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VOLCANIC STRATIGRAPHY OF THE GUADALAJARA AREA, MEXICO

C. M. GILBERT*
G. A. MAHOOD**
I. S. E. CARMICHAEL*

RESUMEN

Dentro de la secuencia volcánica de los alrededores de Guadalajara destacan dos ignimbritas que constituyen buenos horizontes marcadores. La más antigua de las dos, denominada ignimbrita San Gaspar, tiene una edad aproximada de 4.8 millones de años y es de composición correspondiente a andesita silícica. La otra ignimbrita, denominada ignimbrita Guadalajara debido a que ha sido utilizada extensamente como material de construcción en esta ciudad, es más silícica y tiene una edad de aproximadamente 3.3 millones de años. Dos magmas de distinta composición fueron extruidos durante la erupción de estas ignimbritas, como lo demuestra el hecho de que cada unidad contiene fragmentos de pómez de dos composiciones distintas. En algunos fragmentos comprimidos y soldados de pómez (fiamme), los dos tipos de vidrio se encuentran íntimamente mezclados.

La ignimbrita San Gaspar es extensa, delgada, se encuentra fuertemente soldada, y está caracterizada por numerosas fiamme de vidrio porfirítico oscuro que contienen fenocristales de plagioclasa, augita, hiperstena, hornblenda y biotita. El vidrio oscuro (I. R. = 1.521) es la fase predominante de la roca, pero todas las muestras contienen esquirlas y pequeñas fiamme de vidrio incoloro (I.R. = 1.510) que contiene aproximadamente 5% más de SiO_2 y mucho menos CaO, MgO, y FeO que el vidrio oscuro. Análisis de microsonda de los minerales ferromagnesianos indican temperaturas preeruptivas en el magma de cerca de 1000°C. La transformación de la hornblenda común a hornblenda basáltica hacia la cima de la ignimbrita, implica una temperatura de emplazamiento de más de 800°C. Un rasgo característico de la ignimbrita es que en las fiamme más grandes se formaron vesículas después de su compactación y soldamiento.

* *Department of Geology and Geophysics, University of California, Berkeley, California, USA 94720*

** *Department of Geology, Stanford University, Stanford, California, USA 94305*

La ignimbrita Guadalajara se caracteriza por abundantes fiamme de dos composiciones distintas. Las porciones que no están devitrificadas contienen dos vidrios distintos, que se encuentran en aproximadamente la misma proporción; uno de ellos es incoloro y afírico, mientras que el otro es de color oscuro y contiene algunos fenocristales de feldespato alcalino. En general, sin embargo, la ignimbrita se encuentra totalmente devitrificada; las fiamme de color claro tienen textura axiolítica, y las fiamme oscuras son criptocristalinas y vesiculares.

Al este y sureste de Guadalajara la ignimbrita San Gaspar descansa sobre derrames basálticos, pero al noroeste se encuentran extensas unidades riolíticas. Un basalto de olivino caracterizado por megacristales de plagioclasa cubre la ignimbrita al norte de Guadalajara, y constituye un horizonte marcador fácilmente reconocible de una edad aproximada de 4 millones de años. Hacia el oeste, la ignimbrita Guadalajara está cubierta por ignimbritas silícicas y lavas dacíticas de aproximadamente 3 millones de años de edad. El volcanismo posterior ha estado concentrado a lo largo de una zona de orientación noroeste. La mayoría de las erupciones produjeron derrames de basaltos y andesitas basálticas, pero en la Sierra de La Primavera el volcanismo culminó con la erupción de magmas riolíticos con alto contenido de sílice durante los últimos 140 000 años.

ABSTRACT

Two ignimbrites of petrologic interest provide distinctive time horizons in the volcanic succession near Guadalajara. The older of the two, referred to as San Gaspar ignimbrite, is approximately 4.8 million years old and has the composition of dacitic andesite. The younger ignimbrite, called Guadalajara ignimbrite because of its use as the characteristic building stone in the city, is more siliceous and approximately 3.3 million years old. In the formation of both ignimbrites, two contrasting magmas were erupted simultaneously, for each rock contains glass fragments of two distinct compositions. In some fiamme, the two glasses are intricately intermixed.

The San Gaspar ignimbrite is widespread, thin, firmly welded throughout, and characterized by numerous fiamme of porphyritic dark glass containing abundant phenocrysts of plagioclase, augite, hypersthene, hornblende and biotite. Dark glass (R. I.= 1.521) is the predominant phase in the rock, but all samples contain shards and small fiamme of colorless glass (R.I. = 1.510) that contains approximately 5 percent more SiO_2 and significantly less CaO, MgO, and FeO than the dark glass. Microprobe analyses of ferromagnesian phenocrysts indicate pre-eruptive magma temperatures of about 1000°C. Conversion of common hornblende to basaltic hornblende at the top of the ignimbrite signifies an emplacement temperature greater than 800°C. Late vesiculation of the larger fiamme, following compaction and welding, is characteristic.

The Guadalajara ignimbrite is characterized by abundant fiamme of two distinct compositions. Vitric facies consist of two different glasses in nearly equal proportions, one colorless and aphyric, the other dark-colored with sparse phenocrysts of alkali feldspar. Generally, however, the ignimbrite has been completely devitrified, the light-colored fiamme being axiolitic and the darker porphyritic fiamme cryptocrystalline and vesicular.

East and southeast of Guadalajara, the terrane beneath the San Gaspar ignimbrite consists largely of basaltic flows, but to the northwest rhyolitic rocks are widespread. An olivine basalt distinguished by megaphenocrysts of plagioclase overlies the ignimbrite north of Guadalajara and provides a recognizable horizon about 4 million years old. To the west, the younger Guadalajara ignimbrite is overlain by siliceous ash flows and dacitic lavas about 3 million years old. Younger volcanism has been concentrated along a northwest-trending zone where activity has continued since late Pliocene time, culminating at Sierra La Primavera during the last 140 000 years with eruptions of high-silica rhyolite. Elsewhere the young eruptions have produced flows of basalt and basaltic andesite.

INTRODUCTION

Guadalajara stands at an altitude of about 1 600 meters on an elevated surface of low to moderate relief. Cut into this surface and passing close to the city on the east and north is the precipitous canyon of Río Grande de Santiago, some 500 meters deep and so youthful that the elevated older surface remains largely intact and undissected. The city itself is situated on a plain mantled by late Pleistocene pumiceous deposits that continues northwestward for about 20 kilometers beyond the city limits, where it is terminated by hills and mesas of Pliocene dacite (Cerro Tepopote and others) and by entrenched tributaries of Río Grande de Santiago (Arroyo San Lorenzo and others). Near the city's southern margin, three basaltic cones mark a northwest-trending zone of Plio-Pleistocene volcanism. The late Pleistocene rhyolite complex of Sierra La Primavera stands immediately west of the city. To the north, west of the highway to San Cristóbal, a rugged terrane of Miocene volcanic rocks rises several hundred meters above the Guadalajara plain. Geographic features and reference points are represented in Figure 1.

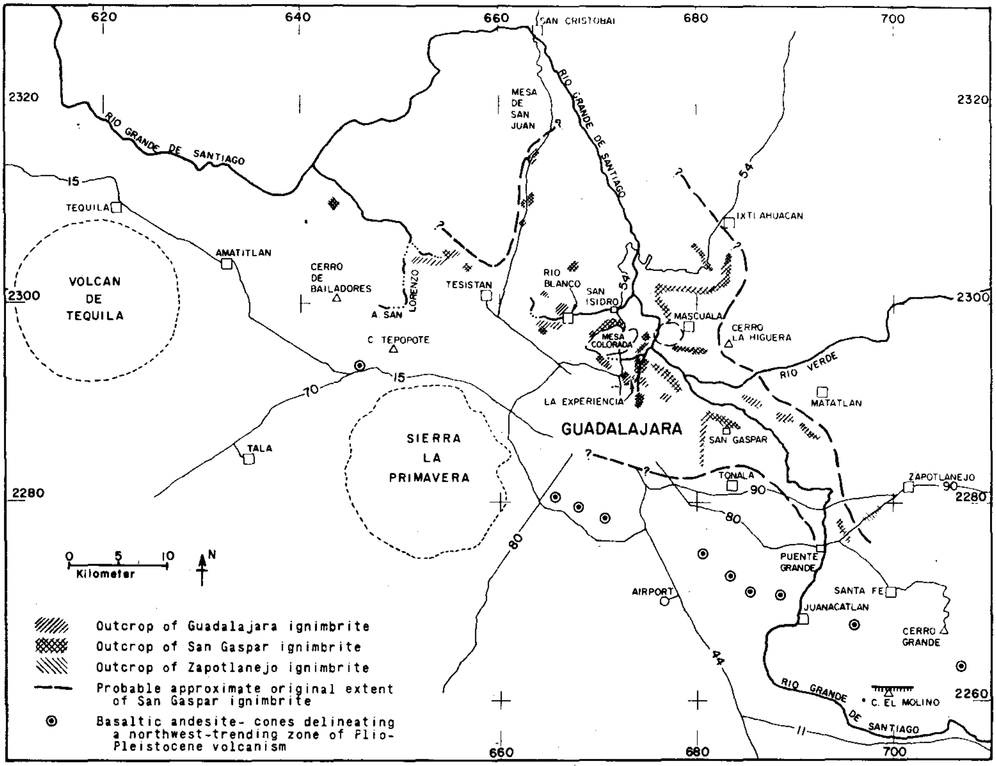

Fig. 1. Sketch map of the Guadalajara region showing major geographic features, towns, principal highways (numbered), and the general distribution of San Gaspar and Guadalajara ignimbrites.

The rocks exposed near Guadalajara are volcanic flows, domes and clastic deposits that range in age through approximately the last 10 million years. In this succession two ignimbrites of Pliocene age provide distinctive time horizons. The younger of the two has been widely used as the characteristic building stone in Guadalajara. Blocks of it were used to construct nearly all of the older buildings, and slabs of it have been used as facing on the walls of many new structures, including the modern airport. We refer to this rock as Guadalajara ignimbrite. The only existing quarry is a small one at La Experiencia near the northern edge of the city.

The older of the two ignimbrites crops out prominently near the top of the stratigraphic sequence exposed in the canyon of Río Grande de Santiago. In their account of that sequence as seen north of the city along highway 54, Watkins *et al.* (1971, p. 1957-1959) designated this ignimbrite as unit Num. 7, described it as "glassy basaltic ignimbrite", and reported its age as $4.71.10^6$ years. We refer to it as San Gaspar ignimbrite for its appearance near the town of that name a short distance east of Guadalajara.

The present report is based on field reconnaissance during a period of several months. A topographic base on a scale of 1/50 000, prepared by the Comisión de Estudios del Territorio Nacional (Cetenal), was used for field work and included the following individual maps: F-13-D-54, D-55, D-56, D-65, D-66, D-67, D-76. Regional coordinates shown on these maps are used to identify specific localities and are indicated on Figure 1 for general reference.

SAN GASPAR IGNIMBRITE

General character, distribution, and age

The San Gaspar ignimbrite is a crystal vitric welded ash flow tuff, typically gray in color but grading to brown at the top. It is characterized by numerous thin horizontally-oriented lenses *(fiamme)* of porphyritic black glass, most of which are no more than several centimeters in length although they range up to about 20 centimeters. The predominant phenocrysts are plagioclase but clinopyroxene, orthopyroxene, hornblende and biotite are all characteristic. Accidental rock fragments up to several centimeters in diameter are numerous and consist of older volcanic rocks, mostly basaltic.

The ignimbrite is thin yet it is widespread and densely welded throughout. Along the northern margin of Guadalajara it forms a prominent cliff below the canyon rim, and also in the opposite wall of the Santiago canyon. East of Río Grande de Santiago, exposures of the ignimbrite occur northward almost to Ixtlahuacan (2305; 683) and southward almost to Puente Grande (2276.5; 695.2). West of the river, remnants occur as far north as Milpilla, just south of Mesa de San Juan (2315; 663), and also northwest of Tesistan (2303; 657, 2305; 655 and 2310; 643.5). Within Guadalajara the ignimbrite is exposed about a kilometer southwest of the stadium in the bed of río San Juan de Dios (2289.5; 673.2), and it presumably extends over much of the area now occupied by the city and the plain to the northwest.

Original limits of the ignimbrite are uncertain except in a few localities where it wedges out against topographically higher areas of older rock. The ignimbrite was limited, for example, by the older highland that rises west of the highway to San Cristóbal, but its northern limit and its extent beneath the Guadalajara plain to the south are unknown. East and southeast of Guadalajara, it appears concordant with underlying basaltic flows exposed in the walls of the Santiago canyon, but it presumably wedges out against higher basaltic areas on both sides of the canyon near Tonalá and Mazatlán. Just north of the city, it surrounds a local high area of older rhyolite (Mesa Colorada) and also a rhyolitic hill, perhaps a volcanic dome, exposed in the eastern wall of the canyon west of Mascuala (Fig. 1).

San Gaspar ignimbrite extended at least 50 kilometers along the present course of Río Grande de Santiago and at least 30 kilometers northwest of Guadalajara; near the city its northeast-southewest extent was at least 25 kilometers (Fig. 1). Probably it extended over more than 1 000 km^2. Its thickness in the walls of the canyon near Guadalajara is about 25 meters and about 12 meters in the westernmost remnant (2310; 643.5); elsewhere it has been partially eroded. If its average thickness was 15 meters, the probable original volume of the ignimbrite was on the order of 15 km^3.

All known exposures of the San Gaspar ignimbrite, except the westernmost remnant which is some 200 meters lower, occur at elevations between 1400 and 1600 meters as though they were parts of a little-deformed subhorizontal sheet. Furthermore, exposures in the canyon walls are continuous for significant distances with dips so low they may well be original. Along the northeastern margin of Guadalajara, for example, the ignimbrite is continuously exposed below the canyon rim for a distance of about 5 kilometers with a northwestward inclination of only 15 m/km. Similar continuity and gentle dip are evident also in the eastern wall of the Santiago canyon north of Río Verde. Farther south, near the town of San Gaspar and for about 10 kilometers along the opposite rim of the canyon the ignimbrite is essentially horizontal. It has been displaced locally, however, as in the canyon just north of La Experiencia. There it has been offset along two westerly-trending faults each of which has vertical displacement (down to the south) of less than 50 meters. Also, the westernmost remnant (2310; 643.5) is preserved in a small graben about 30 meters deep. If the ignimbrite has been faulted elsewhere, the displacements are undoubtedly small.

Samples for age determination were collected from large fiamme in the ignimbrite exposed along highway 54 several kilometers north of the city. Separate samples (995-7B, Table 1) gave potassium-argon ages of $(4.85 \pm 0.11) \times 10^6$ years for the whole rock and $(4.71 \pm 0.07) \times 10^6$ years for glass; plagioclase gave an uncertain age of $(5.32 \pm 1.08) \times 10^6$ years. We assume a probable age of approximately 4.8 million years.

Petrography and chemical composition

The San Gaspar ignimbrite is largely made up of firmly welded glass shards and crystal fragments, but it includes numerous fiamme of porphyritic glass that represent flattened lapilli (Fig. 2A). It has a roughly planar fabric, resembling flow structure, that has resulted from compaction of the glassy particles. Tight compaction is particularly evident where glass particles have been squeezed between and bent around the more rigid crystal and lithic fragments. In view of the general thinness of the ignimbrite, its tightly appressed structure must be attributed largely to relatively low viscosity in the glass at the time of emplacement, probably caused by very high temperature and water content.

Dark glass is the vastly predominant phase in the ignimbrite. As seen in transmitted light, it is clear but dark brown and has a refractive index close to 1.521. However, every thin section also reveals some shards and small fiamme of colorless glass having a refractive index of 1.510. Microprobe analyses of a number of individual fragments of each glass

Table 1
Potassium-Argon age determinations

Sample	Rock type location	Material dated	K Weight Percent	Sample weight	Rad ^{40}Ar moles/g x 10^{-11}	Percent Rad ^{40}Ar	Age x $10^6 \pm 2\sigma$
76-3 (KA4287)	basalt 2267.4/694.6	whole rock	1.313	9.233	3.123	5.2	1.37± .24
995-35 (KA2957)	basalt 2293.3/646	whole rock	1.123	4.41776	3.467	2.3	1.78± .39
995-33 (KA2956)	basalt 2312/632	whole rock	1.067	3.80490	9.772	2.3	0.53± .15
55-25 (KA3076)	pumice 2300.4/649.4	oligoclase	1.059	2.31992	5.637	27.6	3.07± .12
65-4A (KA3051)	Guadalajara 2294.1/671.3	sanidine	4.963	3.89385	2.961	78.2	3.44± .17
55-26B (KA4155)	Guadalajara 2299/665.7	sanidine	5.5122	1.60756	3.086	47.2	3.23± .08
56-3 (KA4288R)	basalt 2297/674.7	whole rock	1.331	3.98591	1.017	8.3	4.4 ± .38
SC55 (SK259)	basalt 2305/681.6	groundmass	1.229	3.41255	0.8477	33.2	3.97± .12
995-7B (SK261)	San Gaspar 2297.7/673	whole rock	3.536	1.02607	2.98	42.2	4.85± .11
995-7B (KA3046)	same	glass	3.982	6.08441	3.257	59.4	4.71± .07
995-7B (KA3045)	same	andesine	0.4604	4.42673	4.254	3.9	5.32±1.08
995-3 (KA4290)	rhyolite 2301.5/672.8	anorthoclase	4.668	6.01998	4.436	77.0	5.47± .17
55-30 (KA3252)	rhyolite 2316.4/664.3	anorthoclase	2.792	3.42318	2.515	80.6	5.19± .06
992-6A (KA3100)	rhyolite 2297/673	glass	4.44	6.69568	5.516	62.1	7.15± .28
66-12 (KA4289)	Zapotlanejo 2283/701	glass	3.260	4.41828	4.379	81.0	7.73± .28

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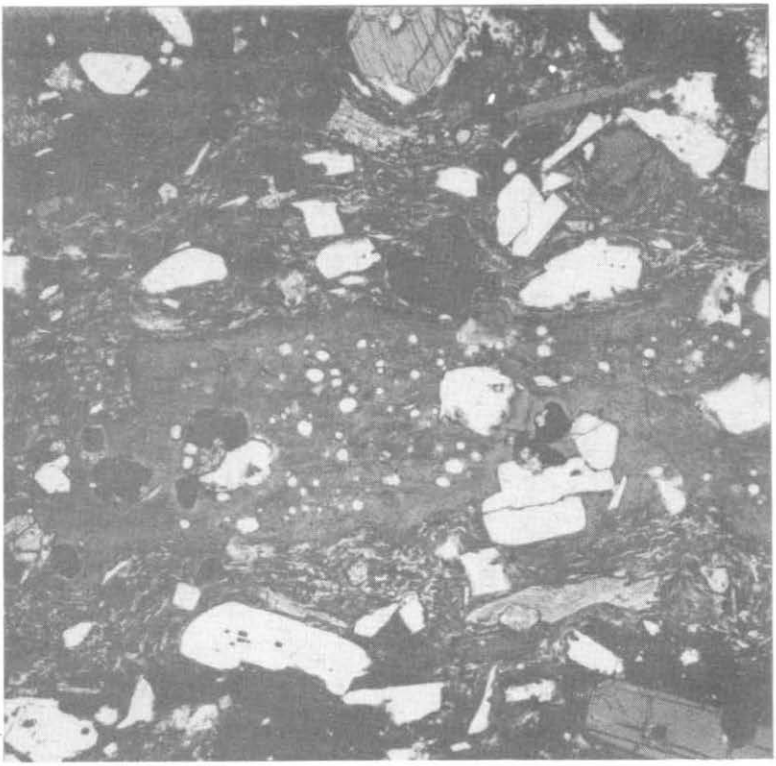
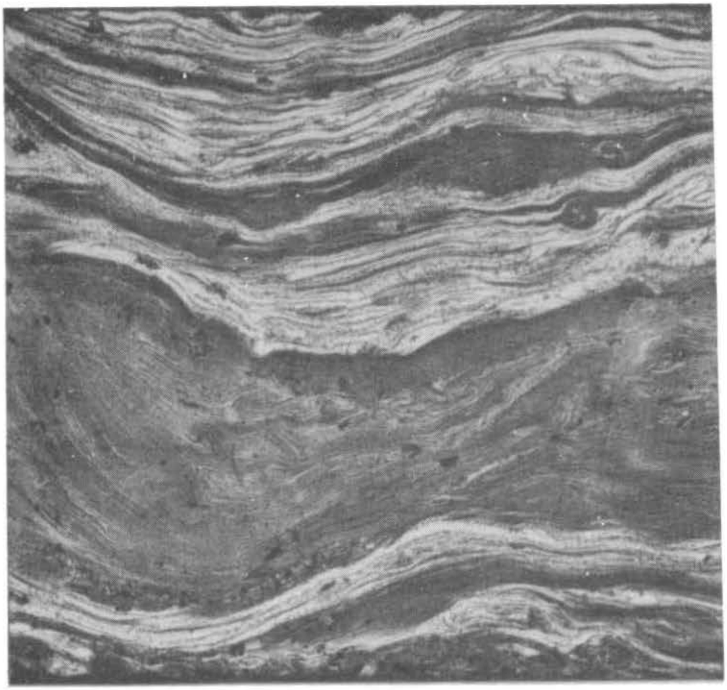


Fig. 2. Composition and texture of the San Gaspar ignimbrite.
A. Width of field = 5 millimeters. Numerous crystals of feldspar and mafic minerals in a matrix of flattened glass shards, mostly dark glass but including an admixture of colorless shards. A single fiamma of porphyritic dark glass (center) includes small spherical vesicles.
B. Width of field = 1 millimeter. Intermixed dark and colorless glasses within a single fiamma. Texture within glasses suggests collapsed pumice.

in eachof several samples from different localities are essentially consistent and indicate that the dark glass contains approximately 5 percent less SiO_2 and significantly more FeO, MgO, and CaO than the colorless glass (Table 3). In some individual fiamme the two glass phases occur together in streaky combination but with sharp contacts indicating incomplete mixing. Typically in such combinations one phase predominates, usually the dark glass, and the other occurs as thin streaks or bands oriented roughly parallel to the length of the fiamme (Fig. 2B). Apparently two magmas, one greatly preponderant over the other, were erupted simultaneously and were, at least inpart, intricately intermixed.

Many fiamme, particularly the larger ones, contain very small spherical vesicles that undoubtedly formed after flattening and welding of



2B

the original lapilli (Fig. 2A). Evidently, after they had been deposited and compacted, these glass particles retained a significant content of volatile constituents and had high enough temperature and low enough viscosity to promote separation of a vapor phase. Generally the vesicles are concentrated toward the central parts of the fiamme, and in some cases they have been slightly flattened and are somewhat elongated parallel to the length of the fiamme. Vesicle walls are usually coated with an exceedingly thin, faintly birefringent incrustation of low relief that appears as a pale gray translucent film in reflected light.

The composition of the predominant magma is indicated by the bulk analysis of a sample (995-7B, Table 2) collected from large dark fiamme at the outcrop along highway 54 north of Guadalajara (2297.7; 673). The mode consists of brown glass (R.I. = 1.521) containing abundant phenocrysts of andesine, clinopyroxene, orthopyroxene, hornblende, biotite, magnetite, ilmenite, and apatite. The SiO_2 content of the analyzed sample (62.28 %) is that of a silicic andesite, while the high content of alkalis and abundant normative quartz is more consistent with a

Table 2
Wet chemical analyses and CIPW norms of ignimbrites and basaltic lavas

	San Gaspar dark fiamme	Guadalajara fiamme dark	colorless		Basalts and basaltic andesites			
	995-7B	65-4A	65-4B	992-182	76-3	995-33	SC-15	SC-55
SiO_2	62.28	66.55	71.30	51.38	54.43	48.33	51.65	49.54
TiO_2	0.90	0.27	0.14	2.23	1.47	2.48	1.78	2.32
Al_2O_3	16.10	13.74	11.89	16.77	17.39	15.94	16.62	16.83
Fe_2O_3	1.99	2.05	1.39	2.87	2.10	2.98	1.71	3.96
FeO	1.96	1.17	1.07	7.89	5.74	8.85	7.69	7.14
MnO	0.12	0.10	0.08	0.15	0.14	0.18	0.09	0.10
MgO	1.40	0.17	0.02	4.75	4.61	6.00	5.37	5.03
CaO	3.25	0.57	0.50	7.74	7.74	9.38	7.67	8.08
Na_2O	4.29	2.70*	3.68⁺	3.68	3.97	3.53	3.63	3.63
K_2O	4.11	7.92*	6.29⁺	1.27	1.47	1.08	1.71	1.41
P_2O_5	0.27	0.01	nil	0.39	0.41	0.52	0.83	0.59
H_2O^+	2.36	3.36	2.82	0.38	0.43	0.22	1.12	1.31
H_2O^-	0.50	0.78	0.56	0.22	0.16	0.19	0.08	0.38
Total	99.53	99.39	99.74	99.90	100.06	99.66	99.95	100.32

* In two corresponding devitrified fiamme, Na_2O = 5.60 and 5.40, K_2O = 5.48 and 5.82

+ In a corresponding devitrified fiamma, Na_2O = 4.91 and K_2O = 4.81

Wet chemical analyses by I. S. E. Carmichael and G. A. Mahood

Alkalies by J. Hampel, flame photometer

		995-7B	65-4A	65-4B	992-182	76-3	995-33	SC-15	SC-55
	qz	13.4	19.2	25.7	–	2.6	–	–	–
	or	24.3	46.8	37.2	7.5	8.7	6.4	10.1	8.3
	ab	36.3	22.8	26.1	32.7	33.6	29.9	30.7	30.7
	an	12.5	2.0	nil*	24.7	25.3	24.5	24.0	25.5
	wo	0.8	0.3	1.04	4.7	4.4	7.8	3.6	4.5
di	en	0.6	0.2	0.03	2.6	2.6	4.5	2.0	2.8
	fs	0.1	0.1	1.14	1.9	1.5	3.0	1.5	1.4
hy	en	2.9	0.2	0.02	9.1	8.9	0.6	9.7	8.2
	fs	0.6	0.1	0.75	6.7	5.1	0.4	7.2	4.1
ol	fo	–	–	–	0.2	–	6.9	1.2	1.0
	fa	–	–	–	0.1	–	5.1	0.9	0.6
	mf	2.9	3.0	–	4.2	3.0	4.3	2.5	5.7
	il	1.7	0.5	0.3	4.2	2.8	4.7	3.4	4.4
	ap	0.6	0.02	–	0.9	1.0	1.2	2.0	1.4

* includes ac 4.0 and ns 0.10

dacite. Microprobe analyses of the principal elements in glass and crystal phases in the same sample are recorded in Tables 3 and 4; for comparison, additional microprobe analyses of glass and crystal phases in two samples from other localities are also recorded (56-5 at 2303.4; 681.5 and 55-29 at 2297.2; 664.5). Differences between the wet chemical analysis of the fiamme (995-7B, Table 2) and microprobe analyses of the dark glass (Table 3) are in accord with the abundant phenocrysts in the chemically analyzed sample.

Together the cognate crystal phases in the San Gaspar ignimbrite make up about 15 percent of the rock with andesine at least three times more abundant than combined mafic minerals. Relative proportions of the different ferromagnesian silicates vary somewhat in different thin sections, but in general hornblende is about equal to combined pyroxenes and biotite is less abundant. Apatite and opaque oxides are minor accessory phases. All of these minerals occur as phenocrysts in fiamme of dark glass. They are unaltered and little if at all resorbed, and presumably they were in approximate equilibrium in the magma at the time of eruption. The same minerals have been observed in colorless glass, but never all together. Fiamme of colorless glass are small, and none includes more than one or two crystals; most contain no crystals at all.

Plagioclase phenocrysts typically show complex twinning and compositional zoning; reverse zoning is common. Several crystals identified on a universal stage, using the method and data of Slemmons (1962), have compositions between An_{35} and An_{40} and have the optical orientation of high-temperature plagioclase. Microprobe analyses of plagioclases in each of three samples average $An_{37\text{-}41}$ (Table 3). Zoning ranges from An_{51} and to An_{24}.

Table 3

Microprobe analyses of feldspar phenocrysts and glass in the San Gaspar ignimbrite

		Feldspar			Dark glass			Colorless glass	
		995-7B	56-5	55-29	995-7B	56-5	55-29	56-5	55-29
SiO_2		57.76	58.48	58.21	66.10	65.47	65.85	70.16	70.95
TiO_2		0.45	0.09	0.06	ND	0.60	0.58	0.37	0.32
Al_2O_3		25.92	26.28	26.55	15.13	15.46	15.69	14.79	14.91
FeO		0.42	0.41	0.44	2.26	2.47	2.29	0.52	0.44
MgO		0.00	0.04	0.04	ND	0.65	0.61	0.08	0.02
CaO		8.36	7.56	7.52	1.62	1.76	1.57	0.50	0.41
Na_2O		6.75	7.00	7.07	4.71	4.44	3.91	3.86	3.15
K_2O		0.47	0.59	0.57	4.59	4.81	5.70	5.68	7.22
Total		100.14	100.45	100.46	94.41	95.66	96.20	95.96	97.42
Weight %	An	40.5	37.5	37.3					
	Ab	57.1	59.2	59.8					
	Or	2.8	3.5	3.4					
Range	An	34-47	24-51	29-48					
	Ab	63-53	71-47	66-51					

Table 4
Microprobe analyses of mafic phenocrysts in the San Gaspar ignimbrite

	Biotite		Hornblende		Orthopyroxene		Clinopyroxene		Magnetite		Ilmenite	
	995-7B	56-5	995-7B	56-5	995-7B	56-5	995-7B	56-5	995-7B	56-5	995-7B	56-5
SiO_2	36.83	37.92	44.28	43.62	53.40	53.67	52.02	51.74	0.47	0.85	0.00	0.00
TiO_2	5.67	5.68	3.66	3.61	0.34	0.31	0.67	0.58	12.10	12.28	42.10	42.87
Al_2O_3	13.26	14.25	9.49	10.10	0.68	0.91	1.65	1.73	2.44	2.64	0.32	0.33
FeO	12.61	13.71	11.74	12.22	17.03	18.33	8.58	8.75	73.20	73.18	50.70	52.04
MnO	0.16		0.34		0.92		0.50		0.55	0.57	0.50	0.52
MgO	16.35	15.77	14.94	14.48	26.35	25.24	15.56	15.14	2.44	2.30	3.80	2.97
CaO	0.00	0.05	11.36	11.53	1.30	1.49	21.00	22.05	0.05	0.05	0.00	0.02
BaO	0.99		0.03		0.00		0.00					
Na_2O	0.95	0.93	2.56	2.53	0.00	0.08	0.43	0.39	0.00	0.07	0.00	0.04
K_2O	8.18	8.25	0.72	0.81	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00
F	0.72		0.36		0.00		0.00					
Cl	0.06		0.03		0.00		0.00					
H_2O(calc)	3.65		1.89									
Total	99.43	96.56	101.37	97.91	100.02	100.03	100.41	100.09	90.7*	91.39+	96.9*	98.27+

* Equilibrium temperature and oxygen fugacity is 1004°C and log $fO_2 = -9.5$
+ Equilibrium temperature and oxygen fugacity is 1012°C and log $fO_2 = -9.5$

Optical properties of the ferromagnesian phenocrysts are consistent with microprobe analyses recorded in Table 4. The clinopyroxene is diopsidic augite. The orthopyroxene is faintly pleochroic hypersthene, approximately $En_{65-70}Fs_{35-30}$. The amphibole is common hornblende, greenish brown in color, and biotite is dark velvet brown. But there are striking changes in the hornblende and biotite, the hydrous crystal phases, between the lower and the uppermost parts of the ignimbrite. Where its original top has been preserved beneath a cover of younger deposits, as in some cliff exposures below the rim of the Santiago canyon, the uppermost several meters of the formation have an over-all brown color, and there both hornblende and biotite show a deep reddish brown color and increased refractive indices. Microprobe analysis shows, however, that their basic compositions are the same as those of the common hornblende and biotite in the lower part of the formation. A reduced extinction angle along with increased refractive indices and birefringence identify the red brown amphibole as basaltic hornblende (oxyhornblende); the two refractive indices measured on cleavage flakes are approximately 1.710 and 1.740 as compared with 1.680 and 1.694 in the greenish brown hornblende below, and dispersion (red$<$violet) is greatly increased. Formation of basaltic hornblende involves dehydration and oxidation of common hornblende at a temperature above 800°C (Barnes, 1930), and its presence in the upper part of the ignimbrite indicates a temperature of at least 800°C after emplacement of the ignimbrite sheet.

That the magma temperature at eruption was much higher than 800°C is indicated by the compositions of ilmenite, magnetite, and pyroxene phenocrysts recorded in Table 4. Using ilmenite and magnetite, the Fe-Ti oxide geothermometer of Buddington and Lindsley (1964) yields temperatures of 1004° and 1012°C (Table 4). Using pyroxenes (Wood and Banno, 1973; Wells, 1977), the calculated temperatures are 965° and 985°C. A pre-eruptive magma temperature of at least 1000°C is probable. The presence of F-poor biotite in apparent equilibrium in magma at that temperature is noteworthy but has been reported in other dacitic and rhyolitic lavas with similar ferromagnesian phenocryst assemblages (Carmichael, 1967, p. 42).

A closely similar ignimbrite crops out to the east near Zapotlanejo (2283; 701 and 2279; 698) and also some 20 kilometers farther east along highway 80 approaching Tototlan (2275; 722). Like the one at San Gaspar, this ignimbrite is characterized by thin fiamme of dark riencia could not have provided the large volume of building stone that has been used. Probably it extends over much of the area of the present city, the building stone presumably being derived from small local quarries that were developed near building sites and were later abandoned and overridden as the city expanded.

Similar ignimbrite occurs farther west along the northern margin of the Guadalajara plain - some 10 kilometers northwest of La Experiencia near the town of Río Blanco and also northwest of Tesistan. The same distinctive composition of the ignimbrite in each of these areas and at La Experiencia suggests that all are parts of the same eruptive unit. A physical connection between them is not visible but seems likely and may occur under the Guadalajara plain. Sanidine phenocrysts from glassy fiamme in Guadalajara ignimbrite about 2 kilometers northwest of La Experiencia yielded a potassium-argon age of $(3.44 \pm 0.17) \times 10^6$ years, and similar phenocrysts from devitrified fiamme in the ignimbrite near Río Blanco gave an age of $(3.23 \pm 0.08) \times 10^6$ years (65-4A and 55-26B, respectively, Table 1). We assume an age of approximately 3.3 million years for the Guadalajara ignimbrite.

Petrography and chemical composition

In the Guadalajara ignimbrite, as in the San Gaspar, two distinct magmas are represented and were undoubtedly erupted simultaneously, but in the younger ignimbrite the two are present in more nearly equal volumes. Vitric samples from the locality northwest of La Experiencia (2294.1; 671.3) contain two distinct types of glass. Some fiamme consist of clear colorless aphyric glass, gray in hand specimen, that has a refractive index close to 1.505; others consist of sparsely porphyritic brown glass, black in hand specimen, that has a refractive index close to 1.516. Fiamme of both types represent flattened pumice lapilli, for traces of collapsed pumice structure are evident; in fact, the dark fiamme are microporous and appear to retain some of the original porosity. The fine-grained matrix of the ignimbrite is a welded mixture of colorless and brown glass shards, in roughly similar proportions, together with sparsely scattered small crystals of alkali feldspar (Fig. 3). Although both types of glass are abundant in the matrix, the dark variety predominates in the fiamme.

The two types of glass separated by sharp boundaries occur together in some fiamme. Typically in such combinations one glass predominates and the other forms thin streaks that trend approximately parallel to the long dimensions of the fiamme (Fig. 3). Evidently intimate intermixing of at least a portion of the two magmas has occurred on a millimeter scale without apparent assimilation of either one by the other.

Fig. 3. Composition and texture of glassy facies of Guadalajara ignimbrite. Width of field = 5 millimeters. A single fiamma of dark glass includes a streak of colorless glass and is enclosed in a matrix made up of colorless and dark glass shards. Sparse crystals of sodic sanidine do not appear in this field of view.

Alkali feldspar is the only conspicuous cognate crystal phase in the Guadalajara ignimbrite, although a few tiny crystals of pyroxene, hornblende, and magnetite have been observed. The crystals occur as phenocrysts in dark fiamme and have nowhere been observed in light-colored fiamme. The feldspar is sodic sanidine, approaching anorthoclase in composition. Microprobe analysis of a few crystals indicates a composition of approximately Or_{40}.

Glassy samples of the Guadalajara ignimbrite are available from only the one locality northwest of La Experiencia; elsewhere the rock has been devitrified completely. But even in devitrified samples the components representing the two magmas can be distinguished, for the two types of glass have devitrified differently and a color contrast is retained. Both texture and mineral composition suggest that devitrification occurred in hot glass during an early stage of the cooling process.

Devitrified light-colored fiamme are tipically axiolitic. Fibrous crystals have grown approximately normal to opposing sides of the fiamme and meet to form a septum along a central axis. Small linear cavities along the septum are characteristic, especially in the larger fiamme, and they commonly contain crystals of tridymite and quartz. The larger axiolites are outlined by a narrow marginal zone of ultrafine texture and slightly darker color, and the texture coarsens progressively toward the central septum. X-ray diffraction indicates that the fibrous structure consists of feldspar together with a prominent silica phase - cristobalite in the ultrafine marginal zone and quartz in the coarser-grained central portion. Weight percentages of K_2O and Na_2O in a typical axiolite, determined by flame photometer, are 4.81 and 4.91, respectively, indicating that the fibrous feldspar has the composition of sodic sanidine. In contrast, devitrified dark fiamme typically are vesicular and crudely spherulitic and are exceedingly fine grained. In two typical samples, the devitrification product is alkali feldspar with relatively minor cristobalite; the weight percentages of alkalis in the two samples (K_2O = 5.48 and 5.82; Na_2O = 5.60 and 5.40) indicate a sodic sanidine. The vesicular structure in devitrified dark fiamme presumably developed during devitrification, for dark-colored glassy fiamme do not show it. Vesicle walls are commonly encrusted with tiny crystals of alkali feldspar, tridymite, or cristobalite, probably precipitated from a vapor phase. Where feldspar and a silica phase occur together in the same vesicle, the feldspar generally appears earlier.

Uncontaminated samples of colorless and dark-colored glass collected from fiamme at the locality northwest of La Experiencia (2294.1; 671.3) have contrasting chemical compositions. The colorless glass (65-4B, Table 2) is rhyolitic and peralkaline, whereas the other glass (65-4A, Table 2), dark brown in color, is trachytic. The latter is the host for sparse phenocrysts of sodic sanidine (approximately Or_{40}), but it has a most unusually high K_2O/Na_2O ratio (2.93), which when recalculated into CIPW salic components and projected into the system SiO_2-$KAlSi_3O_8$-

$NaAlSi_3O_8$ (Carmichael *et al.*, 1974, p. 228-231) is quite apart from other silicic liquids; additionally, the tie line connecting it to its feldspar phenocrysts is opposite in trend to those found either experimentally (Tuttle and Bowen, 1958) or in silicic volcanic rocks in general. The discrepancy disappears, however, if the alkali ratios found in corresponding devitrified fiamme (0.98 and 1.08) are substituted for that in the glass. Evidently devitrification occurred early enough to preserve the alkali ratio of the erupted magma, whereas in the glass the primitive alkali ratio was disturbed during subsequent hydration, as indeed it was in the colorless glass as well (Table 2). Such disturbance of original alkali ratios in vitric phases raises doubt, for the rocks considered here, as to the reliability of potassium-argon ages determined on samples largely composed of a glass phase.

GENERAL VOLCANIC HISTORY

Suggested correlations, approximate ages, and general relationships of the San Gaspar and Guadalajara ignimbrites and associated formations are summarized schematically in Figure 4.

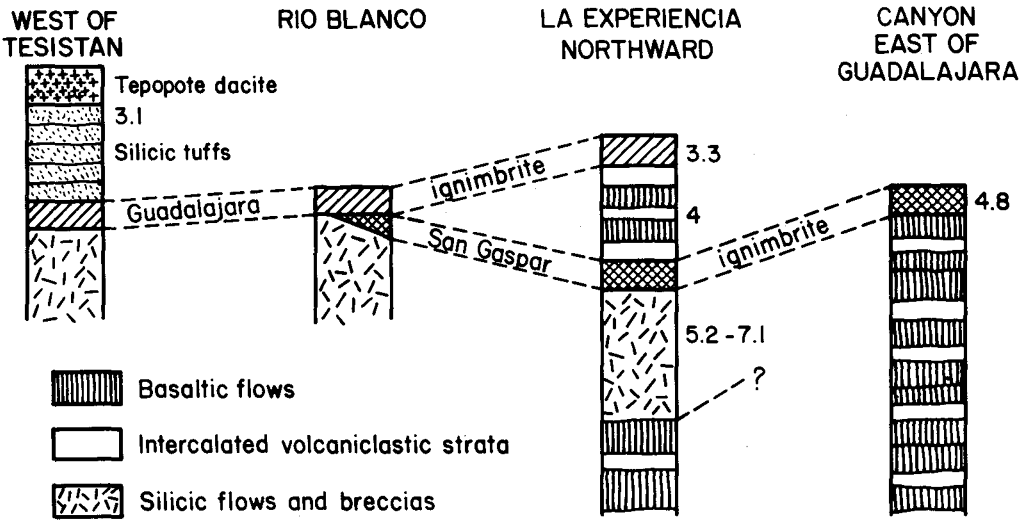


Fig. 4. General relationships of San Gaspar and Guadalajara ignimbrites and associated formations, shown schematically and not to scale. Numbers refer to approximate ages in millions of years.

North and northwest of Guadalajara, the San Gaspar ignimbrite rests on rhyolitic flows and breccias, with andesitic or basaltic flows appearing locally. Partly glassy felsitic and spherulitic flows, generally aphyric and showing contorted flow banding, are exposed between Guadalajara and San Isidro. Obsidian from one of these has a refractive index of 1.498 indicating a high silica content. Flows and breccias near San Isidro and northward commonly are characterized by prominent phenocrysts of anorthoclase and by small relatively sparse phenocrysts of quartz. Typical groundmass textures, as seen in thin section, are finely fibrous and spherulitic, suggesting devitrified glass. Such rhyolitic rocks extend along the western side of the Santiago canyon at least as far north as Mesa de San Juan. To the west, similar rocks probably make up much of the mountainous area north of Tesistan, and they also appear in Arroyo San Lorenzo along the western margin of the Guadalajara plain.

For the succession of rocks exposed in the canyon north of the city, potassium-argon ages reported by Watkins *et al.* (1971, p. 1964) indicate that the rocks immediately below the San Gaspar ignimbrite (their unit Num. 7) are a little more than 5 million years old, while rocks near the bottom of the canyon have ages approximating 9 million years. Our age determination for rhyolitic samples below the ignimbrite are in general agreement. Anorthoclase from a rhyolitic breccia about 2 kilometers north of San Isidro gave an age of 5.47×10^6 years and from a flow at the southeastern end of Mesa de San Juan an age of 5.2×10^6 years (995-3 and 55-30, respectively, Table 1). Obsidian from spherulitic rhyolite south of San Isidro yielded an age of 7.75×10^6 years (992-6A, Table 1).

Rhyolite flows and breccias such as occur north of the city do not appear in the volcanic sequence exposed east and southeast of Guadalajara. There the San Gaspar ignimbrite rests on a terrane made up of basaltic flows with intercalated volcaniclastic strata. Whether any of these pre-San Gaspar basic flows are the same age as the rhyolitic flows and breccias farther north is not known, but that possibility is suggested by abundant siliceous pumice in some of the intercalated strata.

The younger of two basalt flows overlying the San Gaspar ignimbrite on a hilltop about 2 kilometers north of La Experiencia was dated rather imprecisely as $(4.4 \pm 0.4) \times 10^6$ years old (56-3, Table 1). The older of the two, a distinctively porphyritic olivine basalt characterized by abundant phenocrysts of labradorite as much as 3 centimeters across, is probably related to similar coarsely porphyritic basalt that occurs above the San Gaspar ignimbrite along the opposite (eastern) rim of the Santiago canyon north of Río Verde. The groundmass of the latter gave an age of $(3.97 \pm 0.1) \times 10^6$ years (SC55, Table 1); a chemical analysis of the whole rock is recorded in Table 2. This basalt is the most distinctive of the basic flows in the region, because of its numerous unusually large feldspar phenocrysts, and it is also unusually rich in olivine, which occurs both as a phenocryst and as a groundmass phase and makes up at least 15 percent of the mode. Also it contains phlogopite as a consistent minor constituent, and the groundmass includes some alkali feldspar as thin rims on the labradorite and as minor infillings between crystals. Groundmass texture is ophitic in some exposures, in others intergranular, and such textural variations together with some variation in composition probably indicate that more than a single flow is represented by the exposures on the two sides of the canyon. As a group, however, exposures of this rock provide a distinctive horizon having a probable age of about 4 million years.

A period of erosion prior to eruption of the Guadalajara ignimbrite is evident near Río Blanco and also northwest of Tesistan, where the San Gaspar ignimbrite was largely but not entirely removed before emplacement of the younger ignimbrite. Also on the southern flank of Mesa Colorada about 3 kilometers northwest of La Experiencia, Guadalajara ignimbrite overlaps a remnant of San Gaspar to rest directly on upper Miocene rhyolite. But near La Experiencia both northward and eastward, more than 50 meters of volcaniclastic strata and basalt occur between the two ignimbrites, and the underlying San Gaspar ignimbrite appears uneroded. The erosion that preceded eruption of the Guadalajara ignimbrite probably was triggered in some areas by small scale faulting, but evidence of any large displacements or conspicuous warping or tilting during this interval is lacking. Indeed, the relatively uniform altitude and the subhorizontal attitude of the San Gaspar ignimbrite indicate no significant deformation of the Guadalajara region during the last 5 million years, apart from whatever vertical change initiated the late rejuvenation of Río Grande de Santiago.

Overlying the Guadalajara ignimbrite in Arroyo San Lorenzo west of Tesistan is a sequence of siliceous tuffs about 100 meters thick, including several ash flows. The sequence is capped by dacitic lava presumably correlative with that comprising Cerro Tepopote. Oligoclase from pumice in the youngest ash flow beneath the dacite gave a potassium-argon age of 3.1 x 10^6 years (55-25, Table 1). The apparent westward increase in volcanic units of approximate Guadalajara age may indicate that the locus of eruptions lay to the west at that time.

Most of the vulcanism younger than the Guadalajara ignimbrite has been concentrated along or near a narrow zone that trends west-northwest and is clearly delineated by three basaltic cones at the southern edge of Guadalajara and by additional cones aligned along it for about 40 kilometers farther southeast (Fig. 1). West of the city the zone includes a basaltic center near the junction of highways 15 and 70, and the rhyolitic complex of Sierra La Primavera is centered close to it. Presumably this zone is the extension of the regional volcanic belt that continues northwestward to the continental margin, marked by Volcán de Tequila, volcán Ceboruco, and other large stratovolcanoes of andesitic composition. About 40 kilometers southeast of Guadalajara, the zone intersects a belt of east-west normal faulting that continues eastward but is here conspicuously represented by displacement of the basaltic cone Cerro El Molino (Fig. 1) and by the large east-west graben enclosing Lago de Chapala a few kilometers farther south.

Except at Sierra La Primavera where mildly peralkaline high-silica rhyolites were erupted (Mahood, 1980b), the young volcanic activity has produced basic flows, including both basalts and basaltic andesites, composed largely of labradorite or calcic andesine and augite. Most of these flows are porphyritic containing small phenocrysts of plagioclase and olivine; hypersthene phenocrysts are common, and hornblende phenocrysts occur in a few andesites. The principal mafic mineral, diopsidic augite, characteristically occurs as a groundmass phase. Most groundmass textures are intergranular or intersertal; ophitic and hyalopilitic textures are not common. Table 2 records the chemical analyses and norms of the following four representative samples.

Basaltic andesite (76-3) from the cone immediately east of Juanacatlán (Fig. 1) is quartz normative but nevertheless contains sparse phenocrysts of olivine. Its mode consists of calcic andesine (An_{45-50}) about 70%, augite about 25%, olivine 1-2%, and numerous opaque oxide grains and apatite needles. The least siliceous of the four analyzed samples (995-33) represents an olivine basalt flow at the rim of the Santiago canyon north of Amatitlán. Its mode is olivine about 5%, labradorite about 65%, augite about 20%, opaque oxides about 10%. Two of the analyzed samples are essentially saturated tholeiitic basalts having SiO_2 contents intermediate to those of the preceding flows. One of these (992-182) represents basalt exposed beneath sierra La Primavera rhyolite in the southwestern part of that complex; the other (SC15) represents the uppermost flow in the canyon northwest of Tequila.

Volcanism along the young volcanic zone has continued, at least intermittently, from late Pliocene time almost to the present day. Basalt from the eruptive center just northwest of sierra La Primavera gave an age of about 1.8 x 10^6 years (995-35, Table 1). Basaltic andesite from the cone east of Juanacatlán gave an age of about 1.4 x 10^6 years (76-3, Table 1). Olivine basalt at the rim of the Santiago canyon north of Amatitlán was dated as about 0.5 x 10^6 years old (995-33, Table 1); canyon cutting here is younger than this flow.

At sierra La Primavera, volcanic activity has occurred during the last 140 000 years. Eruption 95 000 years ago of approximately 40 km^3 of high-silica rhyolite as the Tala tuff led to collapse of a caldera 11 kilometers in diameter. Subsequent eruptions of lava domes and flows occurred approximately 75 000, 60 000, and 30 000 years ago (Mahood, 1980b). Basaltic cinder cones overlying Tala tuff south of sierra La Primavera and basalt inclusions, incorporated while molten, in the young Primavera lavas are indication that mantle-derived basaltic volcanism continues in the Guadalajara area.

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