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THE SOUTHERN GUADALAJARA VOLCANIC CHAIN, JALISCO, MEXICO

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RESUMEN

La cadena volcánica del sur de Guadalajara consiste en ocho conos pequeños de lava y ceniza, de la edad Plio-Pleistocénica. Dichos conos presentan una tendencia NW-SE y atraviesan la parte sur de la ciudad de Guadalajara. Esta cadena y otros numerosos alineamientos volcánicos en el sector occidental del Cinturón Volcánico Mexicano están relacionados con un episodio vigente de abertura cortical, y nos proporcionan muy valiosa información acerca del campo de esfuerzos en la corteza superior prevaleciente al ocurrir la erupción. Las muestras de lava de los conos al sur de Guadalajara son andesitas basálticas que contienen olivino, de carácter calcoalcalino y muestran poca variación composicional. Se encuentran andesitas basálticas similares en Colima, Paricutín, Jorullo y otros volcanes del sector occidental del Cinturón Volcánico Mexicano, particularmente aquellos cercanos a la Trinchera Meso-Americana. La andesita basáltica es probablemente el tipo de magma más abundante que asciende en la región desde las profundidades del manto superior y de la corteza inferior.

ABSTRACT

The southern Guadalajara Volcanic Chain consists of eight small lava and cinder cones of Plio-Pleistocene age which follow a NW-SE trend through the southern portion of the city of Guadalajara. This chain and numerous other volcanic alignments in the western Mexican Volcanic Belt are related to a major on-going episode of crustal rifting, and provide valuable information concerning the upper crustal stress field at the time of eruption. Lava samples from the southern Guadalajara cones are olivine-bearing basaltic andesites of calc-alkaline character showing little compositional variation. Similar basaltic andesites occur at Colima, Paricutín, Jorullo, and other volcanoes in the western Mexican Volcanic Belt, particularly those closer to the Middle America Trench. Basaltic andesite is probably the most abundant magma type rising from upper-mantle and lower-crustal depths in the region.

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INTRODUCTION

Volcanic activity has been persistent in the western Mexican Volcanic Belt (MVB) at least since the Miocene (Watkins *et al.*, 1971; Allan and Carmichael, 1984; Gilbert *et al.*, 1985). Although andesites dominate at most locations, basalts and rhyolites are also represented. In the Pliocene, a set of three major graben structures began to emerge in the western MVB, intersecting in a graben triple junction some 50 km SSW of the city of Guadalajara (Fig. 1). These extensional structures appear to be active today and are thought to outline a new microplate at its birth, related to eastward jumping of an East Pacific Rise ridge segment beneath the Mexican crustal block (Luhr *et al.*, 1985).

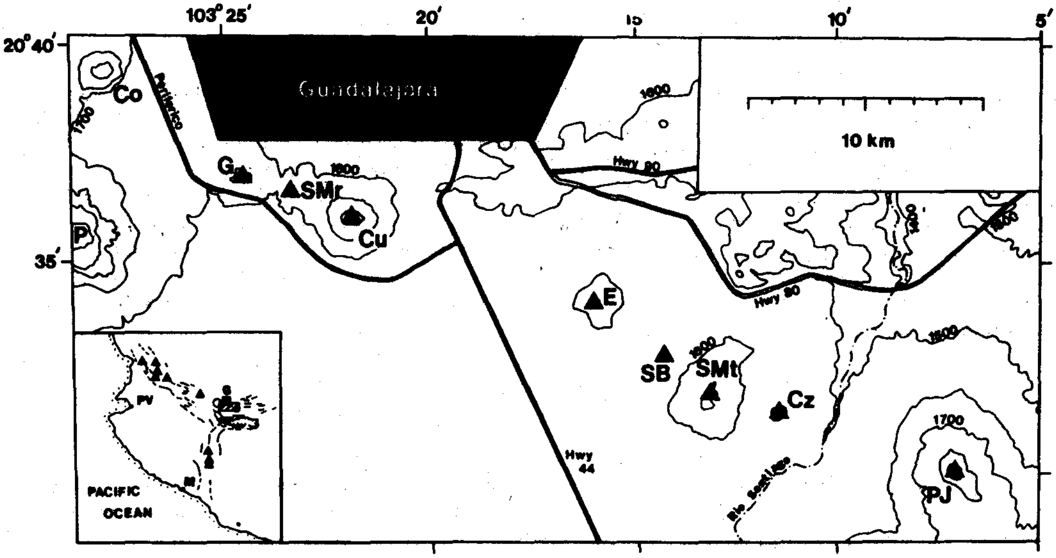

Fig. 1 - Location map for the Southern Guadalajara Volcanic Chain. Triangles show volcanoes of the SGVC: G = Cerro El Gachupín, SMr = Cerro Santa María, Cu = Cerro El Cuatro, E = Cerro Escondido, SB = Cerro San Bartolo, SMt = Cerro San Martín, Cz = Cerro La Cruz, PJ = Cerro El Papantón de Juanacatlán. Two of the easternmost domes of La Primavera are also shown in the western map area: Co = Cerro El Colli, P = Cerro Pelón. Contour lines at 100 m intervals are indicated. In the inset, the diagonally ruled area is the expanded map area, triangles show andesitic stratovolcanoes, Sierra La Primavera is indicated by the open circle, squares show cities: G = Guadalajara, PV = Puerto Vallarta, M = Manzanillo, and short lines indicate traces of major fault scarps.

Volcanic centers of Quaternary age are closely related to the system of grabens. A southward-younging chain of three large andesitic stratovolcanoes has formed on the floor of the southern Colima graben over the last 1 million years (Luhr and Carmichael, 1981; Allan and Carmichael, 1984). This chain terminates southward at

Volcán Colima, the most active volcano in Mexico, which last erupted a small lava flow in 1982 (SEAN, 1982). Accessible samples from the three volcanoes are greatly dominated by andesites; basaltic andesite is the most basic lava composition encountered. On the basal plains surrounding these large andesitic centers, eleven cinder cones erupted during the Quaternary. Nine of these involved basanites, leucite-basanites, and minettes of an unusual nepheline-normative potassic suite. The other two cones produced calc-alkaline magmas: in the case of Volcán Tezontal, basalt that represents a plausible parent to the andesites of Colima, and in the case of Volcán Usmajac, basaltic andesite similar to the lavas described in this report.

The Northwestern Segment of the MVB is a zone of Quaternary volcanic centers and fault scarps extending northwestward from the graben intersection area for over 200 km to the Pacific Coast (Fig. 1). Most prominent among the volcanic centers are six andesitic to rhyodacitic stratovolcanoes (Luhr, 1978; Nelson, 1980; Livieres and Nelson, 1983; Harris and Carmichael, 1983). Magmas more basic than andesite apparently have not erupted from these stratovolcanoes, but a compositionally diverse group of basalts formed cinder and lava cones on their flanks. Basaltic cones in the vicinity of Volcán Sanganguey define five lines trending NW-SE at about 135° (Nelson and Carmichael, 1984); these are subparallel to the trends of the Tamayo Fracture Zone and other offsets of the East Pacific Rise in the mouth of the Gulf of California (Luhr *et al.*, 1985), and also to the Southern Guadalajara Volcanic Chain described in this paper.

In addition to the volcanoes mentioned above, which are all confined by the three graben structures, a smaller number of volcanic centers formed beyond the limits of the grabens. Most prominent of these is sierra La Primavera, which lies just north of the graben intersection area and just west of Guadalajara. Sierra La Primavera is a major rhyolitic complex of domes, lava flows, and pyroclastic deposits, which formed over the last 100 000 years (Mahood, 1980 and 1981; Walker *et al.*, 1981). In this paper we describe a NW-SE alignment of small lava and cinder cones extending from the eastern end of La Primavera through the southern portion of Guadalajara along a trend of 112°. We refer to this alignment as the Southern Guadalajara Volcanic Chain (SGVC). These basaltic-andesite volcanoes have not been mentioned previously in the literature.

FIELD RELATIONS

We consider the SGVC to include the eight volcanic centers listed in Table 1. The chain continues farther to the southeast where it is disrupted by E-W-trending normal faults related to the Chapala graben system (Diaz and Mooser, 1972; Luhr *et al.*, 1985). The chain may also extend farther to the northwest beneath the younger products of La Primavera. The eight volcanoes under consideration include both small scoria cones (cerro San Bartolo) as well as larger composite structures of lavas and scoriae with volumes up to 9 km^3 (cerro El Papantán de Juanacatlán). Total volume for these eight cones is about 14 km^3. No radiometric ages have yet been determined for products of the SGVC. At the three most western volcanoes (cerros El Gachupín, Santa María, El Cuatro), those closest to La Primavera, over 1 m of bedded rhyolitic tuff overlies 1 to 2 m of red soil formed on lavas and scoriae of the cones, indicating that the SGVC is considerably older than La Primavera (100 000 years: Mahood, 1980). Based on their preserved constructional forms, we conclude

Table 1. Volcanoes of the Southern Guadalajara Chain

Cerro	lat.	long.	basal elevation (m)	summit elevation (m)	radius (m)	volume (km^3)	samples M79-
El Gachupin	20.615°N	103.407°W	1,600	1,760	700	0.3	146, 147A, 147B, 148
Santa Maria	20.610	103.389	1,600	1,740	350	0.1	149
El Cuatro	20.599	103.364	1,550	1,860	2,500	2.0	150
Escondido	20.564	103.269	1,550	1,620	2,500	0.5	152
San Bartolo	20.545	103.240	1,550	1,680	500	<0.1	153A
San Martin	20.531	103.220	1,550	1,750	2,750	1.6	
La Cruz	20.524	103.194	1,550	1,660	500	<0.1	154B
El Papanton de Juanacatlan	20.499	103.121	1,500	1,940	4,500	9.3	

Appendix 1. Sample Locations

Cerro El Gachupín-

M79-146 sample from small dike in quarry at 1660 m on northern flank.

M79-147A and -147B are samples of two lavas at 1690 m on northwestern ridge of the cone.

M79-148 sample from lava flow interbedded with scoria-fall layers at 1700 m just northeast of and below eastern peak.

Cerro Santa María-

M79-149 sample from float block at 1650 m near northern foot of cone.

Cerro El Cuatro-

M79-150 sample of lava from base of quarry at 1640 m at northwestern foot of cone.

Cerro Escondido-

M79-152 lava sample from 1570 m on southern flank of cone

Cerro San Bartolo-

M79-153A lava sample from float at 1590 m near western base of cone

Cerro La Cruz-

M79-154B lava sample at 1560 m near eastern foot of cone that the volcanoes of the SGVC formed during Plio-Pleistocene time. As discussed by Nakamura (1977), the orientations of dikes and volcanic chains can be used to interpret regional stress fields; these develop perpendicular to the axis of maximum extensional stress. Precise radiometric dating of the SGVC in the future, therefore, will fix a valuable point in the stress regime history of the western Mexican Volcanic Belt, and give a minimum age for the establishment in this area of a NE-SW oriented extensional field and for the inception of on-going crustal rifting.

PETROLOGY AND MINERALOGY

Major and trace element analyses for nine whole-rock lava samples from the SGVC are given in Table 2 along with a mean analysis; sample locations are given in Appen-

Table 2. Whole-rock analyses by x-ray fluorescence

	N79-146B	147A	147B	148	149	150	152A	153A	154B	Mean	(1 std dev)
Major elements (wt%)											
SiO_2	55.29	55.15	55.19	55.56	53.80	55.50	56.47	54.63	54.73	55.15	(0.74)
TiO_2	0.85	0.88	0.83	0.90	0.86	0.88	0.82	0.82	0.88	0.86	(0.03)
Al_2O_3	18.75	19.02	18.51	18.10	19.42	19.14	19.07	18.86	19.25	18.90	(0.40)
Fe_2O_3	2.38	2.58	1.44	3.05	2.50	4.05	2.09	2.50	2.10	2.53	(0.70)
FeO	4.40	4.44	5.04	3.92	4.24	3.12	4.64	4.00	4.80	4.29	(0.57)
(FeO^t)	(6.54)	(6.76)	(6.35)	(6.66)	(6.49)	(6.76)	(6.52)	(6.23)	(6.69)	(6.57)	(0.18)
MnO	0.11	0.11	0.11	0.11	0.11	0.10	0.11	0.10	0.11	0.11	(0.00)
MgO	4.23	4.90	4.41	4.68	4.31	4.00	4.62	4.14	4.31	4.40	(0.28)
CaO	7.80	7.92	7.73	7.69	7.83	7.24	7.92	7.83	7.94	7.77	(0.22)
Na_2O	3.63	3.52	3.53	3.56	3.51	3.94	3.36	3.53	3.70	3.59	(0.16)
K_2O	1.25	1.31	1.26	1.31	1.09	1.16	1.18	1.26	1.07	1.21	(0.09)
P_2O_5	0.17	0.16	0.17	0.16	0.17	0.15	0.13	0.15	0.15	0.16	(0.01)
LOI	1.08	0.70	1.30	1.12	1.71	1.33	1.05	1.41	1.26	1.22	(0.28)
Total	99.94	100.69	99.52	100.16	99.55	100.61	101.46	99.31	100.30	100.19	
Trace elements (ppm)											
V	134	144	140	141	150	131	136	159	146	142	(9)
Cr	17	52	48	25	27	25	47	19	17	31	(14)
Ni	57	57	52	43	45	35	44	39	35	45	(8)
Cu	41	51	32	38	43	64	43	33	32	42	(10)
Zn	58	64	66	50	66	62	70	65	63	63	(6)
Rb	20	17	21	23	18	20	17	20	16	19	(2)
Sr	710	714	703	719	722	686	696	706	754	712	(19)
Y	17	17	24	19	15	31	23	22	20	21	(5)
Zr	119	128	133	126	134	118	108	113	107	121	(10)
Nb	d.l.	13	d.l.	12	14	d.l.	14	d.l.	12	13	(1)
Ba	353	349	340	367	419	390	343	352	335	361	(27)
La	16	12	15	14	12	20	16	17	18	16	(3)
Ce	27	25	26	21	18	28	15	17	19	22	(5)

Major elements analyzed by lithium tetraborate fusion following Rose et al. (1963)

Trace elements analyzed on pressed powders using energy dispersive techniques. Uncertainties of one standard deviation are equal to the following percentages of the amounts present: V (8%), Cr (10%), Ni (15%), Cu (12%), Zn (10%), Rb (10%), Sr (5%), Y (15%), Zr (5%), Nb (10%), Ba (3%), La (15%), and Ce (10%).

Detection limit for Nb = 8 ppm

dix 1. No significant compositional differences exist among the samples. They are quartz-normative basaltic andesites with 54 - 56 wt% SiO_2, 4 - 5% MgO, and 1.1 - 1.3% K_2O. Sample 147B has the lowest ferric-ferrous ratio in the suite. The model of Sack *et al.* (1980) predicts an oxygen fugacity for this sample lying just above the Ni - NiO buffer.

Modes determined by point counting are given for the nine samples in Table 3, again with mean values. Basaltic andesites of the SGVC are also very similar mineralogically, with phenocrysts (>0.3 mm: after Wilcox, 1954) of olivine and plagioclase and microphenocrysts (>0.03 mm) of plagioclase and rarer olivine, augite, hypersthene, and titanomagnetite enclosed in a microcrystalline to glassy groundmass. Olivine often shows marginal alteration to iddingsite.

Table 3. Modes determined by point counting

		M79-146B	147A	147B	148	149	150	152A	153A	154B	Mean (1 std dev)
Oliv	ph	1.3	0.5	1.3	1.3	1.1	0.5	---	0.3	0.1	0.7 (0.5)
	mp	3.0	2.6	3.1	3.1	1.6	2.6	1.8	3.9	1.7	2.6 (0.8)
Plag	ph	7.4	4.1	5.4	5.4	6.5	4.9	7.4	9.9	13.0	7.1 (2.8)
	mp	35.9	42.7	36.2	36.2	29.2	45.2	42.9	25.6	35.3	36.7 (6.4)
Cpx	ph	---	---	---	---	---	---	---	---	---	---
	mp	0.5	---	---	---	0.1	---	---	---	---	0.1 (0.2)
Opx	ph	---	---	---	---	---	---	---	---	---	---
	mp	---	0.4	0.9	0.9	---	2.9	0.2	---	1.4	0.7 (0.9)
Tmt		---	1.3	---	---	---	---	0.4	---	0.5	0.2 (0.4)
Crystals		48.1	51.6	46.9	46.9	38.5	56.1	52.7	39.7	52.0	48.1 (5.9)
Groundmass		51.9	48.4	53.1	53.1	61.5	43.9	47.3	60.3	48.0	51.9 (6.0)

Grain size conventions after Wilcox (1954): ph = phenocryst (>0.3 mm), mp = microphenocryst (<0.3 mm, >0.03 mm)

DISCUSSION

Basaltic andesites similar to those of the SGVC have erupted from many other volcanoes in western Mexico. In Table 4, the mean whole-rock composition and mode from the SGVC lavas are compared with analyses of basaltic andesites from the historically active volcanoes Colima, Jorullo, and Paricutín, and from the Pleistocene-age volcano Cerro Usmajac. Although slight differences exist in whole-rock TiO_2, K_2O, P_2O_5, Cr, and Ni concentrations, these calc-alkaline basaltic andesites are nearly identical in composition.

Mineralogically the samples all carry olivine and plagioclase with lesser amounts of pyroxenes and titanomagnetite; hornblende occurs only in the Jorullo sample. The SGVC lavas are characterized by abundant microphenocrysts of plagioclase, whereas

Table 4. Comparison of basaltic andesites from western Mexico

		Colima	Usmajac	Jorullo	Parícutin
	SGVC mean	COL 11	SAY 17B	JOR 11	1050 418
major elements (wt%)					
SiO_2	55.15	56.55	55.40	54.18	55.[illegible]
TiO_2	0.86	0.78	1.50	0.92	1.11
Al_2O_3	18.90	16.63	17.08	18.74	17.33
Fe_2O_3	2.53	1.46	1.71	2.47	1.30
FeO	4.29	5.23	5.86	4.31	6.05
(FeO^t)	(6.57)	(6.54)	(7.40)	(6.53)	(7.22)
MnO	0.11	0.11	0.16	0.11	0.13
MgO	4.40	5.94	4.90	4.64	5.43
CaO	7.77	7.75	7.02	7.87	6.92
Na_2O	3.59	4.03	4.31	4.52	4.16
K_2O	1.21	1.06	1.59	1.11	1.21
P_2O_5	0.16	0.20	0.47	0.24	0.33
LOI	1.22	0.20	0.28	0.36	0.37
Total	100.19	99.94	100.28	99.47	99.82
trace elements (ppm)					
V	142	229	146	216	152
Cr	31	210	121	75	187
Ni	45	80	93	44	26
Cu	42	35	16	35	39
Zn	63	77	75	66	105
Rb	19	13	23	16	17
Sr	712	568	856	615	584
Y	21	20	24	21	18
Zr	121	118	187	130	154
Nb	12	—	22	9	10
Ba	361	391	460	355	383
La	16	10	27	13	16
Ce	22	23	57	29	40
Mode (vol%) determined by point counting					
Oliv ph	0.7	1.3	2.6	0.4	2.6
mp	2.6	1.6	6.0	1.3	3.3
Plag ph	7.1	21.9	5.5	0.4	—
mp	36.7	2.9	3.5	6.3	39.4
Cpx ph	—	4.5	—	—	—
mp	0.1	2.5	—	0.2	—
Opx ph	—	3.2	—	—	—
mp	0.7	2.1	—	tr	—
Hbd ph	—	—	—	0.1	—
mp	—	—	—	0.8	—
Tmt	0.2	—	—	—	—
Crystals	48.1	40.0	17.6	9.5	45.0
Groundmass	51.9	60.0	82.4	90.5	55.0

Grain size conventions after Wilcox (1954): ph = phenocryst (>0.3 mm), mp = microphenocryst (<0.3 mm, >0.03 mm)
Sample references:
Col 11 from Luhr and Carmichael (1980)
Say 17B from Luhr and Carmichael (1981)
Jor 11 from Luhr and Carmichael (1985)
1050-418 from T. Hasenaka, pers. commun. (1984)

the Colima sample has abundant plagioclase phenocrysts. Thus, although the orientation of the SGVC is apparently related to a major crustal rifting event (Luhr *et al.*, 1985), the magmas erupted from these centers are typical, subduction-related basaltic andesites without elevated contents of alkalies or incompatible elements. It seems that crustal rifting simply provided an easy conduit to the surface for magmas derived from the underlying subduction zone.

During the 1759-1774 eruption of volcán Jorullo, lava compositions evolved with time from primitive basalts to late-stage basaltic andesites such as Jor 11 (Table 4). As discussed in Luhr and Carmichael (1985), this compositional evolution is most consistent with crystal fractionation of olivine, augite, plagioclase, and spinel under upper-mantle to lower-crustal pressures. By analogy, other basaltic andesites in western Mexico, including those of the SGVC, were also probably derived by relatively high-pressure fractionation of primitive basalts generated through subduction. Accordingly, these basaltic andesites probably represent the principal magma type rising from depth in the region. At small cinder and lava cones such as Jorullo, Paricutín, Usmajac, and those of the SGVC, these basaltic andesites are often relatively unmodified upon eruption, presumably ascending rapidly from subcrustal levels without significantly fractionating on route. At larger stratovolcanoes, however, similar basaltic andesites feed high-level magma chambers wherein andesites, dacites, and rhyodacites evolve through low-pressure crystallization; the Colima basaltic andesite Col 11 is the most basic lava yet found at this andesite-dominated stratovolcano. The abundant plagioclase phenocrysts in Col 11 probably reflect relatively slow crystallization in the large, thermally buffered, stratovolcano magma system. The cones of the SGVC are farther from the Middle America Trench than any of the other volcanoes listed in Table 4. The abundance of plagioclase microphenocrysts in SGVC lavas may indicate relatively rapid cooling during ascent through a thicker crustal section.

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