

# Generation of high-silica rhyolite: A Nd, Sr, and O isotopic study of Sierra La Primavera, Mexican Neovolcanic Belt

Gail A. Mahood<sup>1</sup> and Alex N. Halliday<sup>2\*</sup>

<sup>1</sup> Department of Geology, Stanford University, Stanford, CA 94305, USA

<sup>2</sup> Scottish Universities Research and Reactor Centre, East Kilbride, Glasgow, Scotland G75 0QU

**Abstract.** High-silica rhyolites of the Sierra La Primavera, a late Pleistocene center near Guadalajara, are extremely Sr-poor (0.3–1.3 ppm), yet (with one exception) values of  $^{87}\text{Sr}/^{86}\text{Sr}_i$  are relatively low at 0.7041–0.7048. Values of  $^{143}\text{Nd}/^{144}\text{Nd}$  for all the rhyolites are (within errors) identical to a basalt at 0.5129. These surprisingly primitive values, along with feldspar  $\delta^{18}\text{O}$  of +6.6‰, are consistent with an origin by fractional crystallization of mantle-derived basalt. However, absence of the large volume of associated intermediate rocks that would be expected if the 40 km<sup>3</sup> of erupted rhyolite were produced mainly by fractional crystallization suggests alternative processes involving partial melting of Mesozoic or Tertiary mafic intrusive rocks (or lower-crustal metamorphic equivalents). The latter interpretation is preferred, especially in light of comparative data for other North American, Cenozoic, high-silica rhyolites. Isotopic compositions correlate with basement age, but generally lie between values for associated basalts and the underlying crust. Nearly all can be interpreted as containing both a young mantle-derived component and a crustal component, probably derived by partial melting at intermediate to deep levels of the crust. No matter what the proportions of mantle- and crust-derived material in parental magmas, the extremely low concentrations of Sr and Ba in the high-silica rhyolites require extensive fractional crystallization of feldspar-rich assemblages after parental liquids attain rhyolitic compositions.

At La Primavera, contamination by shallow roof rocks probably led to the 0.708  $^{87}\text{Sr}/^{86}\text{Sr}_i$  ratio of the earliest postcaldera lava dome, which is thought to have erupted through the same vent as the caldera-forming pyroclastic flows. Contamination associated with collapse apparently affected only a small volume of magma in contact with brecciated wall rocks close to the vent, as nearby lavas that erupted during the same episode about 95 ky ago are unaffected. No identifiable lowering of  $\delta^{18}\text{O}$  took place on caldera collapse. Rhyolitic lavas that erupted 75, 60, and 30 ky ago document postcaldera chemical recovery of the chamber to progressively more evolved compositions in its upper reaches, but show little variation in  $\delta^{18}\text{O}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}_i$ , or  $^{143}\text{Nd}/^{144}\text{Nd}$  with time, suggesting that the bulk of the rhyolitic magma within the chamber was isolated from significant wall-rock contamination. Most of the small

range of  $^{87}\text{Sr}/^{86}\text{Sr}_i$  among the rhyolites can be attributed to pre-eruptive, in situ decay of  $^{87}\text{Rb}$ , resulting in a measurable secular increase of  $^{87}\text{Sr}/^{86}\text{Sr}$  in these Sr-poor magmas. The  $^{87}\text{Sr}/^{86}\text{Sr}_i$  of the youngest rhyolite, however, is somewhat lower than predicted, suggesting that the silicic magma chamber was at times open to interaction with more-mafic magmas from below.

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## Introduction

There are two main rationales for this isotopic study of the Sierra La Primavera: (1) the general problem of the origin of voluminous high-silica rhyolites and (2) elucidating the role of wall-rock interaction in the chemical evolution of a high-level rhyolitic magma chamber.

The origins of highly evolved rhyolites – those with SiO<sub>2</sub> greater than 75% and extremely low concentrations of Mg, Sr, and Ba – may be varied and are as yet poorly understood. While it is easy to imagine small volumes being produced by small degrees of partial melting of relatively felsic crustal rocks adjacent to mafic dikes and intrusions, the origin of large volumes is more problematic. The usual occurrence of high-silica rhyolites in areas of thick continental crust leads one to infer that partial melting of the crust is important. Low concentrations of Sr and Ba rule out production of large volumes by single-stage partial melting of any reasonable source lithology, however, and require significant fractional crystallization of less felsic magmas. Recent discussions of the isotopic character of Cenozoic high-silica rhyolites (e.g., Verma 1983, 1984; Halliday et al. 1984; Novak and Mahood 1986; Cameron and Cameron 1986a; Halliday et al. 1986; Ferriz and Mahood 1987; Moll-Stalcup 1987; Hildreth 1987; Halliday et al. 1987) show that although many reflect interaction with the crust through which they erupt, even rhyolites erupted on thick continental crust commonly show evidence of containing a large, young, mantle-derived component. Producing tens to even thousands of cubic kilometers of high-silica rhyolite by greater than 95% fractional crystallization of basalt seems improbable; the large volumes of ultramafic and mafic cumulates that would be produced in the early stages of such fractionation have yet to be identified in the geologic record. This volume problem is mitigated substantially if crustal assimilation accompanies fractional crystallization of mantle-derived basalts. Low concentrations of compati-

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\* Present address: Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109, USA

Offprint requests to: G.A. Mahood

ble elements such as Sr and Ba can then be produced by extensive fractional crystallization of hybrid intermediate rocks. Such a process seems reasonable for volcanic centers that erupt significant volumes of intermediate magmas (e.g., Batopilas region and Los Humeros in Mexico (Lanphere et al. 1980; Cameron and Cameron 1986b; Ferriz and Mahood 1987)), but the case is less compelling for "bimodal" systems in which hybrid intermediate rocks are scarce or absent (e.g., Yellowstone (Halliday et al. 1986) or La Primavera). This isotopic study was undertaken to assess the relative proportions of material derived from the mantle and the crust in Sierra La Primavera magmas and to determine what type of crust was assimilated.

In addition, this study was aimed at tracing the isotopic evolution of a rhyolitic complex through time, interpreting it as the periodic sampling of magma near the roof of an evolving magma chamber. Previous work (Mahood 1981) established that enrichment trends in the magma chamber tapped by pyroclastic flows differed for most trace elements from those in the magma chamber tapped by subsequent postcaldera lava flows. Part of the rationale for this study was to investigate whether isotopic ratios would reveal a change in the degree of wall-rock interaction following caldera collapse that might be compatible with these differences.

### Geologic setting of the Sierra La Primavera

The Sierra La Primavera is a late Pleistocene volcanic center near Guadalajara, Mexico (Fig. 1). Like several other silicic caldera complexes, it lies slightly north of the main trend of cinder cones and active stratovolcanoes that define the Mexican Neovolcanic Belt (Ferriz and Mahood 1986). All nearby exposures are of Tertiary and Quaternary lavas and tuffs (Gilbert et al. 1985); despite 1000 m of relief in the nearby canyon of the Rio Grande de Santiago, the oldest exposed rocks are Miocene ignimbrites (Watkins et al. 1971). Holes drilled within La Primavera caldera during geothermal exploration bottom at 2 km depth in Tertiary volcanic rocks (Dominguez and Lippmann 1983). Andesitic to basaltic cones and their associated lava flows form a significant portion of the surface covered by Primavera eruptive units. One of these, a 52%-SiO<sub>2</sub> olvine-bearing basalt, was analyzed during this study (Sample 182 in Table 1).

The nature of the deeper basement beneath La Primavera is poorly known due to the extensive Cenozoic volcanic cover and a lack of detailed regional mapping and geochronology. The nearest exposures of pre-Cenozoic rocks occur in a block-faulted range

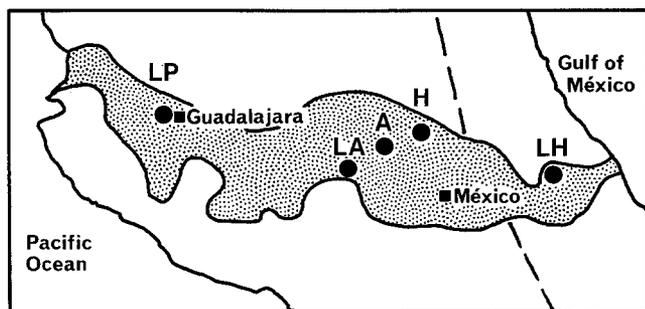


Fig. 1. Location map of central Mexico. The Mexican Neovolcanic Belt is stippled. Circles indicate locations of Pleistocene behind-the-arc rhyolitic centers: LP: La Primavera, LA: Los Azufres, A: Amealco, H: Huichapan, LH: Los Humeros. Dashed line indicates western limit of exposed Middle Proterozoic craton (Ortega-Gutierrez 1981)

about 35 km west in which Tertiary volcanic rocks overlie Cenozoic(?) intrusive rocks, Cretaceous limestones, and metamorphic rocks of uncertain age (Lopez-Ramos and Sanchez-Mejorado 1968). In current tectonic models (e.g., Coney and Campa 1984; Ruiz et al. 1988), the basement for La Primavera consists dominantly of accreted Mesozoic island-arc terranes. Outcrops of Middle Proterozoic rocks north and south of the eastern part of the Mexican Neovolcanic Belt place the interpolated western margin of the craton well east of Sierra La Primavera (Fig. 1; Ortega Gutierrez 1981; Patchett and Ruiz 1987).

### Summary of the geology and petrology (based on Mahood 1980, 1981)

The first lavas of La Primavera center erupted about 140 ky ago. These as well as all subsequent units are high-silica rhyolites. About 95 ky ago, 40 km<sup>3</sup> of magma erupted explosively, forming the compositionally zoned Tala Tuff. Collapse of the roof of the magma chamber on eruption of the Tala Tuff resulted in formation of a caldera 11 km in diameter, which soon filled with water. Shortly thereafter, a lava dome (source of Sample 317 in Tables 1 and 2) erupted in the southcentral part of the lake (Fig. 2) through the area thought to have been the main vent for the Tala Tuff. It was followed by emplacement of a dome (Sample 283) in the northcentral part of the lake. A group of domes (e.g., Sample 37) then erupted along two parallel arcs: one crossing the middle of the lake and one along the ring-fracture zone for the caldera (Fig. 2). The K - Ar ages for these units are indistinguishable from the 95-Ka dates on the Tala Tuff, suggesting that these lavas all erupted within a period shorter than 5-10 ky. About 75 ky ago, a new group of ring domes (e.g., Sample 174) erupted at the southern margin of the lake. Subsequent uplift due to magmatic insurrection caused the lake to drain and culminated about 60 ky ago in eruption of aphyric lavas (e.g., Sample 115) along an arc south of the former lake (Fig. 2). These units young eastward, the youngest ones (including Sample 15) having K - Ar ages of about 30 ky.

The Tala Tuff is the product of the only voluminous eruption, exceeding by a factor of two the total volume of exposed lavas. This ignimbrite is zoned from an aphyric, slightly peralkaline base (Sample 184) to a metaluminous top (Sample 218) containing phenocrysts of quartz and sodic sanidine. The southcentral lava dome that erupted through the same vent is very similar in composition to the last-erupted part of the Tala Tuff, but contains fayalite, ferrohedenbergite, and ilmenite phenocrysts as well. This assemblage also characterizes the 95-Ka ring domes, which are the least-evolved rocks erupted at La Primavera. All the foregoing eruptions document tapping of progressively deeper and less-evolved levels of the Primavera magma chamber as it existed about 95 ky ago. Magmas erupted 75, 60, and 30 ky ago, on the other hand, record recovery of the chamber to more evolved compositions. By the time the 75-Ka ring domes erupted, the upper reaches of the magma reservoir had re-evolved to a major-element composition similar to that of the first-erupted part of the Tala Tuff. The lavas erupted 60 to 30 ky ago are aphyric, richer in SiO<sub>2</sub>, poorer in MgO, and progressively less peralkaline. Enrichment trends of trace elements in the post-caldera lavas are not the same as those displayed within the Tala Tuff; with increasing silica content, the concentrations of Y, Nb, Ta, Pb, and Sb are essentially unchanged, whereas they are strongly enriched in the Tala Tuff; Mn, Fe, Co, Zn, Zr, Hf, MREE, and HREE decline in the lavas, but are enriched or constant in the Tala Tuff. Mahood (1981) attributed this contrast in trace-element enrichment patterns to transport of trace metals as dissolved volatile complexes in the water-rich ignimbrite-forming magma. Equally or perhaps more plausible is that lower volatile contents, lower temperature, and lesser peralkalinity led to stabilization or greater abundance of apatite, zircon, and chevkinite, removal of which (along with the major phenocrysts) depleted residual liquids erupted as the lavas in most trace metals (cf. Wolff and Storey 1984; Cameron and Cameron 1986b; Novak and Mahood 1986).

**Table 1.** Sr and Nd isotopic analyses

Eruptive unit	Sample number	Rb ppm	Sr ppm	Rb/Sr wt.	$^{87}\text{Rb}/^{86}\text{Sr}$ atomic	$^{87}\text{Sr}/^{86}\text{Sr}$ atomic	$^{87}\text{Sr}/^{86}\text{Sr}_i$ atomic	$^{143}\text{Nd}/^{144}\text{Nd}$ atomic	$\epsilon_{\text{Nd}}$
Basalt	182WR	27	795	0.034	0.098	$0.70370 \pm 2$	$0.70370 \pm 2$	$0.512904 \pm 24$	+5.2
Precaldera Dome	193WR	163.1	0.6875	237.2	686.2	$0.70528 \pm 11$	$0.70405 \pm 16$	$0.512911 \pm 16$	+5.3
Early Tala Tuff	184WR	244.1	0.3218	758.7	2195	$0.70741 \pm 14$	$0.70454 \pm 30$	–	–
	184WR	243.8	0.3280	743.4	2151	$0.70730 \pm 11$	$0.70448 \pm 26$	$0.512917 \pm 24$	+5.4
Late Tala Tuff	218WR	152.6	1.348	113.2	327.5	$0.70458 \pm 15$	$0.70415 \pm 17$	$0.512899 \pm 17$	+5.1
	218G	156.6	2.493	62.82	181.7	$0.70425 \pm 4$	$0.70400 \pm 5$	$0.512933 \pm 22$	+5.8
	218F	49.92	2.969	16.82	48.64	$0.70482 \pm 6$	$0.70475 \pm 6$	$0.512870 \pm 37$	+4.5
Southcentral Dome	317G	153.9	0.6042	254.7	737.1	$0.70938 \pm 8$	$0.70841 \pm 13$	$0.512909 \pm 24$	+5.3
	317F	59.31	2.116	28.03	81.07	$0.70507 \pm 11$	$0.70496 \pm 12$	–	–
Northcentral Dome	283WR	132.9	1.288	103.2	298.5	$0.70466 \pm 8$	$0.70427 \pm 10$	–	–
95-Ka Ring Dome	37WR	132.0	1.267	104.2	301.3	$0.70469 \pm 5$	$0.70429 \pm 7$	$0.512923 \pm 21$	+5.6
	37F	42.38	5.926	7.152	20.69	$0.70437 \pm 4$	$0.70434 \pm 4$	–	–
75-Ka Ring Dome	174WR	146.1	1.179	124.0	358.6	$0.70472 \pm 4$	$0.70434 \pm 7$	$0.512895 \pm 21$	+5.0
	174F	56.59	3.190	17.74	51.31	$0.70455 \pm 5$	$0.70449 \pm 5$	$0.512883 \pm 16$	+4.8
60-Ka Southern Arc Lava	115WR	150.6	1.183	127.3	368.2	$0.70469 \pm 13$	$0.70438 \pm 18$	–	–
	115WR	150.4	1.189	126.5	366.0	$0.70475 \pm 6$	$0.70444 \pm 11$	$0.512915 \pm 47$	+5.4
30-Ka Southern Arc Lava	15WR	168.2	0.9179	183.3	530.1	$0.70438 \pm 8$	$0.70413 \pm 16$	$0.512915 \pm 17$	+5.4

Suffixes to sample numbers indicate material analyzed: WR=whole rock, F=sodic sanidine, G=glass separate. Precisions quoted for measured Sr and Nd isotopic ratios are  $2\sigma$ . For samples with large Rb/Sr, the total error in  $^{87}\text{Sr}/^{86}\text{Sr}$  is larger than the analytical precision due to the uncertainty in the age correction that results from uncertainty in the radiometric age. The error quoted for  $^{87}\text{Sr}/^{86}\text{Sr}_i$  includes both the analytical precision and the uncertainty in the age correction. The ages used to calculate  $^{87}\text{Sr}/^{86}\text{Sr}_i$  are from Mahood and Drake (1982) and are as follows: Sample 15=32 Ka, Sample 115=61 Ka, Sample 174=73 Ka, Samples 37, 283, 317, 218, 184=96 Ka, Sample 193=123 Ka. We have no radiometric age for the basalt, Sample 182, but given the known K – Ar ages of other basalts at similar stratigraphic positions in the area (Gilbert et al. 1985), it cannot be more than 5 Ma old and therefore the Sr isotopic ratio requires no age correction

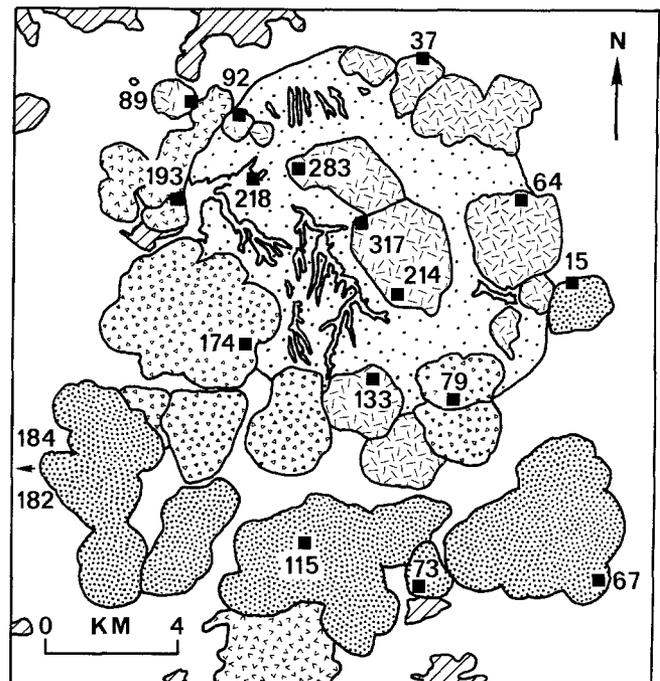
**Table 2.** Oxygen isotopic analyses

Eruptive unit	Sample number	Quartz	Sanidine	Glass
Precaldera Dome	193	7.0, 7.0	6.4, 6.5	–
Early Tala Tuff	184	–	–	7.9, 8.0 <sup>a</sup>
Late Tala Tuff	218	7.5, 7.6	6.6, 6.6	11.0
Southcentral Dome	214	7.0, 7.4	6.8, 7.4	7.0
	317	7.2	6.5	–
Northcentral Dome	283	7.4	–	–
95-Ka Ring Domes	37	7.4	6.7	–
	64	7.5	6.7, 6.8	–
	89	7.7	7.2	–
	92	7.4	5.8	–
75-Ka Ring Domes	133	7.4	–	7.3
	79	7.1	6.3	–
60-Ka Southern Arc Lavas	174	7.4	–	–
	73	–	–	6.8 <sup>a</sup>
30-Ka Southern Arc Lavas	115	–	–	6.5 <sup>a</sup>
30-Ka Southern Arc Lavas	15	–	–	6.6 <sup>a</sup>
	67	–	–	6.8 <sup>a</sup>

<sup>a</sup> These samples are aphyric, so the glass values are equivalent to whole-rock analyses

### Analytical methods

Whole-rock samples were crushed and pulverized in tungsten carbide. Feldspar, quartz, and glass separates were obtained by crushing the rock in steel, followed by bromoform separations and hand picking.



**Fig. 2.** Simplified geologic map of the Sierra La Primavera (after Mahood (1980)). *Diagonal ruling*: pre-Primavera volcanic rocks; *V pattern*: precaldera lavas; *unpatterned*: Tala Tuff, minor ignimbrites, primary and reworked pumice-fall deposits, and alluvium; *light stipple*: caldera lake sediments; *random dash pattern*: 95-Ka lavas; *triangles*: 75-Ka lavas; *heavy stipple*: 60- and 30-Ka lavas. Localities for samples in Tables 1 and 2 shown with *squares*

Rb and Sr concentrations were determined by isotopic dilution by the second author at the Scottish Universities Research and Reactor Centre (S.U.R.R.C.). All isotopic data were acquired using a V.G. Isomass 54E single-collector mass spectrometer. Blanks for Sr were less than 1 ng. Sr analyses were performed on single Ta filaments, except for some small samples for which about 10 ng was loaded on the side of a triple-filament assembly. Nd was analyzed as the metal using Ta side and Re central triple-filament assemblies. For the feldspars, which have very low Nd concentrations, procedures were similar to those used to analyze biotites at S.U.R.R.C., as detailed in Menzies et al. (1987). Blanks were between 30 and 100 pg, and the amount of Nd loaded on the filament was between 10 and 50 ng.

The  $^{18}\text{O}$  analyses were performed by W. Hildreth in the laboratory of J. O'Neil at the U.S. Geological Survey, Menlo Park. Oxygen was extracted using a  $\text{BrF}_5$  method modified slightly from that of Clayton and Mayeda (1963) and was reacted with hot graphite to yield  $\text{CO}_2$  for mass spectrometric analysis.

## Results

We have analyzed whole-rock samples and glass and feldspar separates from the rhyolites for their Nd isotopic compositions (Table 1). Within the analytical errors, all samples have a  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of 0.5129, which is identical to that of an associated basalt (Sample 182).

Quartz, feldspar, and glass were analyzed for their oxygen isotopic compositions (Table 2). Quartz-feldspar fractionations are appropriate for magmatic temperatures, indicating that the phenocrysts retain magmatic values. Pumice lapilli from the Tala Tuff have been hydrated and this is reflected in high  $\delta^{18}\text{O}$  for glass. The dense obsidians from the southern arc lavas have values of +6.5 to +6.8‰, similar to values for sanidine from other units, suggesting that the obsidians (which contain about 0.7%  $\text{H}_2\text{O}$ ) have not been isotopically affected by hydration.

All La Primavera rhyolites are extremely evolved rocks with very low Sr contents – as low as 320 ppb (Table 1). As a result, they have high Rb/Sr ratios, up to 750, and the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are a very sensitive function of the correction for in situ decay of  $^{87}\text{Rb}$  since eruption. All  $^{87}\text{Sr}/^{86}\text{Sr}$  reported here have been corrected for in situ decay using the previously determined K – Ar ages for the units (Mahood and Drake 1982). Indeed, the Rb/Sr ratios are sufficiently large that this study would not have been meaningful without the accurate age data.

Reproducibility of both the isotopic ratio and concentration of Sr is good for splits of the same rock powder (e.g., see 184WR and 115WR in Table 1), indicating that analytical precision is excellent. Despite the low absolute abundances of Sr, the isotopic ratios are low. With the exception of the southcentral dome (Sample 317), the rhyolites have  $^{87}\text{Sr}/^{86}\text{Sr}$  between 0.7040 and 0.7048 and are only slightly more radiogenic than an associated basalt at 0.7037.

At these low concentrations of Sr, sample inhomogeneity and contamination, whether it be caused by assimilation of crustal rocks, by magma mixing, by secular hydration of glass by groundwater, or by laboratory procedures, is potentially severe. An example of this problem is illustrated by Sample 218. Despite the pumice lapilli containing less than 1 wt. % phenocrysts of quartz and sanidine, concentrations of Sr are not the same in whole rock and separated glass. Until microtechniques for analyzing single grains are available, it will be difficult to determine the cause of such discrepancies.

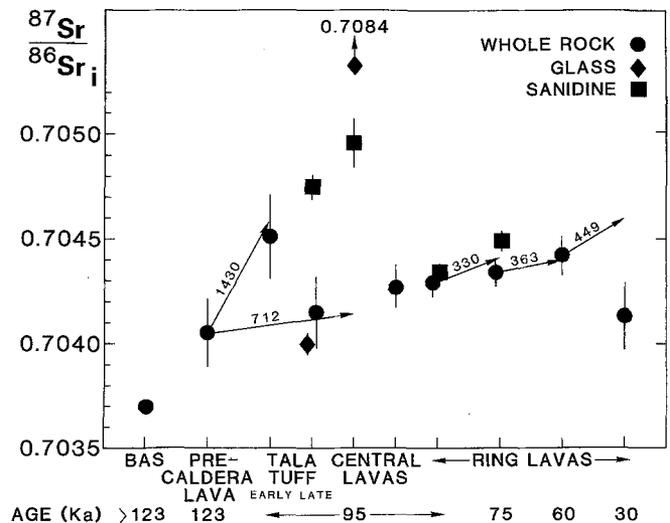


Fig. 3.  $^{87}\text{Sr}/^{86}\text{Sr}$  versus time. Vertical bars are  $\pm 1$  sigma total uncertainty. Arrows show expected growth in  $^{87}\text{Sr}/^{86}\text{Sr}$  due to in situ decay of  $^{87}\text{Rb}$  for the depicted values of  $^{87}\text{Rb}/^{86}\text{Sr}$ , which are the averages of ratios for the designated parent and more evolved younger magmas. The scale of the X axis is not linear (in order to avoid overlapping data points at 95 Ka); as a result, the slopes of the arrows have no meaning and only the offsets in the Y direction are significant.

Pumiceous samples (193WR, 184WR, 218WR, 218G, 174WR) are those most likely to be contaminated by hydration. Strontium added during hydration can affect the calculated  $^{87}\text{Sr}/^{86}\text{Sr}$  in two ways: (1) if the added Sr has an isotopic composition different from the rhyolite, the measured  $^{87}\text{Sr}/^{86}\text{Sr}$  is a weighted average of the values for the rhyolite and the contaminant, and (2) even if the added Sr has the same  $^{87}\text{Sr}/^{86}\text{Sr}$  because it was mobilized from the rhyolite itself, the resulting change in the Rb/Sr in these Sr-poor rocks potentially can lead to an incorrect adjustment for in situ decay since the time of eruption (as would any process leading to differential mobility of Sr and Rb). For these reasons, data obtained on feldspars, which would be unaffected by hydration and contain 2–4 times the Sr of the coexisting glass, are considered the most reliable. For the three samples (other than the southcentral dome) for which we analyzed both feldspar and whole rock, the discrepancy in the Sr isotopic composition between the two phases is a function of the vesicularity and, therefore, the ease in hydration of the sample (Table 1 and Fig. 3). The whole-rock isotopic composition of the nonvesicular but slightly perlitic Sample 37 is identical, within analytical uncertainties, to the feldspar; the pumiceous Sample 174 yields a whole-rock value slightly lower than the feldspar; and the fully inflated pumice lapilli of Sample 218 yield whole-rock and glass values significantly lower than the feldspar. We note that the largest apparent disequilibrium between whole rock and feldspar occurs in the sample with the highest  $\delta^{18}\text{O}$ . Using  $\delta^{18}\text{O}$  as a measure of both hydration and the potential problem with Sr contamination of whole-rock samples, we conclude that the Sr isotopic compositions measured on whole rocks for all but the Tala Tuff are close or equal to magmatic values.

## Problems in interpreting Sr isotopic ratios of low-Sr rocks

The ease of contaminating Sr-poor magmas during the magmatic stage or by post-magmatic processes makes the

interpretation of Sr isotopic compositions of high-silica rhyolites less straightforward than in more-mafic rocks. It casts doubt on models in which disequilibrium between glass and phenocrysts is used to calculate residence times of magmas or phenocrysts (e.g., Christensen and DePaolo 1987). That such an interpretation is incorrect is obvious at La Primavera because the feldspar, which has the lowest Rb/Sr, has the highest  $^{87}\text{Sr}/^{86}\text{Sr}_i$ . This presumably results from the surface rocks being intermediate and mafic volcanic rocks with  $^{87}\text{Sr}/^{86}\text{Sr}$  lower than the rocks under study. In geologic settings where surface rocks have higher  $^{87}\text{Sr}/^{86}\text{Sr}$  than the rhyolites, however, feldspar can have lower ratios than coexisting hydrated glass, and this can lead to an erroneous interpretation of the disequilibria having time significance. The same disequilibrium relationship between feldspar and matrix could also result from minor wall-rock contamination of the magmatic liquid after the feldspar had largely crystallized.

Variations in the fourth decimal place of  $^{87}\text{Sr}/^{86}\text{Sr}_i$  can arise from quantitatively minor processes in these Sr-poor rocks, even if they have been unaffected by post-magmatic contamination. As discussed below, tiny amounts of interaction with wall rocks or other magmas can produce differences of this magnitude. So can variable residence time of magmas in the chamber, which affect  $^{87}\text{Sr}/^{86}\text{Sr}$  through in situ decay of  $^{87}\text{Rb}$  in magmas with large Rb/Sr ratios. As a result, easily measurable and reproducible differences in  $^{87}\text{Sr}/^{86}\text{Sr}_i$  that would have great significance for interpretations of basalt and andesite source regions may not reflect major magmatic processes in high-silica rhyolites.

### Processes affecting high-silica rhyolites within La Primavera magma chamber

#### *Magmatic, in situ decay of $^{87}\text{Rb}$ and secular increase in $^{87}\text{Sr}/^{86}\text{Sr}$*

In highly evolved, Sr-poor magmas, in situ decay of  $^{87}\text{Rb}$  results in a marked secular increase in  $^{87}\text{Sr}/^{86}\text{Sr}$  (e.g., McCarthy and Cawthorn 1980; Javoy and Weis 1987). In situ decay of  $^{87}\text{Rb}$  in La Primavera rhyolites during residence in an upper crustal magma reservoir may contribute to the rhyolites having higher  $^{87}\text{Sr}/^{86}\text{Sr}_i$  than the associated basalt. Although it would require about 174 ky to increase  $^{87}\text{Sr}/^{86}\text{Sr}_i$  from 0.7037, the ratio for the basalt, to a value of 0.7044 typical of the rhyolites, assuming a Rb/Sr ratio of 100, shorter residence times would produce smaller but still measurable increases. Magmas must be stored as high-silica rhyolites for in situ decay to be significant, however, because hypothetical parental magmas with lower Rb/Sr ratios would require unrealistically long residence times (e.g., nearly 9 my for a Rb/Sr ratio of 2).

Because the rate at which the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio increases due to in situ decay is proportional to the Rb/Sr ratio of the magma, compositionally zoned magma chambers can develop gradients in  $^{87}\text{Sr}/^{86}\text{Sr}$  due solely to in situ decay. This is illustrated in Fig. 3, where the time trajectories of magmas of different  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios are plotted. The trajectories are for  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios that are averages of the presumed parent and derivative magmas. The trajectories originating at the precaldern lava illustrate that gradients in Sr isotopic composition can be established within compositionally zoned magma reservoirs containing Sr-poor high-silica rhyolites (and therefore large ranges of Rb/Sr) in peri-

ods of time that are short relative to the life spans of large silicic chambers. Assuming that the Tala Tuff evolved from a magma with the isotopic composition and Rb/Sr of the precaldern lava, in the ensuing  $\sim 30$  ky a difference of more than 0.0004 can develop between its most- and least-evolved parts. Due to the uncertainties introduced by addition of Sr on hydration of the ignimbrite pumice and the lack of feldspar in the most-evolved samples, we cannot use the difference in  $^{87}\text{Sr}/^{86}\text{Sr}_i$  to calculate how long prior to eruption the Tala Tuff compositional zonation existed.

Due to pre-eruptive, in situ decay of  $^{87}\text{Rb}$ , lavas that tap a closed magma chamber should show a slight increase in  $^{87}\text{Sr}/^{86}\text{Sr}_i$  with time. The data for the 95-, 75-, and 60-Ka lavas fit a closed-system model (Fig. 3) within the total uncertainties (i.e., analytical precision plus errors due to uncertainties in the K – Ar ages). The  $^{87}\text{Sr}/^{86}\text{Sr}_i$  of the youngest lava (Sample 15), however, is too low to represent a closed-system differentiate of the 60-Ka lavas. One possibility, suggested by its slightly elevated Ca and Sc contents (Mahood 1981) and the traces of Mg-rich mafic phases found in a heavy-liquid separate extracted from a large volume of the obsidian, is that it has been contaminated by interaction with more-mafic magma. Assuming a model ratio of 0.7046 and a more-mafic magma with an isotopic ratio similar to Sample 182 (0.7037), about half the Sr in Sample 15 could come from the more-mafic magma. If this magma had a Sr content of 800 ppm, like Sample 182, this represents, however, a mass fraction of only 0.0006! Given the tiny amount of contamination necessary, one can imagine it resulting from assimilation of incipient melts of intermediate wall rocks, as well as mixing with dacitic or trachytic magma. Simple mixing of rhyolitic and mafic magma seems less likely because such a small proportion of basaltic or andesitic liquid would be rapidly quenched to a solid on mixing with rhyolite (Frost and Mahood 1987), thereby limiting chemical and isotopic interaction. In any case, contamination in such small amounts would not affect the isotopic compositions of neodymium and oxygen.

#### *Contamination accompanying caldera collapse*

Sanidine from the southcentral dome has the highest  $^{87}\text{Sr}/^{86}\text{Sr}_i$ , 0.7050, and the coexisting glass at 0.7084 is much higher than any other sample analyzed (Table 1 and Fig. 3). This lava dome was the first emplaced after caldera collapse, and it erupted in the region thought to be the main vent for the caldera-forming pyroclastic flows (Mahood 1980). Its elevated  $^{87}\text{Sr}/^{86}\text{Sr}_i$  suggests that some of the magma remaining in the chamber was contaminated on caldera collapse, either by incorporating roof rocks or by engulfing fluids. The fact that the feldspar has a lower  $^{87}\text{Sr}/^{86}\text{Sr}_i$  value than the enclosing glass suggests that at least some of it crystallized from a magma less contaminated than the one that encases it. Without analyses of individual grains, it is not possible to determine if the 0.7050 ratio is the isotopic composition of the magma at the time the feldspar crystallized or if the ratio reflects a mixture of pre-collapse phenocrysts that precipitated from a magma with an initial ratio less than 0.705 and a small amount of feldspar, conceivably occurring as overgrowths, that crystallized after collapse and contamination of the magma. Other lavas erupted during the same episode (e.g., Samples 283 and 37) have lower  $^{87}\text{Sr}/^{86}\text{Sr}_i$ , suggesting that the contamination was only local in scale, not chamber-wide.

The southcentral dome may be more contaminated because it represents magma erupted through the area thought to be the main vent for the preceding pyroclastic flows and therefore had the opportunity to engulf fragments of the roof disrupted in the vent region.

Hildreth et al. (1984) reported on much larger-scale contamination accompanying caldera collapse in the Yellowstone system. Not only were  $^{87}\text{Sr}/^{86}\text{Sr}_i$  elevated, but  $\delta^{18}\text{O}$  values were drastically lowered. There is no drastic lowering of  $\delta^{18}\text{O}$  following collapse at La Primavera. This is not surprising, however, because (1) present-day meteoric water at La Primavera is about 10 permil heavier than that at Yellowstone, providing much smaller contrast with the magma (Mahood et al. 1983), and (2) there is no evidence for a precaldera hydrothermal system at La Primavera that might have contributed low- $\delta^{18}\text{O}$  altered roof rocks.

Other than knowing that it must have a Sr isotopic ratio greater than or equal to 0.7084, the nature of the contaminating roof rock is not well constrained; the abundance of Sr in the magma is so low that only very small amounts of contamination are required to raise the  $^{87}\text{Sr}/^{86}\text{Sr}$ , and these might not be large enough to affect Nd or O isotopic ratios. If the contaminant is not an engulfed fluid or a rhyolitic intrusive rock, it must have been incorporated in very small amount because of the chemical coherence of the southcentral dome with the last-erupted Tala Tuff and the later ring domes (Mahood 1981). La Primavera rhyolite (or its alkali-feldspar granite equivalent) emplaced at an earlier time is an especially attractive contaminant because it has a low melting temperature, high Rb/Sr ratios that result in significant elevation of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in periods as short as 10 ky, and little or no contrast in other isotope systems or in chemical composition.

#### *Wall-rock interaction during differentiation*

Differentiation within the rhyolite range at La Primavera apparently was accompanied by little contamination, as the isotopic ratios of Nd and O are essentially constant in products erupted over a period of more than 100 ky (Tables 1 and 2, Fig. 3), and much of the variation in  $^{87}\text{Sr}/^{86}\text{Sr}_i$  (with the exception of the southcentral dome) can be attributed to magmatic, in situ decay of  $^{87}\text{Rb}$ . This relative isotopic homogeneity cannot be attributed to an absence of isotopic contrast between magma and wall rocks because the unit that had the greatest opportunity for interacting with wall rocks by virtue of erupting through the main vent for the preceding explosive eruptions, the southcentral dome, has a much higher  $^{87}\text{Sr}/^{86}\text{Sr}_i$  than the rest of the lavas, indicating that wall rocks with elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  are present.

The general lack of wall-rock interaction results in part from the low temperatures of rhyolites and the relatively small amount of latent heat produced on crystallization of the dominant phenocrysts, quartz and alkali feldspar. The occurrence of significant contamination only in association with mechanical disruption of the roof, however, suggests that a zone of stagnant and/or partially crystallized magma attached to chamber walls generally buffers the body of the chamber from wall-rock interaction. Only when large-scale disruption of chamber margins by explosive venting or caldera collapse occurs is there significant contamination. The similarity of isotopic ratios in the Tala Tuff and postcaldera lavas suggests that their contrasting trace-element patterns were not caused by interaction with

different wall rocks or by different amounts of contamination.

#### **Sources of magmas parental to La Primavera high-silica rhyolites**

The origin of La Primavera rhyolites is not well-constrained, in spite of their relatively primitive and generally restricted isotopic signatures. Certain possibilities can nonetheless be eliminated. The extremely low concentrations of Sr and Ba in La Primavera (and other) high-silica rhyolites rule out an origin by single-stage melting of any voluminous source lithology and seem to require extensive fractional crystallization after liquids attain rhyolitic compositions. Only in rhyolites are bulk distribution for Sr and Ba large, due to dominance of alkali feldspar in the crystallizing assemblage and the large partition coefficients characteristic of highly polymerized rhyolitic liquids (Mahood and Hildreth 1983). Thus in the following discussion it is the origin of an isotopically and chemically reasonable parental magma that could produce La Primavera high-silica rhyolites on fractionation that is of interest.

The  $\delta^{18}\text{O}$  values near +6.6‰ for the rhyolites eliminate sedimentary and low-grade metamorphic rocks as sources of parental partial melts. These rocks and many other upper crustal lithologies, including most granitic rocks, presumably have Rb/Sr ratios that would produce present-day  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios too high to yield  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios similar to La Primavera rhyolites on partial melting. For the same reason, such rocks are eliminated as major contaminants of more-mafic magmas that might have produced La Primavera rhyolites by fractional crystallization. Partial melting or contamination occurring at deeper levels cannot have involved a significant proportion of ancient crust, as most Precambrian crustal lithologies have  $\epsilon_{\text{Nd}}$  values lower than those observed in La Primavera rhyolites. Finally, the identical  $\epsilon_{\text{Nd}}$  values of rhyolite and basalt rules out the hypothesis that the relatively low  $^{87}\text{Sr}/^{86}\text{Sr}_i$  ratios resulted from contamination of a more radiogenic crustal melt by small amounts of more-primitive Sr-rich liquid, followed by extensive feldspar fractionation to produce the low Sr concentrations.

#### *Fractional crystallization and crustal contamination of mantle-derived basalts*

The simplest interpretation of the isotopic data is that La Primavera rhyolites are derived by fractional crystallization of mantle-derived basaltic magma. Rhyolites have  $\epsilon_{\text{Nd}}$  values identical to the basalt and relatively low  $\delta^{18}\text{O}$  values (+6.6‰), consistent with fractional crystallization of a basaltic parent. The fact that  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of La Primavera rhyolites are slightly higher than those of the associated basalt requires that either the rhyolites have long residence times in crustal magma reservoirs or, more likely, that mantle-derived basalt was contaminated with crustal material. Given the low Sr contents of these rhyolites, the amount of contamination could be very small. The isotopic data allow only tiny amounts of contamination by rocks with high Rb/Sr ratios, such as granitic rocks or early generations of Primavera rhyolites, but partial melts of Tertiary and Mesozoic intermediate and mafic igneous rocks (or their metamorphosed equivalents) could have been assimilated in large amounts prior to fractionation to felsic com-

positions. The peralkaline character of La Primavera rhyolites requires that a significant proportion of the parental magma(s) and/or their contaminants be slightly alkalic; otherwise, calc-alkalic, plagioclase-bearing rhyolites would be produced.

#### Partial melting of crustal rocks

Miocene and Pliocene volcanic rocks in the Guadalajara region range in composition from basalt to rhyolite, and alkali basalts, trachytes, and alkali rhyolites, including some weakly peralkaline felsic varieties (Mahood et al. 1985), are equally common as calc-alkalic rocks. The intrusive equivalents of these rocks would provide a wide range of lithologies that might have been partially melted to produce the precursors to La Primavera magmas. All the felsic rocks can be eliminated as source lithologies, however, because large Rb/Sr ratios lead to present-day  $^{87}\text{Sr}/^{86}\text{Sr}$  too high to produce La Primavera rhyolites on melting. The assumed presence of plutonic equivalents of the felsic volcanic rocks in the upper crust makes it unlikely as the site of melting to produce La Primavera magmas or their parents.

The nature of the deep crust is poorly known in west-central Mexico because the basement is largely covered by Tertiary volcanic rocks. The nearest samples of lower crust come from granulite-facies xenoliths ejected by young alkalic mafic magmas several hundred kilometers northeast of La Primavera (Ruiz et al. 1988); all have  $\epsilon_{\text{Nd}}$  too low to produce La Primavera rhyolites on melting. Ultramafic cumulates, gabbros, and amphibolites forming the roots of accreted Mesozoic island arcs thought to underlie the Guadalajara area (Coney and Campa 1984) could have  $\epsilon_{\text{Nd}}$  values similar to La Primavera rhyolites. Ultramafic cumulate rocks, however, would not produce silicic compositions on partial melting, and partial melts of amphibolites are strongly corundum-normative (Helz 1976), thereby making them a poor match for La Primavera rhyolites. Such melts are also unlikely to yield peralkaline compositions on high-level fractional crystallization.

Partial melting of intermediate and mafic plutonic rocks related to Mesozoic and Tertiary magmatism could produce silicic melts appropriate in chemical and isotopic composition to be parental to La Primavera magmas. Experiments on equilibrium partial melting of gabbroic rocks do not yield high-silica rhyolites, but at  $\text{PH}_2\text{O}$  sufficiently low that hornblende is unstable yet high enough that Fe-Ti oxides are stable over a large temperature interval, rhyolitic melts can be produced (Holloway and Burnham 1972; Dixon-Spulber and Rutherford 1983) that might reasonably evolve into high-silica rhyolites like those of La Primavera. Partial melting of monzonitic rocks under relatively dry conditions is perhaps the most straightforward way to generate a large volume of felsic magma in the absence of comagmatic intermediate lavas; the alkalic nature of the source and the large fraction of refractory plagioclase would produce partial melts capable of yielding peralkaline high-silica rhyolites with very low concentrations of Ba and Sr on fractional crystallization.

#### Comparison with other North American high-silica rhyolites

The isotopic data from La Primavera do not unequivocally distinguish between an origin by fractional crystallization of mantle-derived basalt or partial melting of Mesozoic or Tertiary mafic to intermediate intrusive rocks. To address

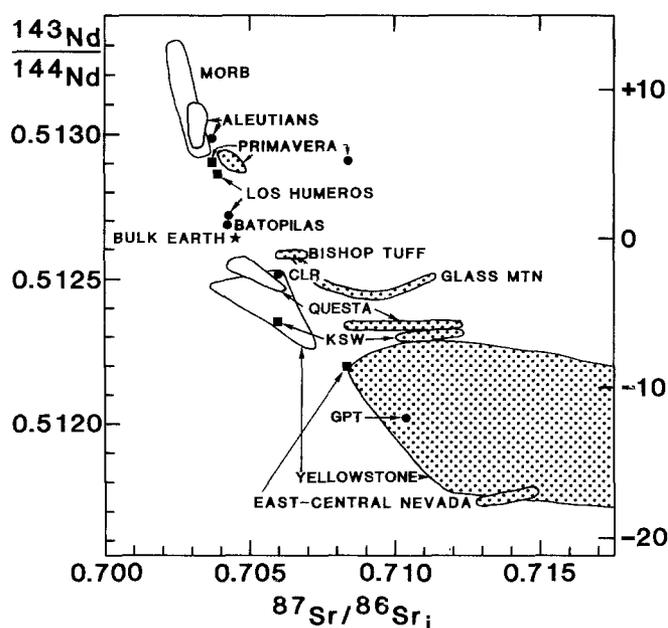


Fig. 4.  $^{143}\text{Nd}/^{144}\text{Nd}$  versus  $^{87}\text{Sr}/^{86}\text{Sr}_i$  for La Primavera and other Cenozoic volcanic centers in western North America containing high-silica rhyolites. Data sources are as follows: Aleutian basalts (Kay et al. 1986); rhyolite marked "Aleutians" is from the Valley of Ten Thousand Smokes, Katmai National Park, on the Alaska Peninsula (Hildreth 1987); Primavera (this study); Los Humeros (Verma 1983); Batopilas (Lanphere et al. 1980; Cameron and Cameron 1986a) and CLR: Cerro de Los Remedios (Ruiz et al. 1987), Sierra Madre Occidental, Mexico; Bishop Tuff (Halliday et al. 1984) and Glass Mountain (Halliday et al. submitted), California; Questa, New Mexico (Johnson 1986); KSW = Kane Springs Wash caldera, southeast Nevada (Novak 1985); GPT = Grizzly Peak Tuff, Colorado (Johnson and Fridrich 1987); Yellowstone (Hildreth et al. in prep.); east-central Nevada (Gans et al. submitted). Data for rhyolites are shown as solid circles or dotted fields; basalts are solid squares and unpatterned fields.

whether this ambiguity results from the basement lacking strong isotopic contrast with young mantle-derived magmas, the isotopic compositions of Cenozoic high-silica rhyolites and associated basalts erupted through basements of different ages were compiled (Fig. 4). It is apparent from Fig. 4 that there is a general correlation between age and thickness of the underlying crust and the isotopic compositions of the rhyolites. The isotopically most primitive rhyolite is from the Valley of Ten Thousand Smokes on the Alaska Peninsula (Hildreth 1987), where the basement is Mesozoic in age. High-silica rhyolites from Long Valley, California, which lie on Paleozoic basement near the edge of Precambrian craton, have  $\epsilon_{\text{Nd}}$  between  $-1$  and  $-4$  (Halliday et al. 1984; Halliday et al. submitted). Samples from Kane Springs Wash, Nevada, and Questa, New Mexico, overlie extensionally thinned Proterozoic crust and have  $\epsilon_{\text{Nd}}$  of about  $-6$  (Novak 1985; Johnson 1986), whereas Grizzly Peak rhyolites, which erupted through the thick Proterozoic crust of the Colorado Plateau, have  $\epsilon_{\text{Nd}}$  of  $-12$  (Johnson and Fridrich 1987). Yellowstone rhyolites range to lower values,  $-8$  to  $-20$ , reflecting the Archean basement (Halliday et al. 1986). Although  $\epsilon_{\text{Nd}}$  values of the rhyolites decrease with basement age (with the exception of the east-central Nevada rocks), they lie between the isotopic compositions of associated basalts and nearby basement rocks, indicating that they contain both a young

mantle component and a crustal component. The crustal component may be produced by partial melting of intermediate to deep levels of the crust by mantle-derived basalts; hybridization of the basalts, their differentiates, and partial melts in varying proportions can account for systems with an abundance of associated intermediate rocks as well as those (like La Primavera) dominated by felsic compositions.

The Oligocene rhyolites and dacites of east-central Nevada, which erupted through Proterozoic crust, have among the lowest  $\epsilon_{\text{Nd}}$  values, suggesting that they contain a larger proportion of crustal melts than the other rhyolites. This may be related to their intimate association with large-magnitude extension and elevated crustal geotherms at this metamorphic core complex (Gans et al. submitted).

Plotting the Primavera samples with respect to other North American samples emphasizes their high  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.5129,  $\epsilon_{\text{Nd}} = +5$ ). Although such a value is common in arc andesites, it contrasts strongly with most rhyolites of North America. The Primavera samples are isotopically most similar to high-silica rhyolites of the Valley of Ten Thousand Smokes, where the basement is Mesozoic in age. This suggests that ancient crust is lacking beneath the western portion of the Mexican Neovolcanic Belt and supports the hypothesis that the basement consists of Mesozoic accreted island-arc terranes (Coney and Campa 1984). The somewhat lower  $\epsilon_{\text{Nd}}$  values for high-silica rhyolites at Los Humeros (Verma 1983), another Mexican behind-the-arc caldera complex (Fig. 1), may reflect involvement of basement that is older and has undergone less Mesozoic and Tertiary magmatism than has other parts of the Mexican Neovolcanic Belt, thereby containing a higher proportion of isotopically evolved lithologies.

At a number of the centers illustrated in Fig. 4 (Katmai, Los Humeros, Batopilas, Grizzly Peak, east-central Nevada), high-silica rhyolites have isotopic compositions similar to associated intermediate rocks, suggesting that differentiation from andesite to rhyolite is accompanied by little if any interaction with crustal rocks (cf. Lanphere et al. 1980; Cameron and Cameron 1986b; Ferriz and Mahood 1987). This does not imply, however, that the magmas contain no crustal component; it means only that most crustal assimilation took place at lower to middle crustal levels during the interval magmas differentiate from primitive compositions to basaltic andesite (cf. Hildreth and Moorbath 1988). Contamination early in the liquid line of descent may be the reason basalts and basaltic andesites of the Mexican Neovolcanic Belt have  $^{87}\text{Sr}/^{86}\text{Sr}_i$  between 0.7034 and 0.7044 (Verma and Verma 1986), rather than the 0.7030–0.7037 typical of intraoceanic arcs. These values are then largely inherited by more-felsic melts that form either by further differentiation of these hybrid magmas or by partial melting of their plutonic or deep crustal metamorphic equivalents. Intermediate and felsic magmas have lower magma temperatures and heats of fusion than basalts and are therefore less likely to cause crustal melting. In addition, shallow wallrocks are cooler, requiring a larger heat input to raise temperatures to the solidi. As a result, fractionation from andesite to rhyolite in upper-crustal magma reservoirs may be accompanied by only minor wall-rock assimilation.

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