The Ventura group consists of the La Joya Honda, La Joyuela and Laguna de los Palau maars. Samples were collected from La Joya Honda, Los Palau, La Joya Prieta and Los Contreras. The volcanic centers are composed of xenolith-bearing basanites and nephelinites probably Quaternary in age (Aranda-Gomez and Luhr, in press). Xenoliths are found to a maximum of about 20 cm in diameter enclosed in an alkali basaltic tuff. The xenolith locality at El Toro is approximately 100 km west of the city of San Luis Potosi and consists of a mildly alkalic basaltic cinder cone of Plio-Pleistocene age. Xenoliths can be up to 25 cm diameter and are always found inside volcanic bombs. At La Olivina cinder cone and Potrillo maar, in Chihuahua, the xenoliths are found embedded in basaltic ash of probable Miocene or Pliocene age. The samples analyzed for this study from these localities include banded pelitic paragneisses and banded plagioclase-pyroxene and two-pyroxene orthogneisses. The mafic and felsic bands range from 1 to 4 mm but are generally 3 mm wide.

Analytical methods and sample preparation

All samples were trimmed carefully with a water-cooled trim saw to avoid weathered surfaces and, in the case of the xenoliths, host material. The trimmed samples were crushed in a Al_2O_3 jaw crusher and hand picked to avoid any pieces with fractures. Very few pieces were actually rejected in this way and it is unlikely that the samples were fractionated during this procedure. The grav-

Table 1. Major element composition of Mexican xenoliths

	Ventura group			Chihuahua group					
	La Joya Honda		Los Palau	La Olivina				Potrillo	
	LJH-1-85	LJH-2-85	LP-2-85	LAO-1-85	LAO-2-86	LAO-3-86	LAO-4-86	P-1-86	P-2-86
SiO_2	61.1	53.6	63.9	46.3	55.4	46.0	52.6	48.2	49.2
TiO_2	1.27	1.48	0.73	2.12	1.41	3.73	0.99	2.71	2.63
Al_2O_3	15.7	16.7	18.1	13.4	21.3	14.1	17.5	13.8	14.1
Fe_2O_3[a]	8.03	6.99	4.02	14.1	13.5	16.0	8.07	13.1	13.0
MnO	0.10	0.11	0.07	0.16	0.20	0.19	0.15	0.20	0.21
MgO	4.16	3.78	2.17	7.65	3.78	7.17	6.83	7.66	7.80
CaO	6.11	11.8	5.21	15.7	0.80	10.3	10.8	9.55	9.08
Na_2O	2.80	3.30	4.50	2.00	0.41	2.40	3.24	3.04	3.41
K_2O	0.28	2.40	0.94	0.30	2.94	0.37	0.62	0.93	0.95
P_2O_5	0.11	0.31	0.15	0.04	0.10	0.05	0.03	0.75	0.44
Sum	99.66	100.5	99.79	101.8	99.84	100.3	100.8	99.94	100.8

	Santo Domingo group									
	La Joya Prieta	Los Contreras								
	LJP-1-85	LC-6-85	LC-7-85	LC-8-85	LC-9-85	LC-10-85	LC-11-85	LC-13-85	LC-14-85	LC-15-85
SiO_2	56.8	57.3	48.3	50.1	53.8	53.4	50.9	54.6	64.4	46.4
TiO_2	0.96	1.27	1.36	0.82	0.43	1.32	2.12	0.25	0.46	0.22
Al_2O_3	17.8	21.7	8.35	13.7	18.0	15.0	15.9	19.2	18.1	20.1
Fe_2O_3[a]	7.74	11.7	11.8	13.2	8.29	9.94	9.8	7.08	3.74	5.79
MnO	0.12	0.15	0.20	0.17	0.14	0.17	0.15	0.11	0.06	0.09
MgO	4.34	2.91	16.0	9.93	5.75	7.20	6.89	5.23	2.16	13.2
CaO	7.69	1.05	15.2	10.6	8.74	9.85	10.3	8.52	6.05	12.0
Na_2O	3.17	0.57	0.65	2.26	3.74	3.08	3.33	4.15	3.51	2.37
K_2O	1.59	2.74	0.07	0.21	0.90	0.82	0.65	1.16	1.31	0.76
P_2O_5	0.19	0.17	0.04	0.02	0.04	0.16	0.32	0.29	0.04	0.03
Sum	100.4	99.56	101.9	101.0	99.83	100.9	100.3	100.3	99.83	100.9

[a] Total Fe as Fe_2O_3

el was washed in 1 M HCl to dissolve any carbonate. This precaution is necessary because some xenoliths were ejected onto limestone and are embedded in caliche. Xenoliths penetrated by caliche were avoided and none of the samples reported here reacted vigorously with acid. Following the acid treatment, the samples were washed with distilled water and then dried. The dry gravel was powdered in a Al_2O_3 mill.

Major element analyses were performed on an automated Phillips X-Ray spectrometer at the University of Michigan on glass disks made by fusing the samples with lithium metaborate. All samples were analyzed in triplicate. For the Rb–Sr analyses, at the University of Arizona, the samples were dissolved with $HF-HNO_3$ and Rb–Sr separation was performed in AG50W-X12 resin ion exchanger. Overall background contamination levels for Sr were less than 200 picograms. Both Sr and Rb contents were measured by isotope dilution. Sr was measured using single oxidized Ta filament and Rb on double Ta filament assembly on a fully automatic VG-354 mass spectrometer with 5 collectors. For a complete description of the isotope dilution and mass spectrometric procedures followed at Arizona refer to Patchett and Ruiz (1987).

Geochemical composition of the lower crust

Table 1 shows the composition of the major elements of Mexican xenoliths. The samples are described in appendix 1. The lowermost crust, as represented by the xenoliths, ranges in SiO_2 from 46.2 to 67.2 wt.% and has an average composition of 53.8 wt.%, which corresponds approximately to a basaltic andesite. The high silica samples represent paragneisses with Al_2O_3 contents up to 23 wt.%. Table 2 lists the Rb and Sr data for the xenoliths. Rubidium values range from 0.4 to 97 ppm, with most samples containing less than 3 ppm Rb, while the higher values are all paragneisses. The most Rb-rich paragneiss samples are LJH-2-85, LC-6-85 and LAO-2-86, which have Rb contents of 72 to 97 ppm Rb. Most of the samples contain between 200 and 600 ppm Sr (Table 2) and have $^{87}Rb/^{86}Sr$ ratios lower than 0.3, which is in the low side of the range of worldwide granulites (Ben Othman et al. 1984) (Fig. 2). Only six of the 39 samples have $^{87}Rb/^{86}Sr$ ratios greater than 1.0 and these samples are all paragneisses.

The Mexican lower crust has, on average, low Rb/Sr ratios, similar to the lower crust from central France (Leyleroup et al. 1977; Dostal 1981). The Rb/Sr ratio of the mexican xenoliths is lower than that calculated by Taylor and McLennan (1985) for the continental crust indicating a lower crust depleted in Rb relative to the upper crust but is greater than the value of the bulk Earth, which is thought to be ca. 0.03 (O'Nions et al. 1977). Taylor and

Table 2. Rb – Sr isotope composition of Mexican basement

Sample #	Rb	Sr	$^{87}Rb/^{86}Sr^{\dagger}$	$^{87}Sr/^{86}Sr \pm 2\sigma$	$(^{87}Sr/^{86}Sr)_i$*	ε_{Nd}**
Lower crustal xenoliths						
Ventura group, San Luis Potosi						
La Joya Honda						
LJH-1-85	0.839	288.6	0.008	0.705002±17	0.70500	−1.9
LJH-2-85	72.67	889.7	0.233	0.704826± 7	0.70473	+2.3
Los Palau						
LP-1-85	3.55	679.5	0.015	0.705225±10	0.70522	−0.8
LP-2-85	6.47	453.0	0.041	0.705540±10	0.70552	−0.3
Santo Domingo group, San Luis Potosi						
La Joya Prieta						
LJP-1-85	26.14	402.0	0.188	0.707100± 9	0.70702	−4.7
Los Contreras						
LC-6-85	88.33	156.9	1.632	0.730435± 5	0.72974	−11.0
LC-7-85	1.76	83.49	0.061	0.704316±11	0.70429	
LC-8-85	4.16	583.1	0.020	0.703663±10	0.70365	
LC-9-85	1.56	959.4	0.004	0.705298±13	0.70524	
LC-10-85	0.37	367.4	0.002	0.706585±10	0.70658	
LC-11-85	0.41	523.9	0.002	0.703936±11	0.70393	
LC-13-85	14.16	449.7	0.091	0.705880±10	0.70584	−1.7
LC-14-85	0.68	585.5	0.003	0.708030± 8	0.70803	−3.2
LC-15-85	1.91	193.5	0.028	0.705318±13	0.70531	
Zacatecas						
El Toro						
T-18-85	1.48	219.3	0.019	0.707188± 1	0.70718	−1.1
Chihuahua group						
La Olivina						
LAO-1-86	2.25	500.4	0.013	0.705410± 9	0.70541	−0.3
LAO-2-86	97.65	108.7	2.60	0.731853± 7	0.73075	−10.5
LAO-3-86	2.53	488.5	0.014	0.704928±10	0.70492	+0.1
LAO-4-86	2.51	569.7	0.012	0.705306± 9	0.70530	−0.2
Potrillo						
P-1-86	17.97	606.9	0.085	0.706451± 9	0.70641	−6.8
P-2-86	18.23	595.2	0.088	0.706668± 9	0.70662	−7.1
Precambrian outcrops						
Oaxaca complex						
OAX-3-85	106.0	394.2	0.777	0.716624± 7		
OAX-3(2)-85	139.4	393.8	1.025	0.716813± 9		
OAX-3(3)-85	106.6	436.1	0.707	0.716797±10		
OAX-4-85	97.6	386.9	0.729	0.711617±10		
OAX-5-85[a]	103.8	138.1	2.183	0.749957± 8		
OAX-7-85	5.710	578.3	0.028	0.703855± 8		
OAX-10-85	4.390	1227.1	0.010	0.704036± 8		
Novillo, Ciudad Victoria						
NOV-4-85[a]	20.65	584.3	0.102	0.707618± 9		
NOV-5-85	20.24	215.5	0.272	0.709435±10		
NOV-6-85	27.76	452.9	0.177	0.708668± 9		
NOV-6W-85	86.38	409.6	0.610	0.719138±10		
NOV-7-85[a]	129.2	254.3	1.47	0.722544± 9		
Molango, Hidalgo						
MOL-1-86	12.08	248.7	0.140	0.706999± 7		
MOL-2-86[a]	19.38	429.0	0.131	0.706254± 7		
MOL-4-86[a]	39.21	444.1	0.255	0.707839±10		
MOL-5-86	60.95	115.3	1.532	0.727074± 9		

Table 2 (continued)

Sample #	Rb	Sr	$^{87}Rb/^{86}Sr$†	$^{87}Sr/^{86}Sr \pm 2\sigma$	$(^{87}Sr/^{86}Sr)_i$*	ε_{Nd}**
Los Filtros, Chihuahua						
LF-1-86	60.09	359.2	0.484	0.707987±10		
LF-4-86	46.45	764.6	0.176	0.708334±10		

† Uncertainty at $2\sigma = \pm 1\%$

[a] Data from Patchett and Ruiz (1987)

* Initital ratios corrected for 30 Ma

** Data from Ruiz et al. (1988). ε_{Nd} calculated for 30 Ma

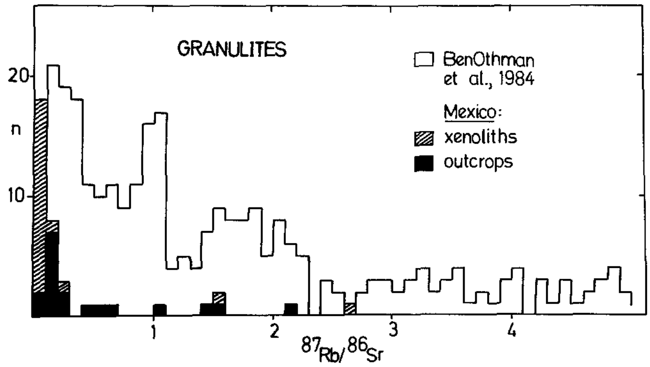

Fig. 2. $^{87}Rb/^{86}Sr$ characteristics of the Mexican basement and worldwide granulites. Compilation of worldwide granulites from Ben Othman et al. (1984). Note extreme low Rb/Sr ratios of the majority of xenolith granulites

McLennan (1985) calculate a Rb/Sr ratio of 0.023 for the lower crust. The observed Rb/Sr ratio of the Mexican lower crust, however, is higher, suggesting that the Taylor and McLennan (1985) value may be too low. It is important to note that the Rb/Sr ratio of the lower crust, as indicated by the granulite xenoliths, is lower than that of exposed basement rocks in Mexico (Fig. 2; Table 2). The exposed basement localities are described in Ruiz et al. (1988) and include granulite facies terrains. The difference in Rb/Sr ratios between granulite xenoliths and exposed terrains in Mexico indicate important chemical differences between these rocks. Geobarometry on some of the exposed granulite facies terrains (Mora and Valley 1985) also suggest that exposed granulites were equilibrated at 7±1 kb (ca 24 km) and do not represent the lowermost crust. The Rb depletion of the Mexican lowermost crust is thought to have been caused by magmatic rather than hydrous processes (Roberts et al. 1987), as was suggested by Heier (1973) for granulite facies rocks elsewhere.

The very low Rb/Sr ratios of the lower crust slowed its Sr isotopic evolution. Consequently, the Sr isotopic composition for the whole range of the Mexican lower crustal samples is low, ranging from about 0.704 to 0.750. Most of the samples, however have values between 0.704 and 0.707; orthogneiss xenoliths are within this range. Metasedimentary rocks, on the other hand, generally contain the most radiogenic Sr.

Ruiz et al. (1988) obtained Nd isotopic data for a large range of samples that represent the Mexican lower crust; the samples included xenoliths from La Olivina, Potrillo and San Luis Potosi. Figure 3 is a measured $\varepsilon_{Nd} - {}^{87}Sr/^{86}Sr$ correlation diagram of all available data for the Mexican basement, which includes xenoliths. The data define four distinct groups based on differences in Nd and Sr isotopic ratios. The important point is that the Mexican basement samples follow the expected negative correlation trend and that orthogneiss xenoliths define a group with Sr and Nd isotopic ratios close to bulk Earth. There are few isotopic analyses of lower crustal xenoliths available from other parts of North America to compare to northern Mexico. An exception are data from the Colorado Plateau (Arculus et al. 1987), where the Nd and Sr isotopic data are remarkably similar to those of Mexico.

Petrogenesis of the silicic volcanic rocks of the Sierra Madre Occidental

The silicic ignimbrites that form the Sierra Madre Occidental are among the most voluminous felsic volcanic piles known and the source of these magmas has important implications for crustal genesis models. Previous Sr isotopic work by Lanphere et al. (1980) and Nd–Sr isotopic work by Cameron and Cameron (1985) for volcanic rocks from a transect from Baja California to Chihuahua (Fig. 1) indicated that the source region for dacites and more silicic ignimbrites had $^{87}Sr/^{86}Sr$ between 0.703–0.705 and ε_{Nd} values between around -1 and -2. These workers concluded that the small isotopic variability, high Nd and low Sr isotope ratios of the ignimbrites precluded the crust as the melt source and suggested that the Sierra Madre Occidental silicic volcanics were a product of crystal fractionation of mantle derived basalts. Major and trace element modelling of the ignimbrites (Cameron et al. 1980; Cameron and Hanson 1982) indicate that the voluminous ignimbrites would represent no more than 20% of the original mass of the mantle-derived mafic parent material. In other words that there was underplating of the Mexican crust by approximately 4 km of mafic material. All these studies, however, were hampered by a fundamental lack of knowledge of the Mexican basement, the other possible source for the melts. Consequently, although the possibility of forming some of the rhyolites by varying amounts of partial melting of the lower crust and crystal fractionation of these melts has been discussed (e.g. Cameron et al. 1980; Cameron and Hanson 1982), these alternative models could not be properly evaluated.

Figure 4 plots the Sr–Nd isotopic data of orthogneisses from the Mexican lower crust, as indicated by xenoliths, and compares them with Nd and Sr isotopic data from mid-Tertiary volcanics from the traverse from Baja California to Chihuahua (Cameron and Cameron 1985) and the Zacatecas and San Luis Potosi area (Verma 1984). Figure 1

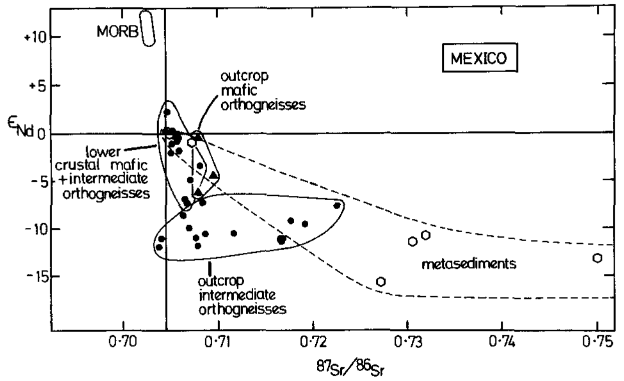

Fig. 3. $\varepsilon_{Nd}-{}^{87}Sr/{}^{86}Sr$ diagram of basement rocks of Mexico from Ruiz et al. (1988)

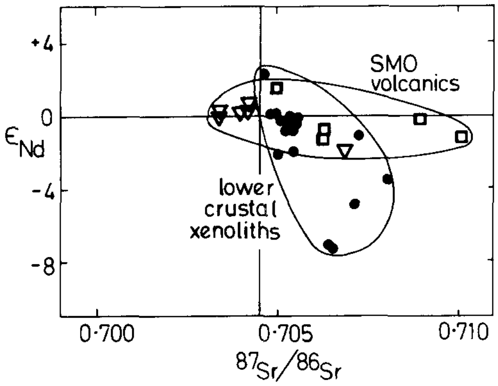

Fig. 4. $\varepsilon_{Nd}-{}^{87}Sr/{}^{86}Sr$ diagram showing overlap of orthogneiss xenoliths from lowermost lower crust and ignimbrites from the Sierra Madre Occidental. Inverted open triangles are data from Cameron and Cameron (1985). Open squares are data from Verma (1984)

shows where our xenoliths were derived in relation to the study areas for the volcanics. Lower crustal paragneisses were not plotted because their bulk chemistry precludes them as a major component (~30%) of source for the ignimbrites. There are numerous sets of data for Sr without corresponding Nd isotopic data available for rocks from the Sierra Madre Occidental (e.g. McDowell et al. 1978; Damon et al. 1980, Lanphere et al. 1980; Ruiz et al. 1980; Moll 1981; Huspeni et al. 1983; Ruiz, in press). All these studies show that the ignimbrites generally range in ${}^{87}Sr/{}^{86}Sr$ between 0.7043 and 0.7075, which is within the range of Sr isotope ratios shown in Fig. 4 for the Sierra Madre Occidental volcanics.

There is an overlap between the Sr and Nd isotopic ratios of the Sierra Madre Occidental volcanics and the lower crustal xenoliths (Fig. 4). Some of the samples analyzed by Cameron and Cameron (1985) are less radiogenic in Sr than the xenoliths suggesting that some mantle-derived material or some lower crust even more depleted in Rb than the orthogneisses was involved in the genesis of those rocks. However, many of the Sr values reported by the authors referenced above are identical to those of the xenoliths. This is strong permissive evidence that the Mexican lower crust could have supplied melts for the ignimbrites. It is important to note that the xenoliths represent the isotopic character of the lower crust of a large part of northern Mexico and that this includes Precambrian basement in Chihuahua and Paleozoic basement in Zacatecas and San Luis Potosi (Ruiz et al., 1988). Thus, regardless of age, it seems that the Mexican lower crust has relatively homogeneous Sr–Nd isotopic properties. The area where the xenoliths are found occurs in the eastern edge of the Sierra Madre Occidental and is probably the most radiogenic crust underlying the Sierra Madre Occidental. West of the xenolith localities, where the main body of the Sierra Madre Occidental occurs, the Mexican basement is thought to be Mesozoic island arc material (Campa and Coney 1983; Coney and Campa 1984), which, because it is young and therefore isotopically unevolved, would have similar isotopic character to the samples plotted on Fig. 4.

One possible reason for the isotopic similarity between the xenoliths and volcanic rocks of the Sierra Madre Occidental, would be that the orthogneiss xenoliths represent cumulates formed during crystal fractionation of the mid-Tertiary volcanics. Trace element studies of the orthogneisses do suggest that they are cumulates (Roberts et al. 1987). Ruiz et al. (1988), however, show that the model T_{DM} ages of the xenoliths from Potrillo and La Olivina in Chihuahua are approximately 1.4–1.6 Ga, which are the same values obtained for 1.0 Ga old crust in west Texas (Nelson and DePaolo 1985) and Grenville-age rocks in eastern and southern Mexico (Patchett and Ruiz 1987; Ruiz et al., in press). *Furthermore, 1.4–1.6 Ga is also the same Nd model age as that of exposed basement rocks only 150 km from La Olivina, at Los Filtros (Blount 1983), which are also Grenville in age (Mauger et al. 1983).* South of Los Filtros, the Nd model ages obtained for the xenoliths are Paleozoic and Precambrian. This agrees with tectonic models of the area (Coney and Campa 1987). These ages argue against the orthogneiss xenoliths being cumulates related to the formation of the Sierra Madre Occidental volcanics since it would be necessary for the cumulates to fortuitously acquire the appropriate Sm/Nd ratio to give the appropriate ages for the Paleozoic and Precambrian rocks. The suggestion is clearly that the xenoliths represent the lower crust already existing at the time the Sierra Madre Occidental volcanics were formed. This crust has the needed isotopic character and the appropriate mineralogy (Cameron et al. 1980; Cameron and Hanson 1982), to produce the voluminous ignimbrites of the Sierra Madre Occidental. Lanphere et al. (1980) and Cameron and Cameron (1985) indicate that mantle derived basalts found in the Sierra Madre Occidental have similar isotopic ratios to the voluminous ignimbrites and use this to argue a mantle derivation for the volcanic package. It is more likely, however, that the basalts have been contaminated during their passage through the crust, as shown in other continental basaltic fields (e.g. Carlson et al. 1981). Indeed, even the simplest modelling shows that it may be rather difficult to bring basaltic magma through continental crust without contamination occurring (Patchett 1980), and any such effects are overwhelmingly more likely in a zone of continental crust that is hot or already molten. Thus, mantle-derived melts related to the subduction of the Farallon plate of the coast of North America (Atwater and Molnar 1973) could have partially melted the lower crust. Our data do not preclude that some mantle-derived magmas could have mixed with the crustal melts. Crystal fractionation of the original crustal melts in large magma chambers (e.g. Hildreth 1981) would produce the rhyolitic rocks, as indicated by major and trace element modelling (Cameron et al. 1980; Cameron and Hanson 1982). The magma chambers would be voided in explosive eruptions producing the large and numerous calderas present in the Sierra Madre Occidental (Swanson and McDowell 1984). Because the latent heat of fusion of basalt and rhyolite are not very different (e.g. Patchett 1980), the volume of basalt needed to produce the rhyolites is about equal to the volume of the rhyolites. Thus, the model presented above avoids the problem of the extensive basalt underplating (about 4 km) needed if the silicic ignimbrites are wholly derived from crystal fractionation from basalt.

Summary

It has been shown that the Mexican lower crust is depleted in Rb and that mafic granulite xenoliths occurring in northern and central Mexico have a narrow range of $^{87}Sr/^{86}Sr$ ratios ranging from approximately 0.7045 to 0.7070. Paragneiss xenoliths are more radiogenic with Sr ratios ca. 0.730. The lowermost crust seems remarkably homogeneous in its isotopic composition regardless of age, suggesting that the Rb-depletion always occurred soon after formation of the crust.

The Sr and Nd isotopic data for the lower crust is similar to that of the Sierra Madre Occidental volcanic rocks. This could indicate that the xenoliths are cumulates formed during crystal fractionation or that the silicic ignimbrites were ultimately produced by melting of the lower crust. Sm–Nd data suggest that the xenoliths are Paleozoic or Precambrian crust and not mid-Tertiary cumulates, and therefore that the Sierra Madre Occidental felsic volcanic rocks could be predominantly lower crustal melts. Thus we believe that the Sierra Madre Occidental igneous event was not a time of major continental crust formation.

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Appendix

Petrography of rock samples

LJH 1-85 *Orthogneiss* Plagioclase 20%; ortopyroxene 35%; clinopyroxene 45%; trace opaques
LJH 2-85 *Paragneiss* Plagioclase 50%; orthopyroxene 22%; clinopyroxene 25%; graphite 3%
LP-2-85 *Paragneiss* Plagioclase 50%; orthopyroxene 20%; clinopyroxene 25%; graphite 3% garnet 2%
LAO 1-86 *Pyroxene granulite* Plagioclase 5% clinopyroxene 65% orthopyroxene 25%; opaques 5%; trace amounts of apatite
LAO 2-86 *Paragneiss* Quartz 20%; sanidine 30%; plagioclase 10%; garnet 22%; sillimanite 15; graphite 2%; trace opaques
LAO 3-86 *Pyroxene granulite* plagioclase 5%; clinopyroxene 65%; orthopyroxene 35%; opaques 5%; trace amounts of apatite
LAO 4-86 *Pyroxene granulite* Plagioclase 20%; clinopyroxene 40%; orthopyroxene 35%; opaques 5%; trace apatite
P 1-86 *Pyroxene granulite* Plagioclase 3%; clinopyroxene 82%; orthopyroxene 10%; apatite 2% opaques 3%
P 2-86 *Pyroxene granulite* Plagioclase 3%; clinopyroxene 82%; orthopyroxene 10%; apatite 2%; opaques 3%
LC 6-85 *Paragneiss* Quartz 25%; sanidine 30%; plagioclase 8%; garnet 20%; sillimanite 15%; graphite 2%
LC 7-85 *Pyroxene granulite* 85% clinopyroxene; 20% orthopyroxene; 5% spinel
LC 8-85 *Pyroxene granulite* 40% plagioclase; 35% clinopyroxene; 20% orthopyroxene; 3% garnet, 2% opaques
LC 9-85 *Pyroxene granulite* plagioclase 55%; clinopyroxene 30% orthopyroxene 13%; opaques 2%
LC 10-85 *Pyroxene granulite* plagioclase 55%; clinopyroxene 25%; orthopyroxene 15% 5% garnet
LC 11-85 *Pyroxene granulite* 40% plagioclase; 35% clinopyroxene; 20% orthopyroxene; 20% opaques
LC 14-85 *Paragneiss* plagioclase 40%; sanidine 20%; garnet 35%; graphite 5%
LC 15-85 *Pyroxene granulite* Plagioclase 20%; clinopyroxene 45%; orthopyroxene 30; opaques 5%