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Petrology and geochemistry of stage-I andesites and dacites from the caldera wall of Volcán Colima, Mexico

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RESUMEN

Se reportan las concentraciones y modos para 10 lavas andesíticas y dacíticas de la Etapa I del Volcán de Colima. Nueve de estas muestras fueron colectadas en la pared de la caldera que se formó por uno o varios eventos tipo colapso Sta. Helena durante el Holoceno. Estos datos se contrastan con los de las lavas emitidas durante la Etapa II, que siguió después de la formación de la caldera, y también se discuten en relación con todos los análisis de la cadena Volcán Cántaro, Nevado de Colima y Volcán de Colima cuya edad disminuye de norte a sur.

Tanto las lavas de la Etapa I como II del Volcán de Colima muestran cantidades significativamente mayores en SiO_2 con relación a la escoria producida contemporáneamente durante el Holoceno. Las lavas de la Etapa I muestran valores mayores en SiO_2 que las lavas de la Etapa II, sin embargo esto también se observa en la evolución del magma del Nevado con el tiempo. Las lavas del Volcán Cántaro están relativamente enriquecidas en K_2O, Sr, La, Ce y Sm comparadas con todas las muestras de la Etapa II del Volcán de Colima, pero cuatro de las lavas de la Etapa I que se discuten en este artículo también muestran estos enriquecimientos.

Comparando las lavas de la Etapa II del Volcán de Colima con las lavas de la Etapa I y del Volcán Cántaro, muestran valores menores en Yb y Lu y mayores en La/Yb y Sr/Yb. Estas características probablemente reflejan un papel relativamente más importante del granate residual en las fuentes de los magmas más antiguos, el que podría retener a las tierras raras pesadas. Las lavas del Volcán Cántaro y las de la Etapa I del Volcán de Colima también muestran valores relativamente menores en Rb/Sr que las lavas de la Etapa II. Esta diferencia puede reflejar un cambio en el tiempo donde disminuye la fuente del manto que contenga anfíbola o cualquier otro mineral que pueda retener Rb cuando se funde. La interpretación preferida para la transición a más altos valores de Yb, Lu y Rb/Sr y más bajos en La/Yb y Sr/Yb después de la formación de la caldera del Volcán de Colima es un cambio en las contribuciones relativas de los componentes de la fuente con una disminución en la fusión de la placa subducida que contiene granate y anfíbola y un incremento en la fusión derivada del mante sobreyaciente.

PALABRAS CLAVE: Colima, México, andesita calcialcalina, dacita, fusión de la placa.

ABSTRACT

Major and trace element concentrations and modes are reported for 10 andesitic and dacitic lavas from stage-I activity at Volcán Colima. Nine of these samples were collected from the walls of the summit caldera, formed by one or more major, Mount St. Helens-type collapse events during the Holocene. These data are contrasted with data for lavas erupted during stage II, following formation of the caldera, and are also discussed in the light of all available analyses for the southward-younging volcanic chain that runs from Volcán Cántaro in the north, through Nevado de Colima, to Volcán Colima in the south.

Both the stage-I and stage-II lavas of Volcán Colima are significantly richer in SiO_2 than contemporaneous scoriae erupted during the Holocene. Stage-I lavas range to higher SiO_2 values than stage-II lavas, however, a pattern that is also evident in the evolution of magma compositions with time at Nevado. The lavas from Volcán Cántaro are relatively enriched in K_2O, Sr, La, Ce, and Sm compared to all samples from stage-II activity at Volcán Colima, but four of the stage-I lavas discussed in this paper also show these enrichments.

Compared to the stage-II Volcán Colima lavas, those from both stage I and from Volcán Cántaro have lower Yb and Lu abundances and higher La/Yb and Sr/Yb values. These features probably reflect a relatively greater role for residual garnet in the source regions for the earlier magmas, which would act to retain the heavy rare earth elements. The lavas from Volcán Cántaro and the stage-I lavas from Volcán Colima also show relatively lower Rb/Sr values than the stage-II lavas. This difference could reflect a shift with time away from a mantle source containing amphibole or any other mineral that could retain Rb upon melting. The preferred interpretation for the transition to higher Yb, Lu, and Rb/Sr and lower La/Yb and Sr/Yb following caldera formation at Volcán Colima is a shift in the relative contributions of source components to the magmas, with a decrease in melting of the garnet-amphibole-bearing subducted slab, and an increase in melts derived from the overlying mantle wedge.

KEY WORDS: Colima, Mexico, calc-alkaline andesite, dacite, slab melting.

INTRODUCTION AND GEOLOGIC SETTING

A fault-bounded portion of mainland Mexico lying southwest of the city of Guadalajara and covering some 45,000 km^2 began to rift away from the rest of North America sometime in the Pliocene. This area is called the Jalisco Block (Figure 1a), and appears to be in the early stages of northwest motion relative to North America; it is slowly being transferred from the North American Plate to the Pacific Plate in much the same manner as Baja California

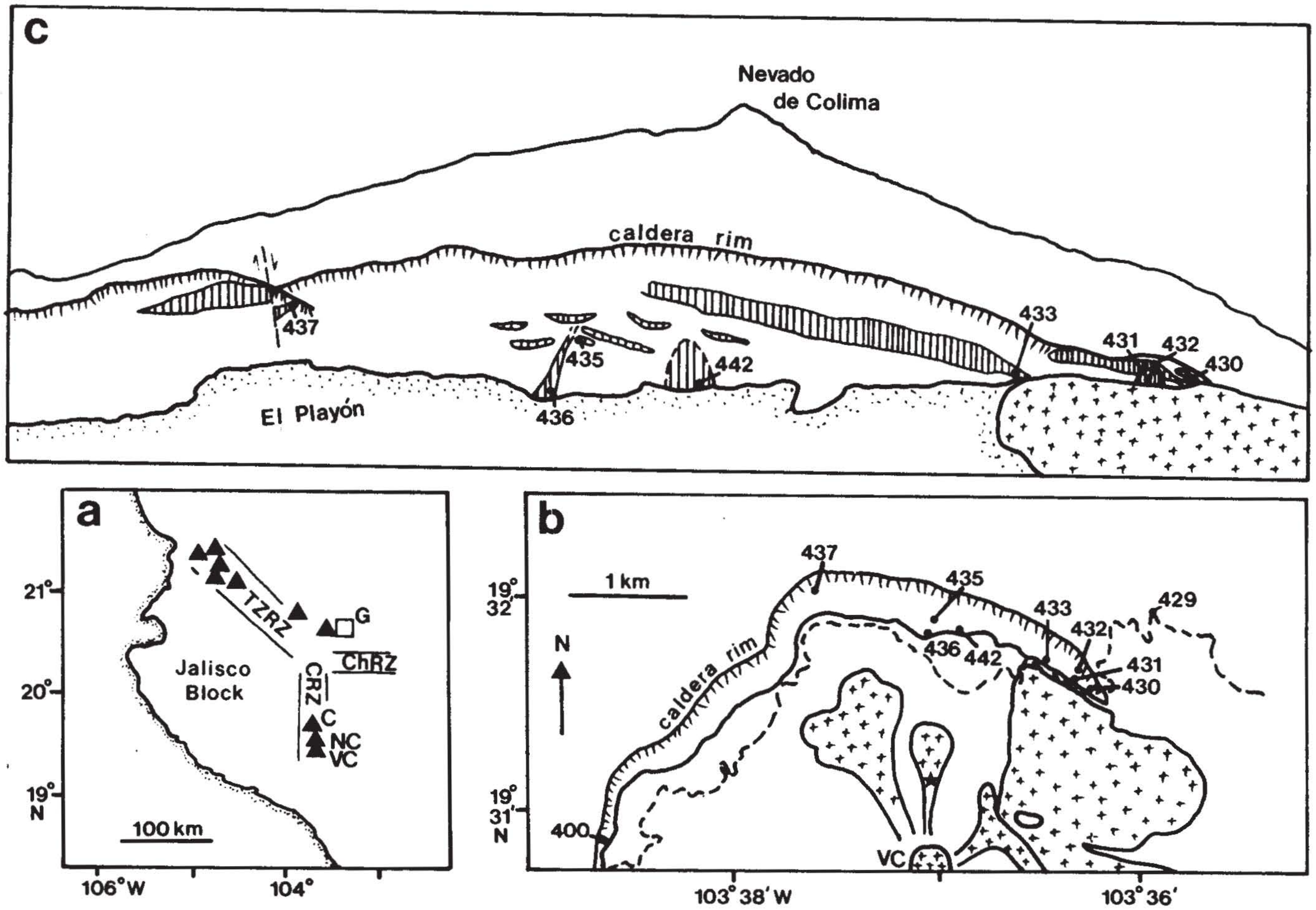

Fig. 1. Sample locations. (1a) sketch map of western Mexico that shows major Quaternary volcanic centers as triangles, including Volcán Cántaro (C), Nevado de Colima (NV), and Volcán Colima (VC). The three major rift zones are labelled: Tepic-Zacoalco Rift Zone (TZRZ), Chapala Rift Zone (ChRZ), and Colima Rift Zone (CRZ). The open square shows the city of Guadalajara (G). (1b) sketch map of the summit showing the caldera rim and walls, the old road into the caldera (dashed), historical lava flows (plus pattern), the summit of Volcán Colima (VC), and the locations of samples described in this study (labelled dots). The small star just north of the summit shows the position from which the panoramic photos used for Figure 1c were taken. (1c) Sketch drawn from a panoramic series of photos taken looking north from 2/3 of the way up the 1961-62 lava flow on the north face of Volcán Colima (star on Figure 1b). Vertical lines indicate important outcrops of lava flows, domes (431, 442), and a dike (436) in the caldera walls. A normal fault is shown just west of sample 437. The plus pattern indicates the lava flow from Volcancito, erupted in 1869. El Playón is the floor of the caldera.

was transferred in Mio-Pliocene time (Sawlan, 1991). Rifting of the Jalisco Block is thought to be related to eastward jumping of an offshore segment of the East Pacific Rise (Luhr and Carmichael, 1981; Luhr *et al.*, 1985; Bourgois *et al.*, 1988a, 1988b; Allan *et al.*, 1991; see DeMets and Stein (1990) for an alternative mechanism). This rifting event is presently expressed in three major rift zones that meet in a triple junction about 50 km southwest of Guadalajara: the N-S-trending Colima Rift Zone, the NW-SE-trending Tepic-Zacoalco Rift Zone, and the E-W trending Chapala Rift Zone (Figure 1a). The Colima and Tepic-Zacoalco Rift Zones mark the eastern and northern margins, respectively, of the Jalisco Block.

Volcanic eruptions have accompanied this tectonic activity in all three rift zones. In the southern portion of the Colima Rift Zone, a N-S-trending chain of three major composite volcanoes has developed during the Quaternary, with the focus of volcanism shifting southward over time. Volcán Cántaro, in the north (Figure 1a), is an eroded andesite-dacite cone that rises to 2,925 m from a base at about 1,600 m. Allan (1984;1986) reported K-Ar ages of 0.95 ± 0.17 Ma and 0.99 ± 0.01 Ma for two lava flows from Volcán Cántaro proper, ages of 1.33 ± 0.20 Ma and 1.66 ± 0.24 Ma for two domes on the northern flank, and a seemingly anomalous age of 4.56 ± 0.22 Ma on a pumice-fall deposit at the foot of one of the domes.

Following formation of Volcán Cántaro, the focus of andesitic magmatism shifted southward by about 16 km and the massive cone of Nevado de Colima began to grow (Figure 1a). Robin *et al.*, (1984;1987) discussed the geologic and petrologic evolution of the Colima Volcanic Complex, which includes both Nevado and the younger Volcán Colima. They divided the evolution of Nevado into three stages, separated by episodes of caldera formation. Stage I saw the growth of a large andesite-dacite cone, for which Robin *et al.* (1984) reported K-Ar ages of 0.53

±0.10 Ma and 0.35 ± 0.05 Ma. The same authors reported ages of 0.29 ± 0.08 Ma and 0.14 ± 0.04 Ma for andesitic lavas from the small stage-II cone, which collapsed to form a Mount St. Helens-type debris avalanche directed toward the east (Robin *et al.*, 1990). Stoopes and Sheridan (1992) reported a ^{14}C age of 18,520 ± 260 years from a carboni-zed tree trunk embedded in this debris-avalanche deposit. They traced the deposit 120 km southward to the Pacific coast, and estimated its volume as 22-33 km^3, making it the second largest debris-avalanche deposit yet discovered. During stage III, an andesitic cone formed in the avalanche caldera. This summit cone is only slightly eroded and reaches an elevation of 4,320 m.

The focus of activity shifted southward again by about 5.5 km as the cone of Volcán Colima began to grow. The age of the first eruption from Volcán Colima is not known, but Robin *et al.* (1984;1987) argued that it probably took place during stage II activity at Nevado; thus, the active periods of the two volcanoes may have overlapped for a considerable time. After rising to an estimated height of 4,100 m, Volcán Colima also collapsed in the fashion of Mount St. Helens to form a major debris-avalanche deposit and a large horseshoe-shaped caldera, 5 km in diameter. Luhr and Prestegaard (1985;1988) discussed the formation of the caldera and described the debris-avalanche deposit that covers the southern flank of the volcano. They presented a ^{14}C age of 4, 280 ± 110 years for charcoal from beneath the debris-avalanche deposit, which they considered to closely approximate the age of the caldera. Luhr and Prestegaard (1988) considered the possibility that more than one debris-avalanche deposit might be present on the southern flank of the volcanic complex but were unable to prove or refute this idea. Later studies, aided by new roadcuts along the Colima-Guadalajara toll road, have shown that indeed multiple deposits are present; the 18,500-year-old debris-avalanche deposit from Nevado (Stoopes and Sheridan, 1992), was incorrectly included in the area assigned to the deposit from Volcán Colima by Luhr and Prestegaard (1988). Robin *et al.* (1987; 1990) also described the caldera of Volcán Colima and its debris-avalanche deposit, and reported a ^{14}C date of 9,370 ± 400 years for charcoal from a pyroclastic layer above the debris-avalanche deposit. The number and distribution of debris-avalanche deposits from Volcán Colima continues to be debated (Martin-del Pozzo *et al.*, 1990; Siebe *et al.*, 1992). In addition to possible deposits of 9,370 years (Robin *et al.*, 1987; 1990) and 4,280 years of age (Luhr and Prestegaard, 1988), another ^{14}C date of 2,300 years has been obtained (M.F. Sheridan, pers. commun.). Until many more carbon dates are obtained from the debris-avalanche deposits on the southern flank of Volcán Colima, and field criteria are established for distinguishing the deposits of different age, the details of the collapse history and the formation of the summit caldera will remain unclear. For the purposes of this study, the main complication is that the time of transition from stage-I activity (pre-caldera) to stage-II activity (modern, post-caldera cone) cannot be precisely specified. This problem affects interpretation of the carbon-dated pyroclastic-fall deposits from the upper northeast flank of Volcán Colima, studied by Luhr and Carmichael (1982). Because the timing of caldera formation is not clear, it is not possible to relate these deposits to the stage-I/stage-II nomenclature established for the lavas. Although these scoria-fall samples are included on compositional diagrams in this paper, they are only briefly discussed.

Since the last major collapse event at Volcán Colima, an andesitic cone has grown within the horseshoe-shaped summit caldera. This cone, built during stage-II activity, has now reached a height of over 3,900 m, and is one of the most active volcanoes in North America. Volcán Colima has erupted frequently in historical times (Luhr, 1981; Medina-Martínez, 1983), including major explosive eruptions in 1818 and 1913, and important lava eruptions in 1869, 1961, 1975-76, 1981-82, and 1991.

Although they are not considered in this report, for completeness it is important to note the presence of two andesitic domes and small lava flows that occur on the southern flank of Volcán Colima, about 3 km in map view from its active crater. These domes, prosaically named "Los Hijos del Volcán" (The Children of the Volcano), probably erupted since formation of the caldera, and may mark the site of the next major volcanic center in the southward-migrating Cántaro-Colima chain.

Robin *et al.* (1987,1991) presented major-element analyses for volcanic rocks from all stages in the evolution of the Colima Volcanic Complex. Luhr and Carmichael (1980, 1990) gave major and trace element analyses, mineral abundances, and mineral compositions for Stage-II andesites, and Luhr and Carmichael (1982) discussed similar data for the scoria- and ash-fall deposits from Volcán Colima. No petrological data of any kind have yet been published for Volcán Cántaro, and no trace element or mineral abundance data have yet been published for Nevado or the stage-I lavas of Volcán Colima. The present paper was designed to partially fill this gap. It is based on petrographic and geochemical data for 10 stage-I andesites and dacites from Volcán Colima. These data show that the stage-I and stage-II products are compositionally distinct, and shed light both on the details of magmatic evolution during development of an individual volcano along the Cántaro-Colima chain, and on the longer term development of the chain itself. Data for these stage-I samples may also aid in the identification of source materials for blocks present in the debris-avalanche deposits on the southern flanks of Volcán Colima.

SAMPLE LOCATIONS

Nine of the ten samples considered in this study were collected from the caldera wall of Volcán Colima, which is shown in map view in Figure 1b and in a panoramic sketch in Figure 1c; the other sample is a lava collected from the upper cone in an outcrop along the road into the caldera

(Figure 1b). Sample 1004-400 is an andesitic block from a fragmental deposit beneath a lava flow. Sample 1004-436 is from the prominent dike in the northern part of the caldera wall. Samples 1004-431 and -442 are from dome-like bodies exposed in the wall, and all other samples are from lava flows exposed in the caldera wall (Figure 1c).

ANALYTICAL TECHNIQUES

All samples were analysed for major and trace elements by X-ray fluorescence (XRF) spectroscopy. Details of the analytical techniques are given in Table 1. Additional trace elements were measured by instrumental neutron activation (INA) analysis, as also described in Table 1. Modes were determined by point counting (Table 2).

MAJOR ELEMENT DATA

In this section, major element data for samples from Volcán Cántaro (unpublished), Nevado (Robin *et al.*, 1984, 1987), and Volcán Colima (Luhr and Carmichael, 1980, 1982, 1990; Robin *et al.*, 1984, 1987, 1991) are used to address the evolution of magmatic compositions along the Cántaro-Colima volcanic chain. The nomenclature used in this paper for calc-alkaline volcanic rocks is based simply on SiO_2 content (normalized anhydrous with $Fe^{3+}=0.2x\ Fe^{total}$: basalt <53 wt. % < basaltic andesite < 56% < andesite < 63% < dacite < 67%.

Whole-rock SiO_2 contents for 154 lava and scoria samples are plotted on histograms in Figure 2 for Volcán Cántaro (Figure 2a), Nevado (Figure 2b), and Volcán Colima (Figure 2c). The 17 lava samples from Volcán Cántaro include one basaltic andesite, with the other samples evenly split between andesites and dacites. The 11 stage-I samples from Nevado include 6 andesites and 5 dacites. In contrast, the 9 samples from stages II and III are all andesites, demonstrating a clear progression toward lower SiO_2 contents with time (Robin *et al.*, 1987). In similar fashion, the 18 stage-I lavas from Volcán Colima include 10 andesites and 8 dacites, whereas the 46 stage-II lavas from Volcán Colima are all andesites, with a strong mode at 60-61 wt. % SiO_2. As emphasized by Luhr and Carmichael (1982), Holocene scoriae erupted from Volcán Colima are considerably poorer in SiO_2 than all of these temporally associated lavas. The scoriae include 2 basalts, 6 basaltic andesites, 21 andesites, and no dacites. A similar contrast between lava and scoria compositions is not evident in the data of Robin *et al.*, (1984, 1987) for Nevado. The most silica-poor analysis plotted in Figure 2c is a likely parental basalt (sample 22E) from the cinder cone Tezontal on the eastern flank of the Cántaro-Colima chain (Luhr and Carmichael, 1981). It is arbitrarily assigned to stage-II activity of Volcán Colima, but the age of Tezontal is not known. This sample is also included on most of the following diagrams as a circled open square.

The same 154 samples plotted on the histograms of Figure 2 are shown on a plot of SiO_2 versus K_2O in Figure 3. Although the stage-II lavas from Volcán Colima (open squares) show a tight trend on this diagram, all other age groups show considerable diversity, with a spread of 0.5 wt. % or more K_2O at a given SiO_2 value. Among the lavas from Volcán Cántaro (asterisks), 14 of 17 are relatively enriched in K_2O compared to most samples from Nevado and Volcán Colima. A few samples from Nevado stage-I (solid dots) and one sample from Nevado stage-III (open dots) show similarly high K_2O values. Four of the stage-I lavas from Volcán Colima analyzed in this study (large solid squares) also show elevated K_2O, all of which (429, 430, 431, 432) were collected in a small area near the eastern entrance to the caldera. An additional sample (F17) reported by Robin *et al.* (1984), which was collected in the same area, shows a similar enrichment in K_2O (Figure 3). Five of the other stage-I samples from this study form a tight trend at slightly lower K_2O levels than shown by the stage-II lavas from Volcán Colima. Stage-I dacitic dome sample 442 has even lower K_2O, a characteristic that is shared by four stage-I samples analyzed by Robin *et al.* (1984,1987). Three scoriae from Volcán Colima (open triangles) show strong enrichments in K_2O, on a trend of increasing K_2O with decreasing SiO_2. Luhr and Carmichael (1982) showed that these samples represent physical mixtures between calc-alkaline magmas and strongly potassic, silica-undersaturated basanites and minettes that erupted from cinder cones on the flanks of the Cántaro-Colima chain (Luhr and Carmichael, 1981).

TRACE ELEMENT DATA

Only a small subset of the samples considered in the preceding discussion have been analyzed for trace elements, with none of the Nevado samples represented. A small group of trace elements (Sr and the light rare earth elements La, Ce and Sm) generally mimics the behaviour of K_2O in that most Volcán Cántaro samples and the same 4 stage-I samples from Volcán Colima (429, 430, 431 and 432) are relatively enriched compared to other samples from the volcanic chain. A plot of La versus SiO_2 is shown in Figure 4 to illustrate these features. Four of the most SiO_2-rich stage-I lavas (400, 432, 433 and 437) again show a relative depletion in La, Ce and Sm, but two of these samples (400 and 437) are enriched, rather than depleted, in Sr.

The heavy rare earth elements Yb and Lu are relatively depleted in most samples from Volcán Cántaro and from the stage-I suite of Volcán Colima. To illustrate these rare earth element trends, a plot of Yb versus SiO_2 is shown in Figure 5, a plot of La/Yb versus Yb is shown in Figure 6, and a chondrite-normalized rare earth element plot is shown in Figure 7. The latter includes 4 representative samples from the stage-I suite of this study, one stage-II sample (Col-9: Luhr and Carmichael, 1980), and one sample from Volcán Cántaro. Relative to the stage-II andesites from Volcán Colima, all samples from Volcán Cántaro have higher La/Yb values and most have lower Yb concentrations. Among the 10 stage-I samples of this study, 9 have lower Yb concentrations than the stage-II andesites and 8 have higher La/Yb values. Thus, the rare earth element data for the stage-I andesites and dacites of Volcán Colima are quite distinct from the stage-II andesites, but show many similarities to the suite from Volcán Cántaro.

Table 1

Whole-rock major and trace element analyses

Sample:	1004-400	1004-429	1004-430	1004-431	1004-432	1004-433	1004-435	1004-436	1004-437	1004-442
Lat. (°N)	19.512	19.533	19.527	19.528	19.529	19.530	19.531	19.531	19.534	19.531
Long. (°W)	103.643	103.599	103.605	103.606	103.606	103.608	103.618	103.618	103.627	103.615
Major elements by XRF (wt. %)										
SiO_2	62.45	58.74	62.29	62.30	61.87	62.18	60.60	60.17	63.28	63.56
TiO_2	0.66	0.76	0.70	0.71	0.70	0.65	0.74	0.65	0.65	0.54
Al_2O_3	16.80	17.22	16.41	16.34	16.19	17.28	17.35	16.96	16.65	16.86
Fe_2O_3	3.14	2.54	1.98	2.14	2.15	1.83	2.51	2.40	1.80	4.53
FeO	1.72	3.47	2.77	2.62	2.80	2.99	3.12	3.20	2.72	0.16
MnO	0.10	0.10	0.09	0.09	0.09	0.09	0.11	0.12	0.08	0.08
MgO	2.78	3.43	2.98	3.05	3.14	2.57	2.85	3.75	2.75	2.43
CaO	5.72	6.33	5.56	5.61	5.60	5.53	5.94	6.15	5.54	5.10
Na_2O	4.42	4.56	4.48	4.52	4.43	4.66	4.48	4.40	4.50	4.84
K_2O	1.45	1.62	1.84	1.83	1.84	1.40	1.26	1.18	1.59	1.32
P_2O_5	0.20	0.28	0.22	0.24	0.24	0.19	0.17	0.16	0.20	0.16
LOI	0.35	0.28	0.23	-0.09	0.27	0.27	0.33	0.41	0.25	0.20
Total	99.79	99.33	99.55	99.36	99.32	99.64	99.46	99.55	100.01	99.78
Trace elements by XRF (ppm)										
V	99	147	117	112	123	106	132	119	109	72
Ni	25	23	31	29	35	21	20	49	27	21
Cu	28	27	33	44	33	30	15	57	29	17
Zn	51	57	55	54	59	51	74	66	53	45
Rb	12	19	20	20	20	18	17	15	15	17
Sr	953	783	891	899	897	585	541	536	850	613
Y	13	16	14	15	15	16	15	17	13	13
Zr	135	153	157	154	155	137	133	124	141	119
Trace elements by INA (ppm)										
Sc	10.84	16.10	12.81	12.68	13.14	13.36	15.70	15.80	12.10	11.58
Cr	16.9	32.4	27.9	27.7	28.5	17.4	10.7	118.7	26.7	13.7
Co	14.5	19.2	15.7	15.6	15.7	15.2	18.0	20.0	14.4	13.4
Cs	0.32	0.37	0.34	0.25	0.32	0.30	0.28	0.37	0.34	0.27
Ba	373	570	540	546	541	599	555	513	423	627
La	10.6	15.1	15.7	16.0	16.1	12.2	11.2	10.7	11.2	10.1
Ce	24.2	33.3	33.6	34.3	34.2	25.5	23.7	22.3	24.4	21.8
Nd	14	20	17	19	16	12	11	12	14	10
Sm	3.13	3.89	3.94	3.95	4.03	3.05	2.99	2.87	3.20	2.52
Eu	0.99	1.19	1.18	1.18	1.17	0.93	0.95	0.89	1.01	0.78
Tb	0.39	0.48	0.45	0.46	0.48	0.43	0.45	0.45	0.41	0.35
Yb	1.13	1.54	1.29	1.30	1.31	1.48	1.48	1.50	1.20	1.17
Lu	0.169	0.241	0.185	0.198	0.206	0.227	0.231	0.227	0.184	0.187
Hf	3.17	3.65	3.63	3.61	3.62	3.32	3.24	3.00	3.28	3.05
Ta	0.14	0.23	0.23	0.22	0.22	0.24	0.25	0.23	0.17	0.20
Th	1.71	2.13	2.69	2.68	2.66	1.48	1.47	1.20	1.99	1.39
U	0.60	0.83	1.01	0.97	0.86	0.86	0.54	0.51	0.70	0.57

Major element analyses were determined by XRF at Washington University on glass disks prepared with 1:10 weight ratios of rock:Litraborate; disks were prepared by Gary Stoopes. Trace elements by XRF were determined at the Smithsonian Institution on disks made from 4:1 weight ratios of rock:cellulose and backed by boric acid. Trace element analyses by INA were determined at Washington University (Lindstrom and Korotev, 1982). Analytical errors are given in Luhr and Carmichael (1990). FeO values were determined by K-dichromate titration. LOI values were determined in a muffle fur-nace at 950°C for 50 minutes on powders previously dried at 110°C.

Table 2

Modes determined by point counting

Sample:	1004-400	1004-429	1004-430	1004-431	1004-432	1004-433	1004-435	1004-436	1004-437	1004-442
(vol. %)										
Pl ph	17.3	21.2	19.1	15.5	16.5	23.4	28.2	12.8	17.4	21.2
Pl mp	12.4	6.8	10.3	10.7	11.7	11.4	4.1	6.8	11.2	11.5
Pl Tot	29.7	28.0	29.4	26.2	28.2	34.8	32.3	19.6	28.6	32.7
Cp ph	3.8	3.2	3.3	4.0	3.7	0.5	2.5	2.9	3.0	1.5
Cp mp	0.5	1.5	0.4	0.5	0.5	1.2	0.1	0.6	0.7	0.5
Cp Tot	4.3	4.7	3.7	4.5	4.2	1.7	2.6	3.5	3.7	2.0
Op ph	0.7	1.4	1.0	1.2	1.3	2.0	3.2	0.6	1.1	2.9
Op mp	4.8	2.6	2.7	2.9	2.9	3.7	1.5	1.5	1.9	2.0
Op Tot	5.5	4.0	3.7	4.1	4.2	5.7	4.7	2.1	3.0	4.9
Hb ph		1.2				2.2		3.6		0.3
Hb mp		0.4						0.8		0.1
Hb Tot		1.6				2.2		4.4		0.4
Ox ph		0.2								
Ox mp	2.3	1.4	1.4	2.3	1.9	1.4	1.0	2.5	0.8	3.7
Ox Tot	2.3	1.6	1.4	2.3	1.9	1.4	1.0	2.5	0.8	3.7
Xlls Tot	41.8	40.0	38.2	37.1	38.5	45.8	40.6	32.1	36.1	43.7
Grndm	58.2	60.0	61.2	62.9	61.5	54.2	59.4	67.9	63.9	56.3

Modes determined by counting >1,000 points on one thin section of each sample. Abbreviations: Pl= plagioclase, Cp = clinopyroxene, Op = orthopyroxene, Hb = hornblende, Ox = titanomagnetite, Grndm = groundmass, Xlls = all crystals, ph = phenocryst (> 0.3 mm, following Wilcox, 1954), mp = microphenocryst (< 0.3 mm and > 0.03 mm). Sample 1004-429 also contains 0.1 vol. % xenocrystic olivine surrounded by orthopyroxene and titanomagnetite. Sample 1004-430 also contains 0.6 vol. % metavolcanic xenolith with granulitic texture. Samples 1004-400 and especially 1004-442 show reaction of orthopyroxene rims to a fine-grained opaque assemblage.

Several trace element ratios also indicate a close relationship between the stage-I samples from Volcán Colima and the Volcán Cántaro suite. Plots of Rb/Sr and Sr/Yb versus SiO_2 are shown in Figures 8 and 9, respectively. A dotted line, drawn by eye on Figure 8, marks the upper bound of all samples from Volcán Cántaro and stage-I lavas from Volcán Colima. All but 2 of the 47 stage-II lavas from Volcán Colima plot above this line. The Sr/Yb versus SiO_2 plot of Figure 9 shows that all Volcán Cantaro samples and most stage-I samples from Volcán Colima have significantly higher Sr/Yb values than the stage-II andesites.

DISCUSSION

Three hypotheses are considered to explain the differences in trace elements abundances for the Volcán Cántaro and stage-I Volcán Colima suites on the one hand and the stage-II Volcán Colima suite on the other: 1) magma mixing of basanites-minettes and calc-alkaline magmas, 2) assimilation of garnet-bearing lower-crustal granulites, and 3) slab versus mantle-wedge source contributions.

Magma mixing. As mentioned above, Luhr and Carmichael (1982) showed that mixing of basanite-minnette magmas and calc-alkaline magmas has occurred at Volcán Colima, in the extreme producing highly unusual mixed scoriae containing a disequilibrium assemblage of the minerals from the two end-member magmas. This same process could have produced some of the features observed in the Volcán Cántaro and stage-I Volcán Colima suites: high K_2O, Sr, La, Ce, and Sm. The concentrations of Yb and Lu, however, are not significantly different in the two end members, and mixing would not produce the low values of the Volcán Cántaro and stage-I Volcán Colima suites. In addition, because the basanite-minette suite is strongly enriched in P and Ba, such mixing should generate relatively high concentrations of these elements. Phosphorus and Ba, however, are not elevated in the Volcán Cántaro and stage-I Volcán Colima rocks. In summary, this hypothesis can be safely dismissed.

Lower-Crustal contamination. Studies of crustal xenoliths carried to the surface by Quaternary basanitic magmas in the southernmost Basin and Range Province of cen-

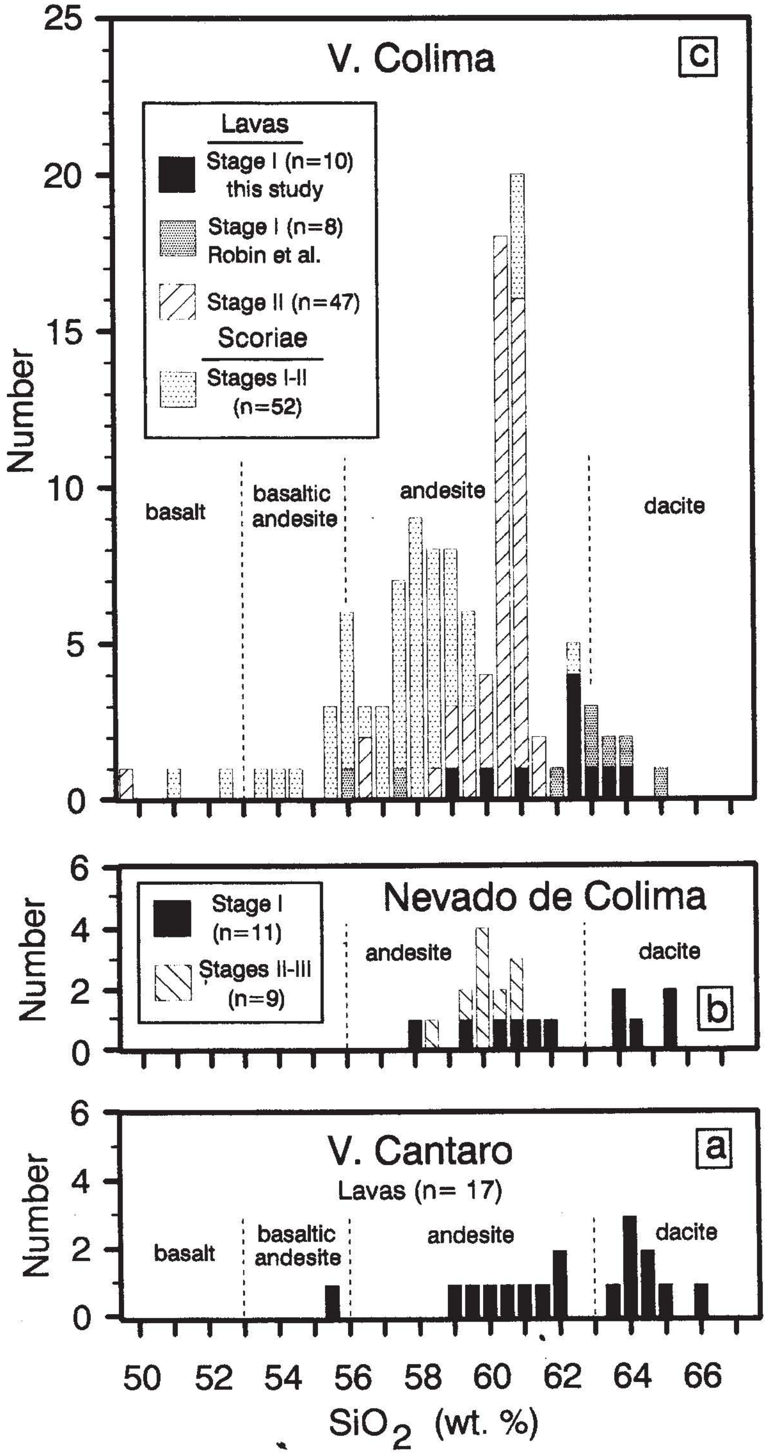

Fig. 2. Histograms of SiO_2 contents for lava and scoria samples. Major elements were normalized to 100% anhydrous with $Fe^{2+} = 0.8 \times Fe^{total}$. (2a) Unpublished data for lavas from Volcán Cántaro. (2b) Lavas and scoriae from Nevado (Robin *et al.*, 1984; 1987). (2c) Lavas and scoriae from Volcán Colima. Stage-I lavas from this study and Robin *et al.* (1984; 1987) are distinguished by pattern. Stage-II lavas are from Luhr and Carmichael (1980; 1990), and include basalt sample 22E from Luhr and Carmichael (1982). The stage-I and -II scoria analyses include data from Robin *et al.* (1987; 1991) and published data for the pyroclastic sequence described by Luhr and Carmichael (1981).

tral Mexico, several hundred kilometers north of the study area, show that the lower crust includes garnet-bearing metasedimentary lithologies (Roberts and Ruiz, 1989; Pool, 1991; Cameron *et al.*, 1992). Garnet is important to the problem under consideration in that it strongly concentrates the heavy rare earth elements. If the magmas of Volcán Cántaro and stage-I activity at Volcán Colima were contaminated by partial melts from lower-crustal gran-

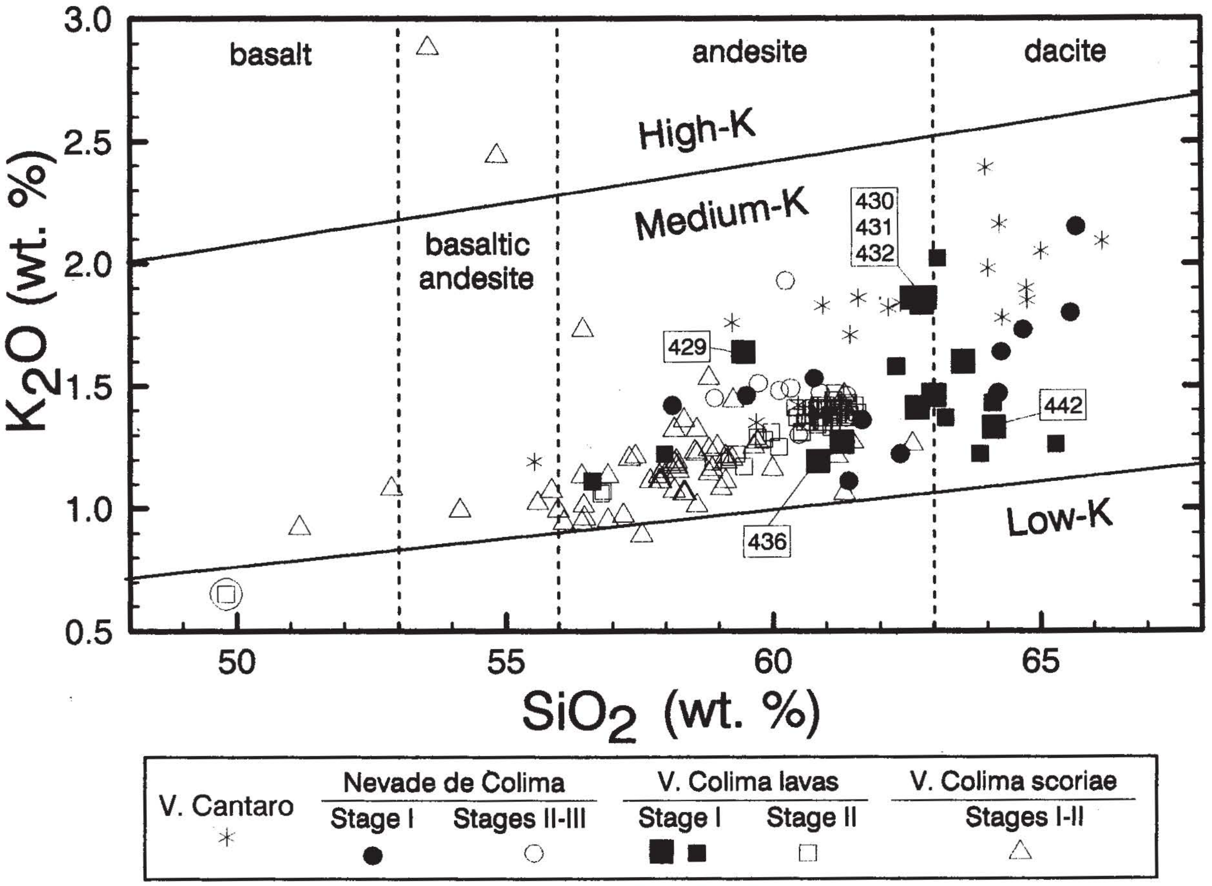

Fig. 3. Whole-rock SiO_2 versus K_2O for the samples shown in Figure 2; the circled open square is basalt SAY-22E (Luhr and Carmichael, 1981). Large solid squares show the 10 pre-caldera lavas from this study. Small solid squares show the 8 pre-caldera lavas from Robin *et al.* (1984; 1987). Classification lines for low-K, medium-K, and high-K are extrapolated from those given for andesites in Gill (1981).

ulites, and if garnet was residual during melting, this process could produce the observed low Yb and Lu concentrations. As pointed out by Defant and Drummond (1990), however, partial melting of lower-crustal granulites will likely produce melts with negative Eu anomalies, formed in the presence of residual plagioclase. The Volcán Cántaro and stage-I Volcán Colima samples have average Eu/Eu* values of about 0.95 that are not significantly different from those of the stage-II andesites from Volcán Colima. Partial melts of the lower crust should also be depleted in Th and U, which are not significantly lower in the andesites-dacites from Volcán Cántaro or the stage-I suite from Volcán Colima. Thus, lower crustal contamination is an unlikely mechanism to explain the observed differences between the stage-II andesites of Volcán Colima and earlier rocks.

Slab versus wedge melting. Garnet can also exert an influence on heavy rare earth element abundances of subduction-related magmas in the mantle source regions. Defant and Drummond (1990) and Drummond and Defant (1990) discussed the likely geochemical consequences of generating partial melts within the subducted slab versus within the overlying mantle wedge. At depth beneath volcanics arcs, the slab is likely to be in the form of garnet amphibolite or eclogite. Thus, partial melts of the slab should show low Yb and Lu, and because of high partition coefficients for Rb in amphibole, low Rb concentrations. Accordingly, the above authors argued that Rb/Sr values should be lower, and Sr/Y (Sr/Yb) values should be higher in magmas influenced by slab melting. This is precisely the difference between the Volcán Cántaro and stage-I Volcán Colima samples relative to the stage-II Volcán Colima samples (Figures 8 and 9). These authors also noted that slab melting is most likely in subduction zones where relatively young, and therefore hot, oceanic crust is being subducted. The East Pacific Rise lies immediately offshore of western Mexico, and the oceanic crust subducting beneath the Cántaro-Colima chain is extremely young and prone to melting. Therefore, the most likely scenario to explain the observed differences in magmatic composition along the Cántaro-Colima chain is a decrease in the contribution of slab-derived melts relative to wedge-derived melts since formation of the caldera of Volcán Colima. It must be stressed, however, that no trace element data are presently available for Nevado de Colima, which constitutes the ma-

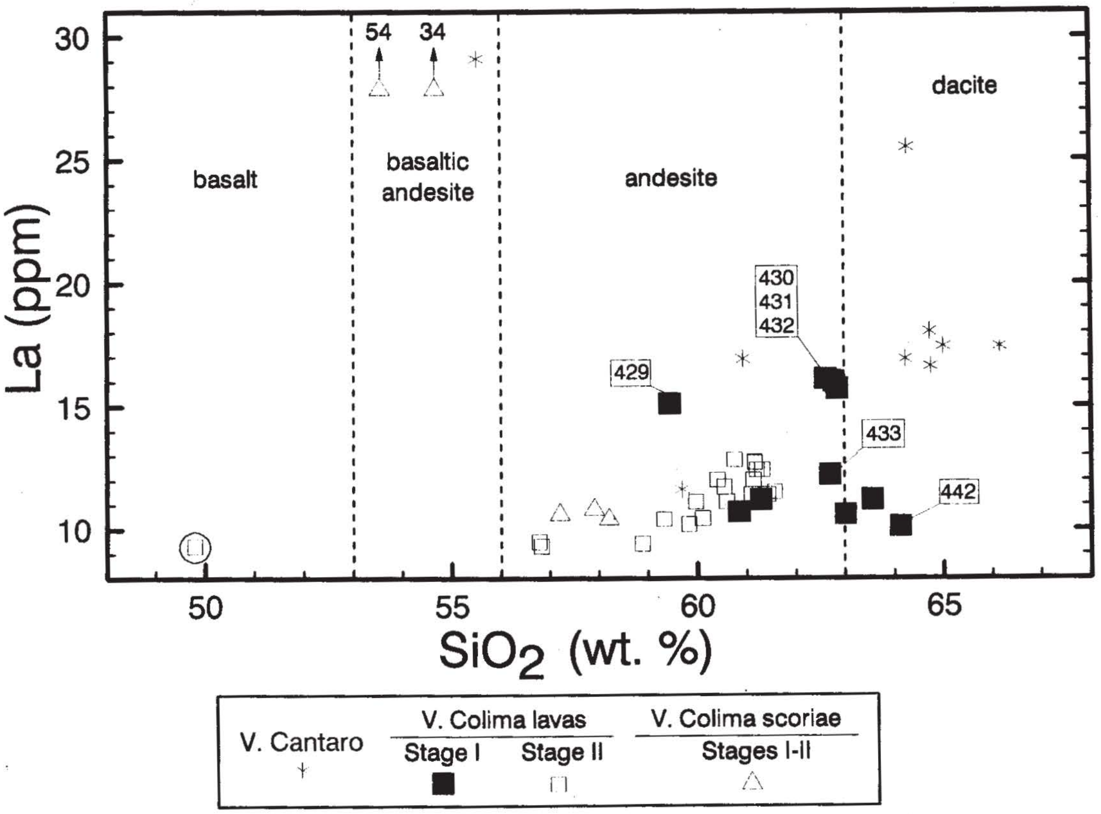

Fig. 4. Whole-rock SiO$_2$ versus La for a subset of the samples shown in Figure 3.

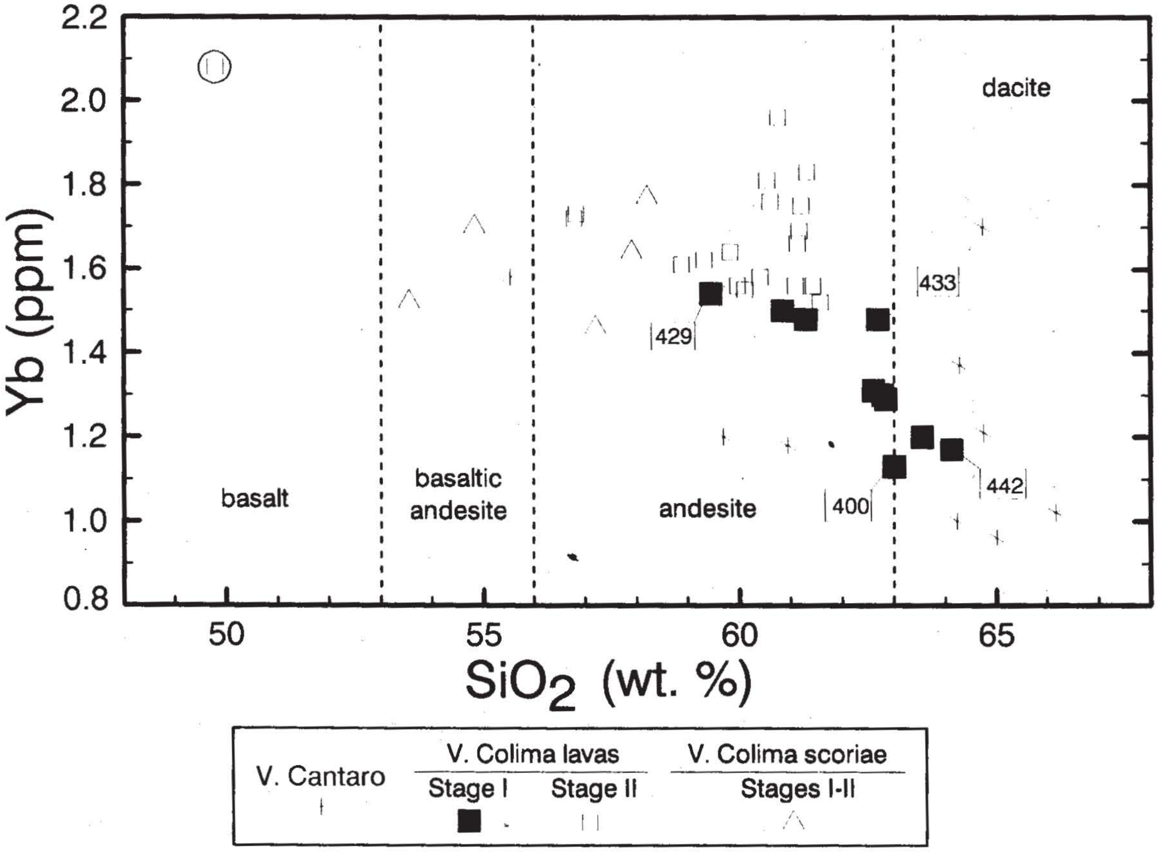

Fig. 5. Whole-rock SiO$_2$ versus Yb for a subset of the samples shown in Figure 3.

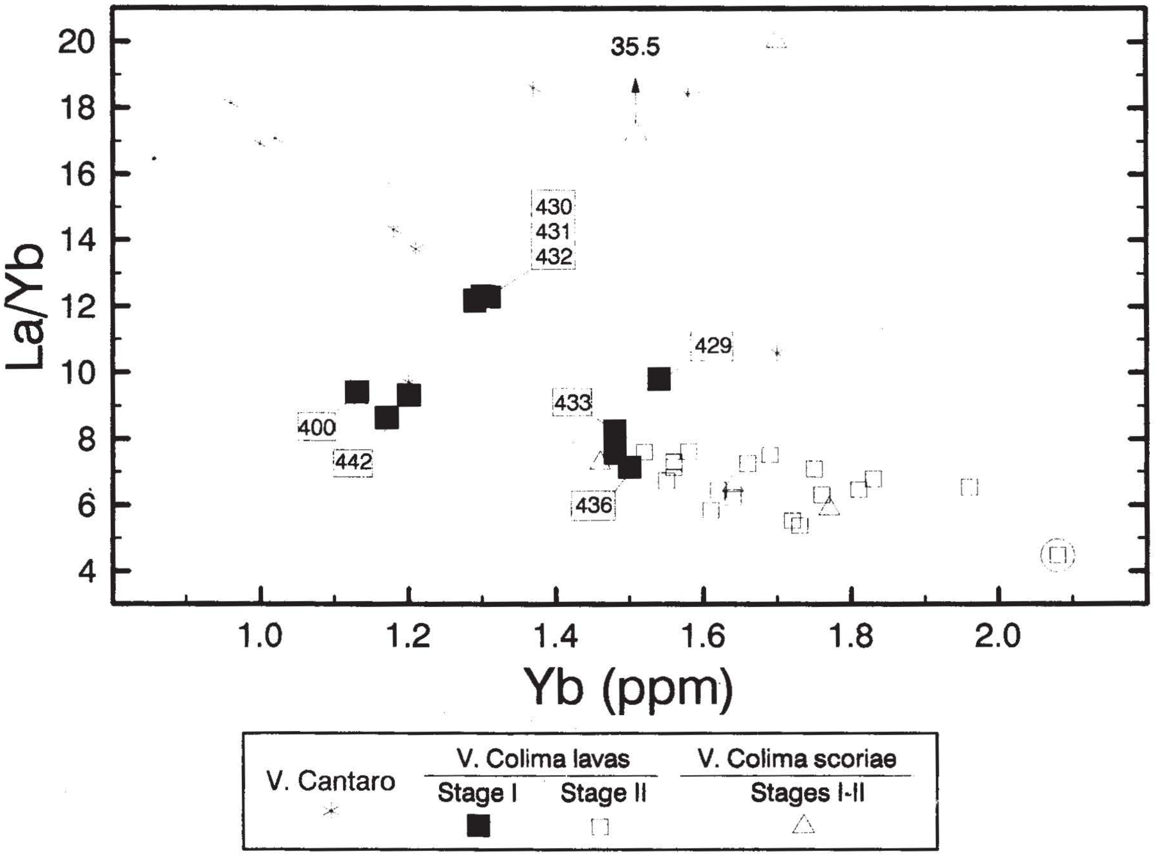

Fig. 6. Whole-rock Yb versus La/Yb for a subset of the samples shown in Figure 3.

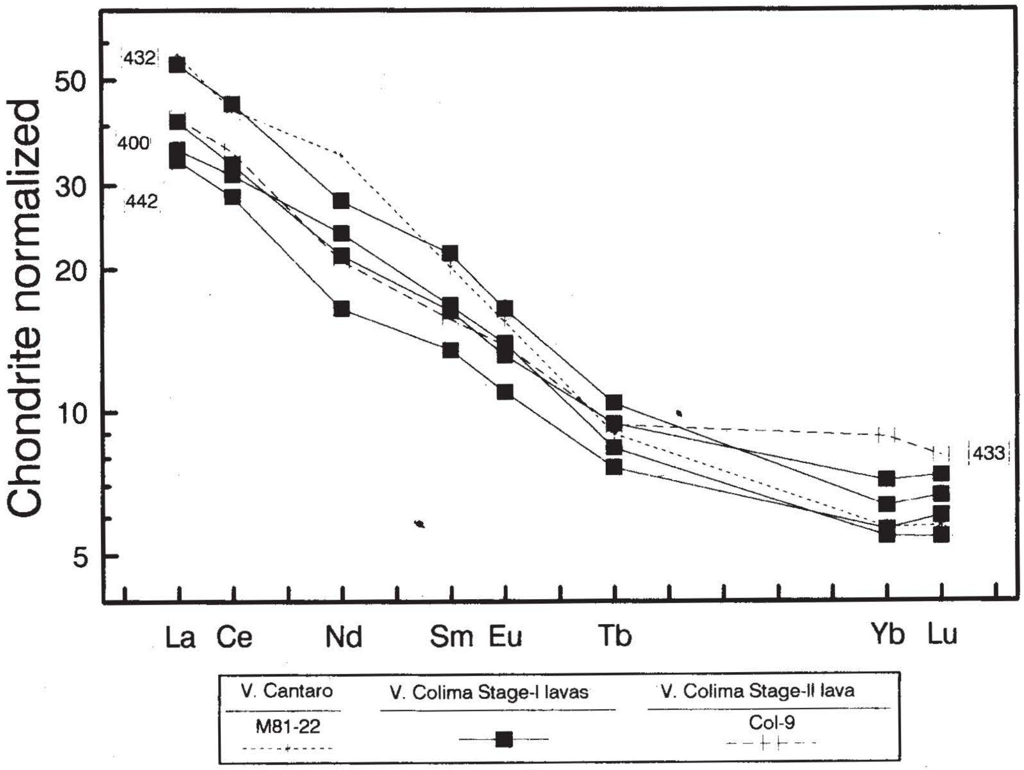

Fig. 7. Chondrite-normalized rare earth element diagram showing 4 representative samples from the stage-I Volcán Colima suite of this study and one sample each from Volcán Cántaro and the stage-II suite of Volcán Colima. Values are normalized to 1.274 x the concentrations listed for the mean Cl chondrite from Anders and Grevesse (1989), which corrects the latter to a volatile-free equivalent.

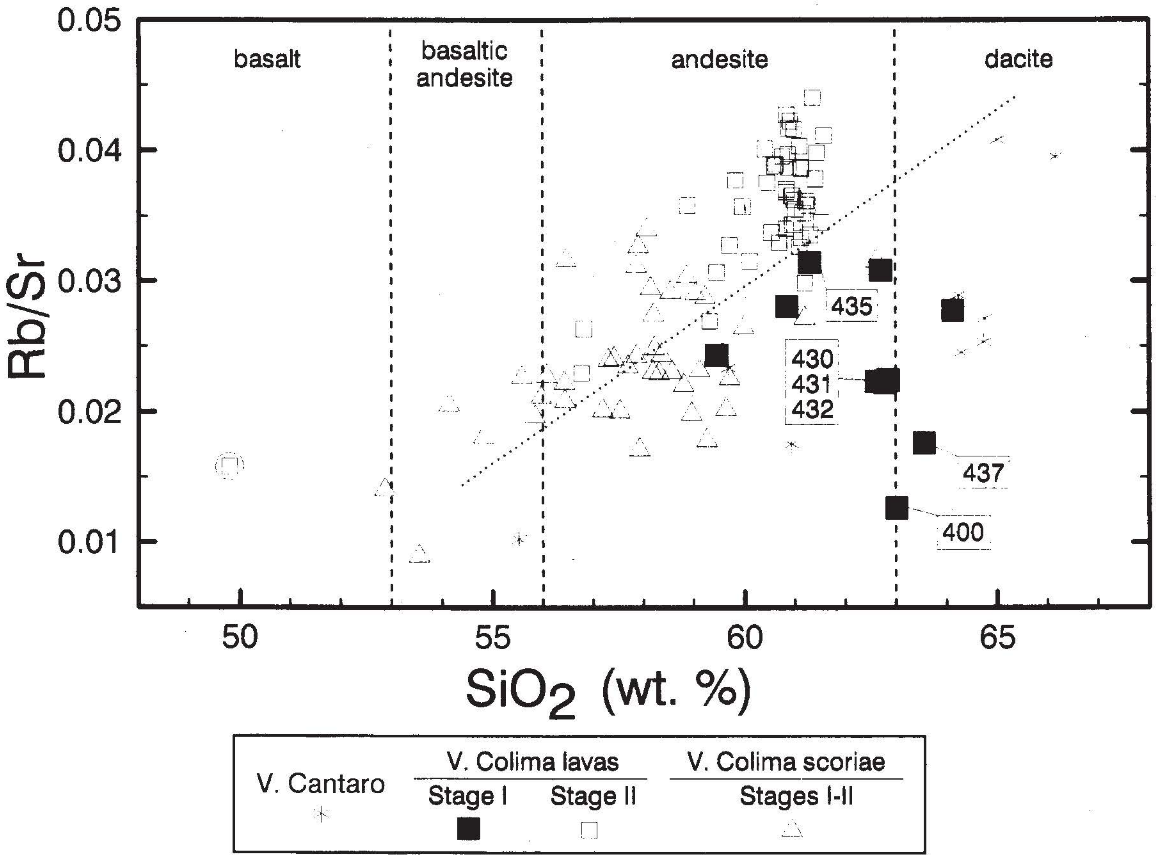

Fig. 8. Whole-rock SiO_2 versus Rb/Sr for a subset of the samples shown in Figure 3. The dotted line was drawn by eye to separate the suites from Volcán Cántaro and stage-I Volcán Colima from stage-II andesites from Volcán Colima.

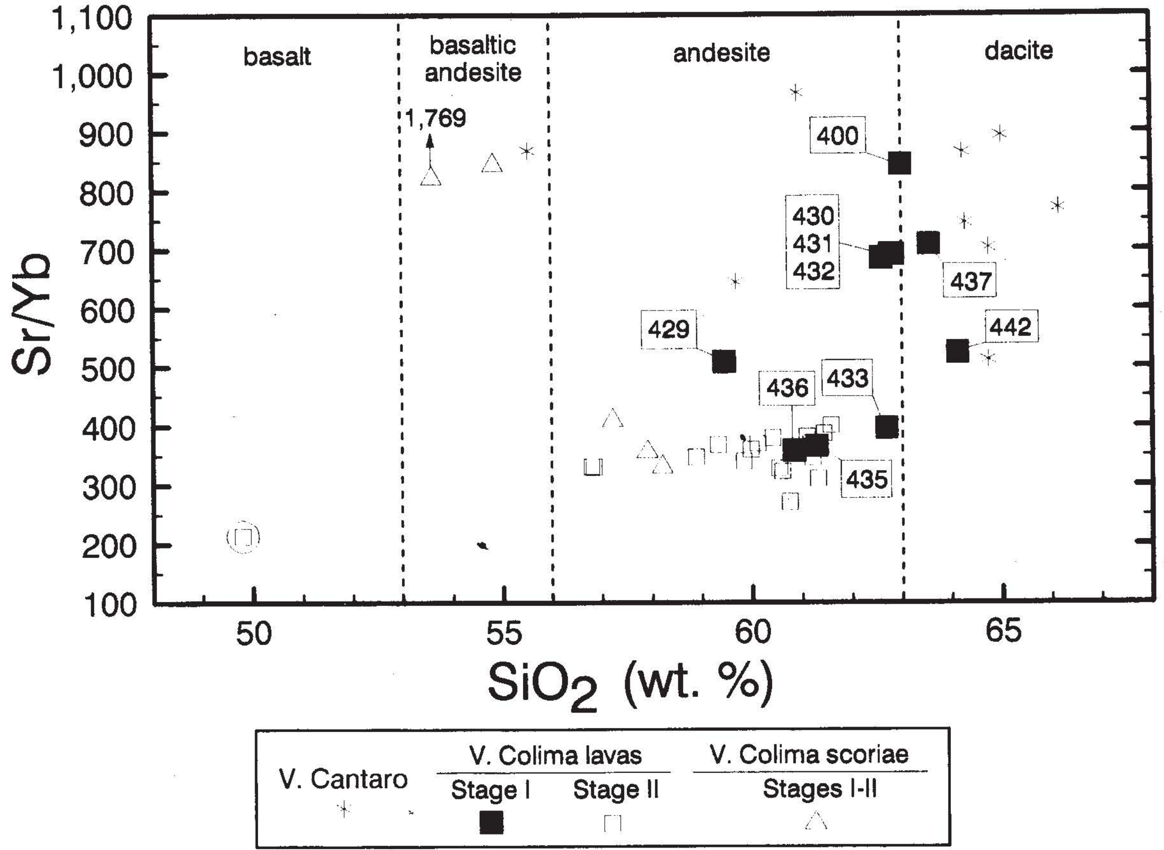

Fig. 9. Whole-rock SiO_2 versus Sr/Yb for a subset of the samples shown in Figure 3.

jor volumetric portion of the Cántaro-Colima chain, and for Los Hijos del Volcán, the southernmost eruptive centers. As a consequence, this interpretation must be considered as preliminary and conjectural.

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