Geology of the boundary between the Sierra Madre Occidental and the Trans-Mexican Volcanic Belt in the Guadalajara region, western Mexico

Andrea Rossotti[1], Luca Ferrari[2*], Margarita López-Martínez[3], and José Rosas-Elguera[4]

[1] Posgrado en Ciencias de la Tierra, UNAM, Campus Juriquilla, A.P. 1-742, 76001 Querétaro, Qro., México
[2] Centro de Geociencias, UNAM, Campus Juriquilla, A.P. 1-742, 76001 Querétaro, Qro., México,
[3] Departamento de Geología, CICESE, A.P. 2732, 22860, Ensenada, Baja California, México
[4] Centro de Ciencias de la Tierra, Universidad de Guadalajara, A.P. 4-045, 44840 Guadalajara, Jal., México
*e-mail: luca@unicit.unam.mx

ABSTRACT

To investigate the time-space relationship between the Sierra Madre Occidental (SMO) and the Trans-Mexican Volcanic Belt (TMVB), as well as the early volcanic activity of the TMVB, a field study was carried out in the region north of Guadalajara City, along the boundary between the two volcanic provinces. Detailed field mapping at 1:50,000 scale, supported by published and new isotopic ages allow to propose a new stratigraphy (30 lithostratigraphic units) and to clarify the volcanic evolution of the region. The SMO succession is made of about 400 m of regional ash flows tuffs of early Miocene age, capped to the south by a basaltic sequence for which we obtained an $^{40}Ar/^{39}Ar$ age of 21.8 ± 0.3 Ma. The SMO units are sub-horizontal north of García de la Cadena but dip up to 25° to the south of this town, where they are covered in unconformity by the TMVB volcanism.

A gap of about 10 Ma in the volcanism is observed between the two volcanic provinces. Volcanism pertaining to the TMVB is largely bimodal and can be divided into four stages: 1) a late Miocene mafic episode; it produced the Río Santiago group that consists of a >800 m thick basaltic succession extending toward the east into the Los Altos de Jalisco; 2) a latest Miocene (7-5 Ma) silicic episode with the emplacement of domes and flows that form the Guadalajara group; 3) an early Pliocene (4.7-3.7 Ma) episode characterized by the emplacement of ignimbrites that show evidence of mingling between a mafic and a silicic magma (San Gaspar and Guadalajara ignimbrites) and alkali-basalts with an intra-plate affinity (Mirador de Ixcatán basalts); 4) a late Pliocene to Pleistocene episode with the eruption of rhyolitic domes and flows (Cerro Chicharrón group) and alkali-basalts, also showing an intra-plate affinity (Santa Rosa basalts).

New K/Ar ages of 10.2 ± 0.4 and 7.5 ± 0.8 Ma, together with previous dates, confirm that most of the Río Santiago Group was emplaced between 11 and ~8 Ma. Its aggregate volume in the Guadalajara region is about 1,800 km^3. The silicic volcanism covers more than 1,000 km^2 and has an aggregate estimated volume of 300 km^3, which is about nine times the volume of magma extruded by the late Pleistocene La Primavera caldera. The vents of the silicic domes belonging to the Guadalajara group and Cerro Chicharrón group follow an average N-S trend, and represent the surficial expression of a long-lived silicic upper crustal chamber with the La Primavera caldera at its southern end. By contrast, the Mirador de Ixcatán and Santa Rosa alkali-basalts are associated with the Plio-Pleistocene WNW-ESE trending faults of the Plan de Barrancas-Santa Rosa graben and their eruption coincide with the beginning of two extensional pulses along these faults. This agrees with models suggesting that mafic volcanism preferentially erupt along arc-parallel, high strain rate faults, whereas arc-normal, low strain rate faults control the location of more differentiated lavas. Magma mixing found in the San Gaspar and Guadalajara ignimbrites suggest that the arrival of mafic magma in the upper crust during the early Pliocene extensional phase triggered these pyroclastic eruptions.

Keywords: Geology, Sierra Madre Occidental, Trans-Mexican Volcanic Belt, Guadalajara, Mexico.

RESUMEN

Para investigar las relaciones espacio-temporales entre la Sierra Madre Occidental (SMO) y la Faja Volcánica Transmexicana (FVTM), así como la actividad volcánica temprana de la FVTM, hemos llevado a cabo un estudio de campo en la región al norte de Guadalajara, Jal., a lo largo de la frontera entre estas dos provincias volcánicas. Nuestra cartografía geológica detallada a escala 1:50,000, soportada por nuevas edades radiométricas y otras más publicadas, permite proponer una nueva estratigrafía (30 unidades litoestratigráficas) y aclarar la evolución volcánica de la región. La secuencia de la SMO está formada por aproximadamente 400 m de ignimbritas de edad Mioceno temprano, coronadas hacia el sur por una secuencia basáltica que hemos fechado por el método $^{40}Ar/^{39}Ar$ en 21.8 ± 0.3 Ma. Las unidades de la SMO son subhorizontales al norte de García de la Cadena pero se inclinan hasta 25° al sur de esta población, donde son cubiertas por el volcanismo de la FVTM.

Un hiatus de volcanismo de 10 Ma se observa entre las dos secuencias volcánicas. El volcanismo perteneciente a la FVTM es esencialmente bimodal y puede dividirse en cuatro estapas: 1) un episodio máfico del Mioceno tardío que produjo el grupo Río Santiago, representado por una secuencia basáltica que alcanza los 800 m de espesor y se extiende al este a Los Altos de Jalisco; 2) un episodio silícico entre 7 y 5 Ma con emplazamiento de domos y coladas riolíticas que forman el grupo Guadalajara; 3) un episodio del Plioceno temprano (4.7-3.7 Ma) caracterizado por la erupción de ignimbritas que muestran evidencias de mezcla entre un magma máfico y uno silícico (ignimbritas San Gaspar y Guadalajara) y basaltos alcalinos con una afinidad intraplaca (basalto Mirador de Ixcatán); 4) un episodio del Plioceno tardío hasta Pleistoceno con la erupción de domos y coladas riolíticas (grupo Cerro Chicharrón) y basaltos alcalinos, tambien con una afinidad intraplaca (basalto Santa Rosa).

Nuevas edades K/Ar de 10.2 ± 0.4 y 7.5 ± 0.8 Ma, junto con datos previos, confirman que el grupo Río Santiago se emplazó entre 11 y ~8 Ma. Su volumen agregado en la región de Guadalajara es de aproximadamente 1,800 km^3. En su conjunto, el volcanismo silícico cubre más de 1,000 km^2 y tiene un volumen estimado de 300 km^3, lo que representa casi nueve veces el volumen de magma asociado a la caldera pleistocénica de La Primavera. Los puntos de emisión y la distribución general del volcanismo silícico tienen una burda orientación N-S y se interpretan como la manifestación superficial de una cámara silícica de larga duración en la corteza superior, con la caldera de La Primavera en su terminación meridional. En contraste, los basaltos alcalinos Mirador de Ixcatán y Santa Rosa están asociados a las fallas plio-pleistocénicas de orientación ONO-ESE que bordean el graben Plan de Barrancas-Santa Rosa y su erupción coincide con el inicio de dos pulsos extensionales a lo largo de las mismas. Esto soportaría un modelo según el cual el volcanismo máfico se emplazaría preferentemente a lo largo de fallas con alta tasa de deformación paralelas al arco, mientras que fallas ortogonales al arco, con baja tasa de deformación, controlarían la emisión de lavas diferenciadas. La mezcla de magmas que presentan las ignimbritas San Gaspar y Guadalajara sugiere que el arribo de magma máfico a la corteza superior durante el episodio extensional del Plioceno temprano haya disparado estas erupciones piroclásticas.

Palabras clave: Geología, Sierra Madre Occidental, Faja Volcánica Transmexicana, Guadalajara, México.

INTRODUCTION

Cenozoic subduction-related volcanism in central Mexico has built two major volcanic arcs: the north-northwest-trending Sierra Madre Occidental silicic volcanic province (SMO) and the roughly east-west-trending Trans-Mexican Volcanic Belt (TMVB) (Figure 1). Ferrari *et al.* (1999) have shown that the locus of this volcanic activity has progressively rotated counterclockwise since late Oligocene. They further point out that the time of transition between these volcanic provinces may be placed in middle Miocene, when the dominant composition of the volcanic products switched from silicic to intermediate-mafic. Since late Miocene the arc had already a distribution similar to the Quaternary one.

The TMVB overlaps the SMO between the Pacific coast and the longitude of Mexico City. The details of the transition in space and time between the two arcs, however, are scarcely known. The western TMVB is one of the most complex areas in this respect. Geologic maps (Ortega-Gutiérrez *et al*., 1992; López-Ramos, 1995), traditionally considered silicic rocks as pertaining to the SMO and mafic rocks as belonging to the TMVB. A number of studies, however, have reported rhyolites and ignimbrites of early Pliocene age (Gilbert *et al*., 1985; Nieto-Obregón *et al*., 1985) as well as basaltic rocks of early Miocene age (Nieto-Obregón *et al*., 1985; Moore *et al*., 1994). Additionally, a recent regional geologic map (Ferrari *et al*., 2000a) shows that the northern part of the western TMVB, in the proximity of the SMO, is charac-

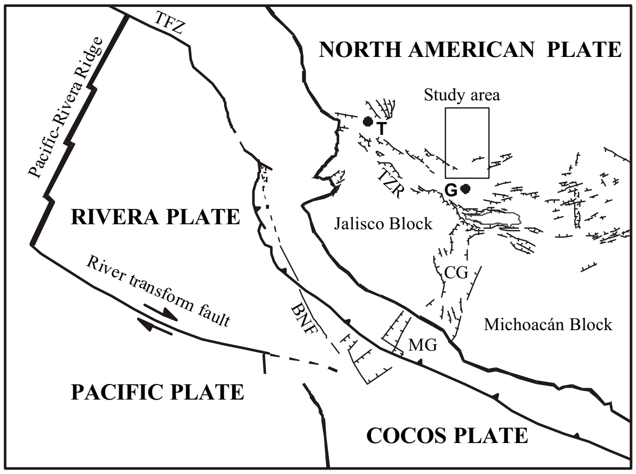

Figure 1. Tectonic setting of western Mexico with indication of the main plates. TFZ = Tamayo Fracture Zone; BNF = Barra de Navidad Fault; MG = Manzanillo Graben; TZR = Tepic-Zacoalco Rift; CG = Colima Graben; G = Guadalajara; T = Tepic.

terized by a bimodal volcanism (rhyolite/basalt) but a detailed mapping and volcanic stratigraphy for this area is not available.

On the other hand, the structure of the transition between the SMO and the TMVB is not completely understood. The SMO ignimbrites stand at a mean elevation of 2,100 m north of the western TMVB but are absent to the south, in the Jalisco block, where silicic volcanism is late Cretaceous to early Paleocene in age (Wallace and Carmichael, 1989; Righter *et al*., 1995; Rosas-Elguera *et al*., 1997). Moreover, Tertiary ignimbrites of the SMO were not found in the 2 to 2.8 km deep wells drilled by CFE in the Ceboruco, La Primavera and San Marcos areas (Ferrari, 1995; Ferrari *et al.,* 2000a) (Figure 2). Therefore some tectonic structure must exist beneath the northern part of the western TMVB in order to account for the absence of the SMO ignimbrites.

In this paper we present a detailed geologic study of an area covering the boundary between the SMO and the TMVB north of Guadalajara, which illustrates the transition in space and time between these two volcanic

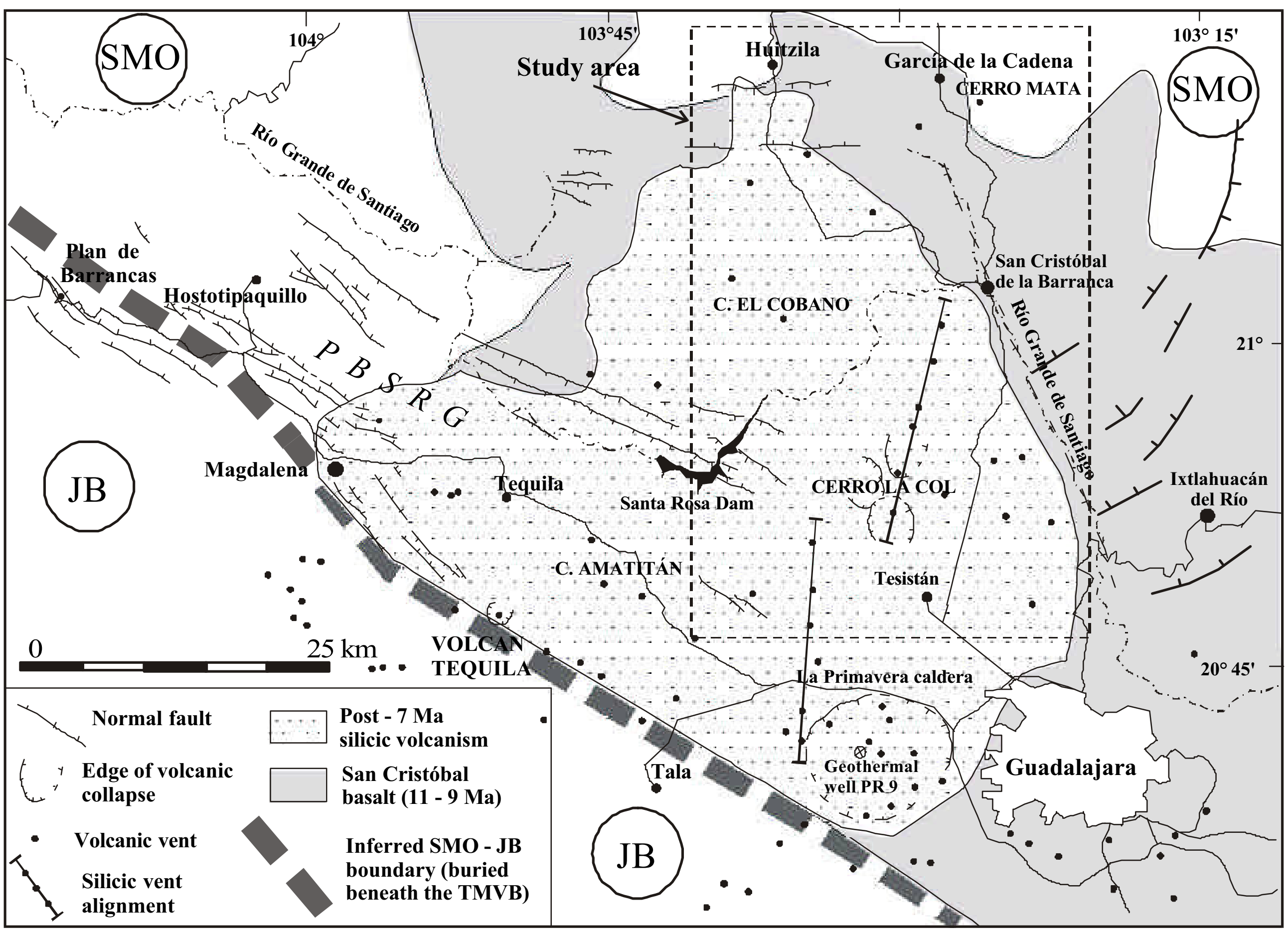

Figure 2. Volcanic and tectonic setting of the study area (adapted from Ferrari *et al*., 2000a, and Ferrari and Rosas-Elguera, 2000). SMO = Sierra Madre Occidental; JB = Jalisco block; PBSRG = Plan de Barrancas-Santa Rosa graben. Alignments of volcanic vents discussed in the text are also indicated.

Table 1. New age determinations for the study area

Sample	Site	Long. W	Lat. N	Rock Type	Method	Material dated	Age (Ma)	Error (Ma)
PR 103	Los Jacalitos, Jal.	103.45	21.12	Basaltic-andesite	$^{40}Ar/^{39}Ar$	gms	21.80 t_p	0.3
PR 67	Mesa Chinacatiahua, Zac.	103.61	21.18	Basalt	K/Ar	WR	10.20	0.4
PR 90	Arroyo Mezcala (near Cerro La Col), Jal.	103.61	21.18	Basalt	K/Ar	WR	7.50	0.8

Ages obtained at CICESE Geochronologic Laboratory by M. López. All errors are 1σ. The abbreviations are: t_p = plateau age with the error in J included. Detailed results are given in the Appendix 1. gms = groudmass, WR = Whole rock.

provinces. Our 1:50,000 scale geologic mapping coupled with new and published isotopic ages allows to elaborate a new volcanic stratigraphy and to better understand the tectonics of the boundary.

LOCATION AND METHODOLOGY

The study region lies at the eastern termination of the Plan de Barrancas-Santa Rosa graben (Ferrari and Rosas-Elguera, 2000) and to the north of the late Pleistocene La Primavera caldera (Mahood, 1981) (Figure 2). It is also at the eastern end of the western TMVB, where alkaline and calcalkaline volcanism has been emplaced concurrently during the last 5 Ma (Ferrari *et al.*, 2000a).

The study region covers an area of ~2,000 km^2 comprised in the 1: 50,000 scale topographic sheets García de la Cadena (F13-D45) and Tesistán (F13-D55), published by INEGI. The region is a semi-arid plateau at elevations ranging between 1,500 and 2,200 m that is cut by the deep canyon of the Santiago River, flowing at 700 m of elevation. Access is scarce in most of the area. The Guadalajara-Zacatecas federal highway 23 is the only paved road and crosses the area from north to south. From this road a number of all season dirty roads branch off and reach the main villages (Plate 1).

Table 2. Summary of $^{40}Ar/^{39}Ar$ results.

Temp °C	%^{39}Ar	t Ma[1]	%$^{40}Ar_{atm}$	$^{37}Ar_{Ca}/^{39}Ar_K$
500	1.3	12 ± 48	98.9	1.29
800	11.9	10 ± 1	76.8	1.65
1000	42.8	22.0 ± 0.3	25.8	1.57
1500	44.0	21.3 ± 0.3	13.1	3.19

t_i = 18.2 ± 0.9 Ma, [2]t_p = 21.8 ± 0.3 Ma, J = 1.291 ± 0.007 × 10^{-3}

All errors are reported at the 1 σ level. IUGS constants were used (Steiger and Jäger, 1977). t_i integrated and t_p plateau age include error in J factor; [1] age for individual fractions does not include error in J; [2] weighted mean of two fractions, see text for details.

The geologic mapping was first accomplished along these roads and then extended through several traverse on foot. The fieldwork was carried out during a total of four months.

We distinguished a total of 30 units based on unconformity boundaries, lithology, ages, and stratigraphic relationships. The rocks were studied in thin sections and analyzed for major and trace elements. A petrographic description is presented here whereas the geochemical results will be discussed in a forthcoming paper (Ferrari *et al.* in preparation). Our new volcanic stratigraphy is supported by 3 new $^{40}Ar/^{39}Ar$ and K/Ar ages (Table 1) plus several tens of published ages (compiled in Ferrari *et al.*, 2000a). The new ages were obtained at CICESE's geochronology laboratory using a MS-10 mass spectrometer; details on the methodology are given in Cerca-Martínez *et al.* (2000). The samples were step-heated between 700 and 1,500 ºC. A summary of the results of the $^{40}Ar/^{39}Ar$ experiment is given in Table 2. In the case of sample PR 103, notwithstanding that the $^{40}Ar/^{39}Ar$ data did not permit a realistic calculation of an isochron age, 3 fractions yielded an age of 21.4 ± 0.5 Ma, in agreement with the plateau age defined by 2 fractions representing > 86% ^{39}Ar released, we take the latter as our best age estimate for this sample (Table 1).

Silicic rocks dominate the region (75% of the area) whereas mafic flows constitute the remaining part (Plate 1). Most of the former consist of extensive sheets of rhyolitic flows with very low aspect ratio (thickness/area), which resemble pyroclastic flow deposits. However, the presence of a basal autobreccia and the absence of pumice and shards allowed to classify them as rhyolitic flood flows (in the sense of Henry and Wolff, 1992). Plate 1 shows the geology of the area. It includes several geologic profiles that illustrate the stratigraphic relationships observed in the field.

STRATIGRAPHY

In this section we describe the stratigraphic units recognized in the study area, which pertain to the SMO and the TMVB. SMO units are mostly exposed in the

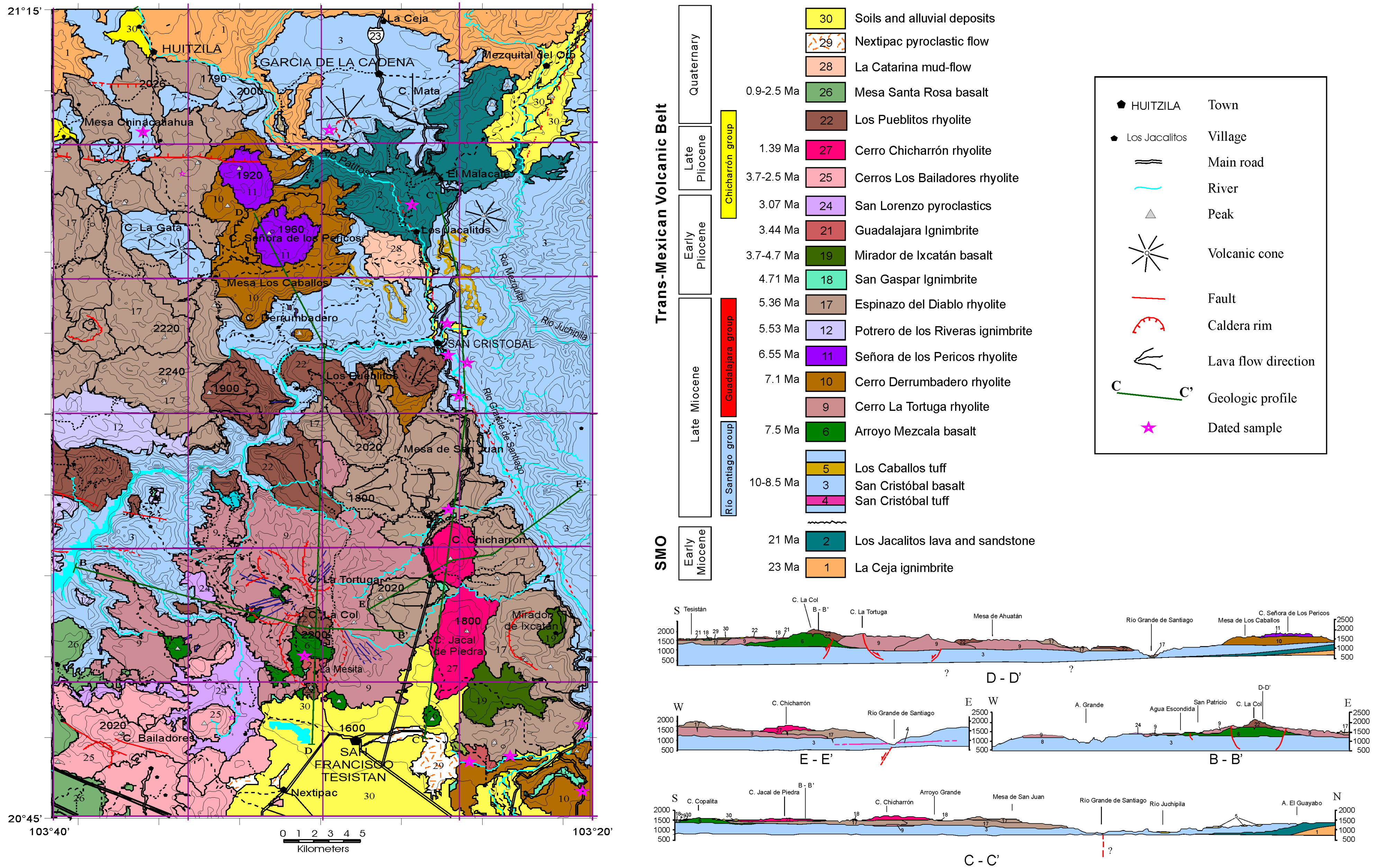

Plate 1. Geologic map of the San Francisco Tesistán - García de la Cadena area.

northern half of the region. A gap of about 10 Ma separates the two volcanic provinces in the area.

Sierra Madre Occidental

La Ceja ignimbrite

This is the oldest rock unit recognized and represents the typical ignimbrite succession of the SMO. In the study area it is exposed mainly in the valley cut by Patitos River (Plate 1), to the west of García de la Cadena, and consists of several ignimbritic sheets, each with thickness up to 20 m. Near the village of La Ceja, the unit is found beneath the San Cristóbal basalt unit. Here the succession is made of light pink, strongly welded ash flows that contain flattened pumice 2 cm in size without any preferential flow direction, and rare basaltic-andesitic lithics smaller than 1 cm in size. Some rare crystals are also present; they are sanidine, quartz, sericitized plagioclase and, rarely biotite. Some xenocrysts of iddingizited olivine are also found. The small size of lithics and pumice indicate that the unit is a distal facies of an ignimbrite.

Moore *et al.* (1994) obtained two identical $^{40}Ar/^{39}Ar$ ages of 22.99 ± 0.05 Ma for these ignimbrites in samples collected close to the site of El Tambor, about 8 km north of our study area. These ages agree with those obtained by Nieto-Obregón *et al.* (1981, 1985) in the Bolaños area to the north and in the Santa Rosa dam area to the southwest of the study area. These ignimbrites are part of a widespread pulse of silicic explosive activity now recognized along the entire southwestern SMO from Sinaloa to Jalisco (Ferrari *et al.*, 2002).

Los Jacalitos lava and sandstone

This sequence consists of dark gray lava flows and red sandstone that crop out in the canyon of the Cuitzila River between the village of Los Guajes and Los Jacalitos. The succession is also exposed along the federal highway 23 at the site El Malacate. The volcanic part of the succession is made of microcrystalline basaltic-andesitic lava flows characterized by pervasive fracturing and alteration. The rock is porphyritic with a microcrystalline groundmass. Phenocrysts consist of altered plagioclase or its relicts, pyroxene, sometimes twined, and iddingizited olivine. The flows are often covered by red arenaceous sediments and strongly welded andesitic conglomerate that toward the east of the study area can reach 200 m in thickness. These continental sedimentary beds were not distinguished in the map.

We have dated a groundmass concentrate from one of the lowermost flows of the succession by the $^{40}Ar/^{39}Ar$ method at 21.6 ± 0.3 Ma (Figure 3). This age agrees very well with several other ages of basaltic flows and shield volcanoes capping the SMO ignimbrites some tens of kilometers to the north of the study area in the Bolaños (Nieto-Obregón *et al.*, 1981; Scheubel *et al.*, 1988) and Teul areas (Moore *et al.*, 1994).

Trans-Mexican Volcanic Belt

The sandstone and conglomerate at the top of the Los Jacalitos unit bears evidence of a volcanic lull and a period of erosion and redeposition of the SMO volcanic succession. Indeed a gap of about 10 Ma exists in the study area between the SMO and the first volcanic activity related to the TMVB. The volcanic products of the latter were divided into three informal groups and 2 informal units.

Río Santiago group

In this group we include the dominantly mafic volcanic products, which marks the inception of the TMVB (Figure 4). The most extended unit is formed by basaltic flows that cover most of the study area and are well exposed along the Santiago and Mezquital river canyons, for most of their depth. Moore *et al.* (1994) named this main basaltic succession as San Cristóbal Basalts and estimated a total volume of about 1,800 km^3 for the succession. Ferrari *et al.* (2000b), however, showed that the basalts exposed in the Santiago river canyon continued up to 200 km to the east in the Los Altos de Jalisco region and to the south of Guadalajara, giving a maximum aggregate volume of around 3,000 km^3 for this succession. Ferrari *et al.* (2000b) further show that the basalts of the Río Santiago group have a calcalkaline to transitional character. Interbedded with the basalts are two

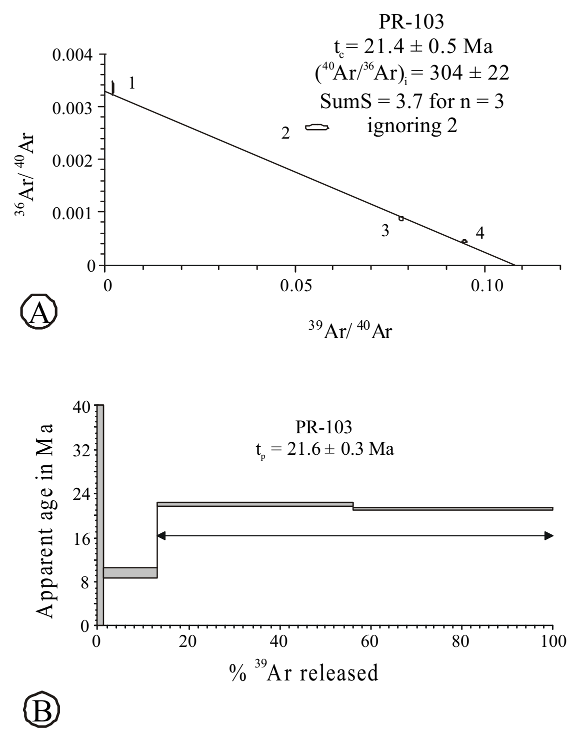

Figure 3. Isochron (a) and age spectrum (B) for sample PR 103. The errors are reported at the 1ó level. The widths of the boxes in the age spectrum indicate within-spectra errors, ignoring the uncertainty in J.

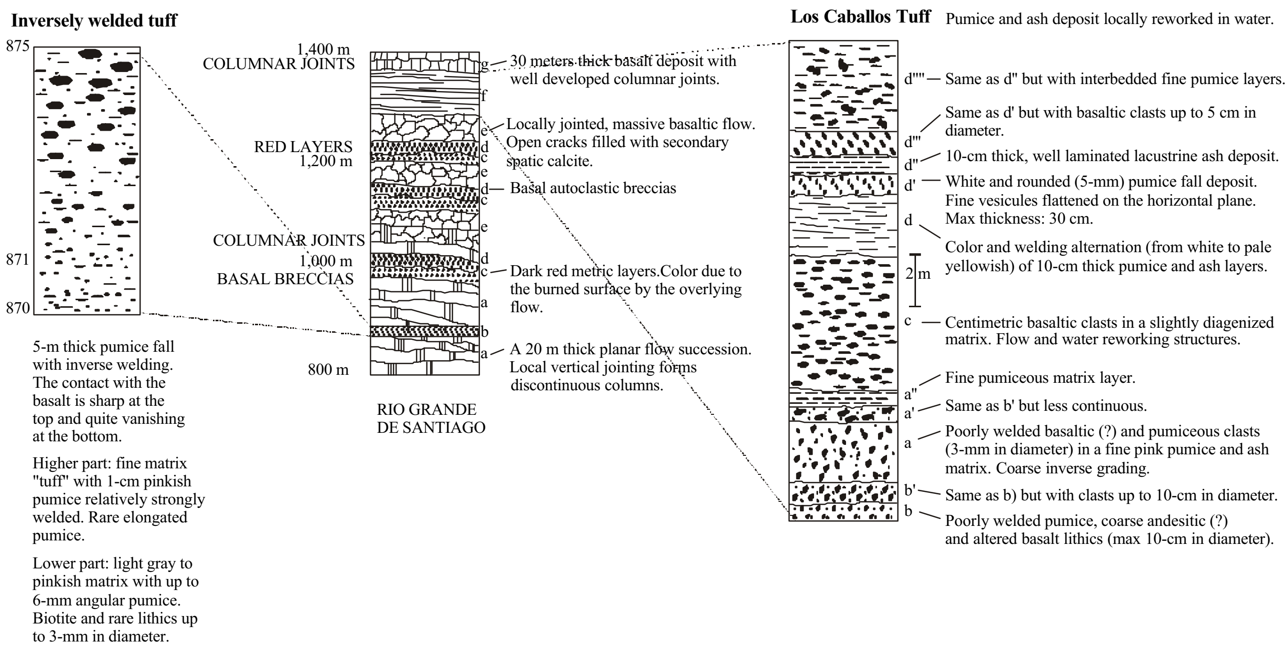

Figure 4. General stratigraphy of the Río Santiago group based on exposures 3 km to the southeast of San Cristóbal.

silicic stratigraphic markers named Inversely Welded Tuff and Los Caballos Tuff by Moore *et al.* (1994), found in the lower and in the upper part of the main basaltic sequence respectively.

San Cristóbal basalt. This basaltic succession constitutes the main body of the Río Santiago group and is well exposed in the Santiago river canyon from over 1,800 m down to the 900 m of the riverbed. The base is not exposed and the maximum observable thickness is 800 m. The unit is a massive sequence of 2 to 20 m thick basaltic flows (generally 5-10 m) often dipping 5°-8° toward the SSE. At the top of each flow it is often possible to find thin red layers due to the thermal alteration of the bed caused by the next flow coming over. The base shows autoclastic breccias due to the advancing of the flow. In the lower part of the succession, the basalt look massive and show rare vesicles filled by secondary mineralization. Petrographically, lavas are porphyritic with rare plagioclase and olivine phenocrysts. In the upper part, the basalt is more evolved; we found basaltic-andesites with abundant plagioclase and olivine, less altered that in the lower part of the section. These flows however have more fractures and abundant 2-3 cm vesicles filled by microcrystalline and rare spatic calcite. We observed a few feeding dikes in the lower Santiago river canyon, suggesting that the southernmost part of the sequence has a fissural origin. Several authors dated the basalts and obtained ages ranging between 11 and 8.5 Ma (Watkins *et al.*, 1971; Damon *et al.*, 1979; Moore *et al.*, 1994). The northern part of the succession originated from two small shield volcanoes located near García de La Cadena (Plate 1). Moore *et al.* (1994) dated one of this volcanoes at 10.99 ± 0.23 Ma, thus they constitute the initial activity of this mafic volcanism. To the west of these volcanoes there are several mesas of black and massive porphyritic basaltic flows with a maximum thickness of 400 m. Microphenocrysts are Carlsbad and polysynthetic twinned plagioclase (around 60% of the largest minerals) always smaller than 1 mm in length. We dated the basalt of Mesa Chinacatihua by K-Ar at 10.2 ± 0.4 (Table 1), confirming that these mafic flows are also part of the San Cristóbal basalt unit.

San Cristóbal tuff. We gave this name to a 2 to 8 m thick ignimbrite sheet with sharp and clear contacts, intercalated in the lower part of the San Cristóbal Basalts (Figure 4). The unit, also named the Inversely Welded Tuff by Moore *et al.* (1994), is easily observed along the federal highway 23 in the proximity of the San Cristóbal village on both sides of the Santiago river canyon (because of its limited thickness, this unit could not be shown in Plate 1). Pink and weak at the bottom, the layer turns dark red and relatively more welded at the top. The upper part is rich in flattened and rounded pumices, up to 1 cm in size, and rare fine (1 mm) mafic lithics. In the lower part are larger and sub-angular pumice, more abundant and larger (max. 3 mm) lithics and rare mica crystals. In thin section it is possible to see glass shards with sanidine phenocrysts, quartz, green augite, fayalite and rare basaltic fragments. Although the unit was dated earlier by Watkins *et al.* (1971), Moore *et al.* (1994) reported a more reliable 10.17 ± 0.04 Ma $^{40}Ar/^{39}Ar$ age, obtained on a sanidine concentrate. The peculiar characteristics of this layer make it an important and easy-to-detect marker for the lower part of the Río Santiago Group.

Los Caballos tuff. This unit crops out within the upper 100 m of the San Cristóbal basalts and is mainly observed north of the Santiago River, NW of the town of San Cristóbal (Plate 1). It is a 100 m thick pyroclastic sequence composed by white ash and pumice pyroclastic flows locally reworked in an underwater environment (paleo lake or river) (Figure 4). West of San Cristóbal, the tuffs are covered by about 100 m of flows belonging to the San Cristóbal basalt. To the south, however, they are directly capped by the younger silicic domes and flows. This implies a period of erosion and weathering before the emplacement of the following units.

Arroyo Mezcala basalt. The uppermost part of the Río Santiago group is made by a massive basaltic sequence that form small and only partly exposed lava moulds north of Tesistan in the arroyo Mezcala (Plate 1). No flows are observed in the available outcrops, suggesting that the unit could be a unique massive flow or a laccolith emplaced at very shallow depth. Apparently, the unit reaches 600 m in thickness, however the real thickness could be less due to southward tilting. This basalt shows red to red-green banding. Groundmass is aphanitic, with no visible crystals in hand specimen, apart from rare recrystalization white coating. In thin section, microphenocrysts of twinned plagioclase with increasing reabsorption can be observed. The outcropping area is 21 km^2. An average thickness of 250 m gives us a minimum volume of 5.2 km^3. We obtained a 7.5 ± 0.8 Ma K-Ar age for the basalt exposed at arroyo Mezcala (Table 1). Accordingly, these basaltic lavas could be correlative with the upper part of the San Cristóbal basalt that cover the Los Caballos tuff to the north of Río Santiago.

Guadalajara group

We use this informal classification to define the older silicic domes and flows that also do not show evidence of magma mixing. Stratigraphically, they cover the Río Santiago group and are overlain by the San Gaspar Ignimbrite; its age ranges between 7 and 5 Ma. The Guadalajara group covers more than 750 km^2 and has an estimated volume of 212 km^3 (Table 3).

Cerro La Tortuga rhyolite. This is an extensive rhyolitic complex (210 km^2) (Figure 5) located a few kilometers north of the town of Tesistán (Plate 1). Cerro La Tortuga is made by an alternation of viscous rhyolitic lava flows and pyroclastic flows, which resulted from the coalescence of several large domes. Some of the domes collapsed toward the periphery producing deposits of ash and block flows. Several rhyolitic dikes are exposed in the collapsed area. They converge toward an area between Cerro La Col and Cerro La Tortuga (Figure 5), suggesting the existence of a central feeding conduit and a unique magmatic chamber at depth. The base of Cerro La Tortuga is dominated by pyroclastic flows, which likely represent the early stage of high energy and gas rich eruptions. In the lower part, the pyroclastic flows are massive with glassy brown groundmass, rare quartz crystals, altered feldspar up to 5 mm in length and vesicles elongated in the flow direction. In the upper part, the groundmass is similar but vesicles are absent. Rhyolitic lava flows are frequently brecciated with black glassy micro-blocks with a maximum of 15 cm in size. They often show alteration bands with development of clay minerals. Strongly welded and up to few meters thick ash and block flows deposits related to dome col-

Table 3. Volume estimation for the geologic units of the study area.

Unit name	Inferred area (km^2)	Max thickness (m)	Mean thickness (m)	Computed volume (km^3)
Cerro Chicharron Unit	19.000	400	300	5.700
Cerro Los Bailadores Unit	154.500	500	200	30.900
San Lorenzo Unit	187.000	200	100	18.700
Los Pueblitos Unit	81.250	300	200	16.250
Total for Chicharrón group				**71.550**
San Gaspar Ignimbrite	1000.000	25	15	15.000
Espinazo del Diablo Unit (North)	240.000	700	250	60.000
Espinazo del Diablo Unit (South)	180.500	600	250	45.125
Cerro Derrumbadero Unit	130.500	400	300	39.150
Cerro La Tortuga Unit	210.000	800	300	63.000
Señora de Los Pericos Unit	16.000	400	300	4.800
Total for Guadalajara group				**212.075**
Total silicic rocks	**2218.750**			**298.625**
Río Santiago Group	4000.000	600	450	1800.000

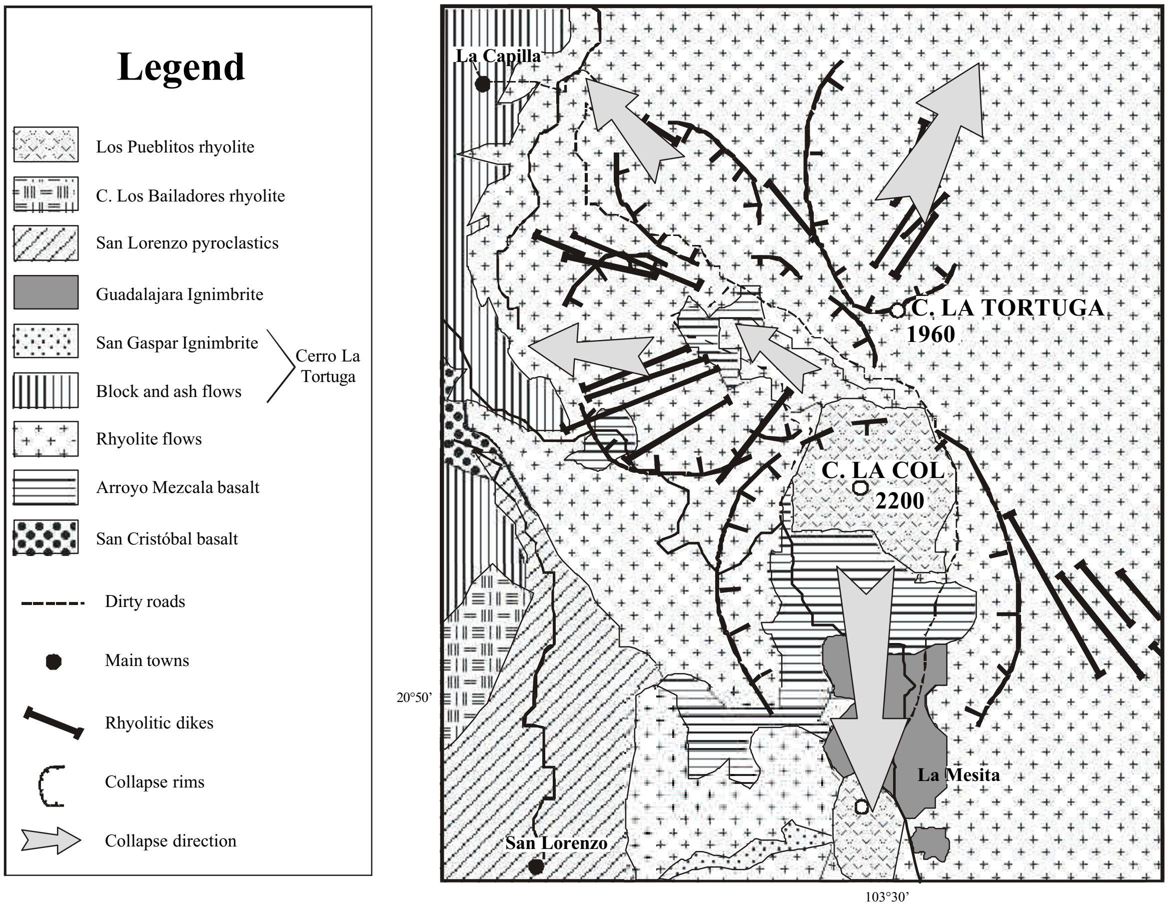

Figure 5. Geologic map of the Cerro La Tortuga area with details of the dome collapses.

lapse are also found locally. A fine silicic matrix sustains clasts up to 20 cm in size of rhyolite and, rarely, basalt. The latter appear to be fragments dragged from the underlain San Cristóbal basalt over which the flow has passed.

Cerro Derrumbadero rhyolite. This is a giant exogenous dome located about 10 km southwest of García de la Cadena (Plate 1) which reaches 500 m of thickness and a volume of about 39 km^3 (Table 3). The erosion produced by the Santiago River has exposed the internal structure of the southern side of the dome for over 8 km. Spectacular columns, with a diameter of 40 to 60 cm and up to 100 m high can be observed. Towards the top of the dome, the columnar joints are replaced by glassy rhyolite lava with spherulites. In thin section, the rock shows flow microstructures and a porphyritic texture with a microcrystalline groundmass with minor olivine and altered plagioclase. Phenocrysts of biotite (20%) and feldspar (80% plagioclase) are abundant and reach 4 mm in length.

Cerro Señora de los Pericos rhyolite. Two peaks, Señora de los Pericos and El Charco del Perro domes, overlap the Cerro Derrumbadero unit. They are typical endogenous rhyolitic domes with abundant black, green and gray-blue obsidian veins intruded into the thick rhyolite lava. A total estimated area of 16 km^2 and an average thickness of 300 m yield a calculated total volume of 4.8 km^3 (Table 3).

Potrero de los Riveras ignimbrite. It is a silicic ash flow tuff mostly exposed on the northern side of the Santiago River to the west of the study area, in the Santa Rosa dam area. It overlays the San Cristóbal basalt and, south of the reservoir, is covered by the San Gaspar Ignimbrite. The Potrero de los Riveras ignimbrite sequence has a maximum thickness of 500 m north of the Santa Rosa reservoir but thins to just 30 m to the south. At the base of the sequence are 6 m of reworked pumices and lithic fragments in a fine ash matrix. The following 30 m are primary pyroclastic flows deposits with 15-20 cm thick layers with white to red obsidian clasts, up to 10 cm in size, and gray-blue shards in a red matrix. The rest of the unit is inaccessible but judging from fallen blocks appears to consist of a massive and welded ignimbrite. Nieto-Obregón *et al.* (1985) dated the ignimbrite at 5.53 ± 0.01 Ma by K-Ar methods just to the north of the

Santa Rosa dam. In the same place Ferrari and Rosas-Elguera (2000) estimated 450 m of vertical offset of the unit caused by the Santa Rosa WNW-ESE trending normal fault system.

Espinazo del Diablo rhyolite. The unit is composed by at least 15 exogenous domes with associated large flows emplaced on the western side of the Santiago River valley and west of Cerro Derrumbadero (Plate 1). They sit on the Río Santiago group and, in the northern part, partially cover the Cerro Derrumbadero and Señora de los Pericos silicic flows and domes. Towards the south, they are covered by the Los Pueblitos and Chicharrón Quaternary domes. The domes cover an extension of about 460 km^2, with an average thickness of 250 m (but with a maximum of 900 m) that gives an estimated total volume of around 105 km^3 (Table 3). The lava forming the domes displays an increasing viscosity upsection. Low viscosity lavas are widespread at the base, whereas more viscous lavas typically constitute a mould at the top of the structure. Ash and pumice flow deposits are found at the base of the domes and constitute the first products of the whole eruptive event. A 300 m thick and low viscosity rhyolitic flow, resembling a rhyolitic flood flow, forms the lower part of the Mesa de San Juan plateau, where an outstanding array of columnar joints is exposed (Figure 6). A partially reworked pumice flow deposit caps the columns. It is made of millimetric to centimetric black elongated pumice that forms a 10 m thick, dark brown layer. The top of the layer is covered by another rhyolitic flow with smaller columnar joints (tens of meters) and flow structures. The topmost layer is a massive dome-like structure, which lacks columnar jointing, and show contorted flow structures. Gilbert *et al.* (1985) dated the base of two of the largest domes exposed in the western side of the Santiago River at 5.47 ± 0.17 and 5.19 ± 0.06 Ma.

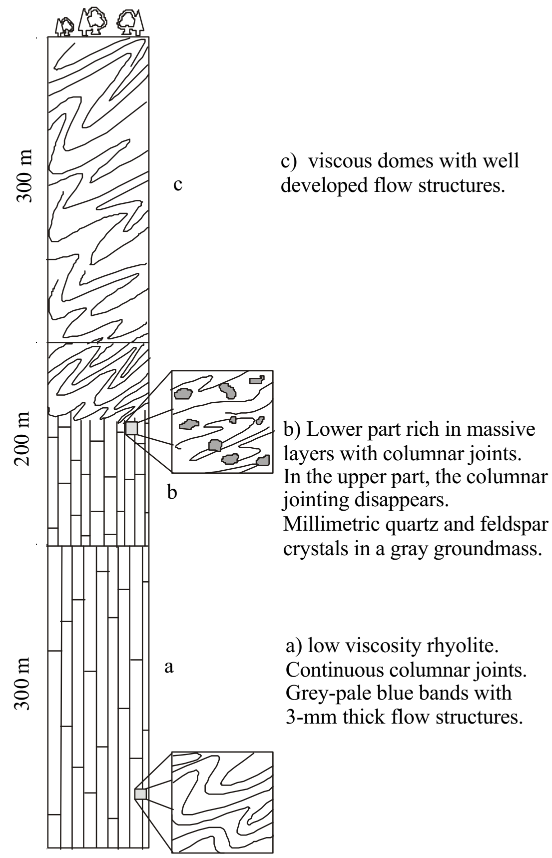

Figure 6. Stratigraphic section of Mesa de San Juan rhyolitic dome.

San Gaspar Ignimbrite

This is a distinctively dark and welded ignimbrite first described by Gilbert *et al.* (1985), which crops out mostly in the southern part of the area between 1,400 and 1,600 m of elevation. In the study area, the ignimbrite is only 10 to 25 m thick but often forms well-preserved hard caps above the underlying units. It overlies the Mesa de San Juan rhyolites as well as Cerro La Tortuga and Potrero de los Riveras pyroclastic flows.

The ignimbrite is glassy, strongly welded and gray-black in color and contains abundant clear and dark fiammae. The dark fiammae contain mainly plagioclase phenocrysts, rhombic and monoclinic pyroxene, hornblende and biotite. The clear fiammae are up to 20 cm long, contain twinned and zoned plagioclase phenocrysts and some centimetric basaltic xenoliths. As a whole, the rock has an andesitic composition but the clear glass has 5% less silica and more CaO, MgO and FeO than the dark glasses (Gilbert, *et al.*, 1985), suggesting that the ignimbrite is the result of a magma mixing process. Gilbert, *et al.* (1985) estimated an original extension of 1,000 km^2 and a mean thickness of 15 m, which give a volume of 15 km^3. Watkins *et al.* (1971) and Gilbert *et al.* (1985) dated the ignimbrite 4.80 ± 0.1 Ma and 4.71 ± 0.07 Ma, respectively. The San Gaspar Ignimbrite thickens towards the south, which suggests that its source was located in the Guadalajara city area.

Mirador de Ixcatán basalt

North of Guadalajara, on the western side of the Santiago River, several basaltic flows cover the thick rhyolite flow of the Mesa de San Juan (Espinazo del Diablo rhyolite) at the site known as Mirador de Ixcatán (Plate 1). Similar basalts are also exposed on the opposite side of the valley, to the east of the study area. The rocks are porphyritic olivine basalt with abundant megacrysts of a slightly zoned and up to 3 cm long plagioclase. The olivine-bearing groundmass is slightly altered to iddingsite and also contains pyroxene, Fe-oxides, micas, and altered glassy shards. Within these megacrysts-bearing lavas we also find some flows with plagioclase phenocrysts, orthopyroxene and augite. The megacrystic basalts were called Guadalajara Basalts by Moore *et al.* (1994), who show that they have an intraplate affinity. Moore *et al.* (1994) and Gilbert *et al.*

(1985), reported ages between 4.7 ± 0.1 and 3.7 ± 0.1 Ma for these basalts.

Guadalajara Ignimbrite

This ignimbrite also was first defined by Gilbert *et al.* (1985), who called it Guadalajara because it was used as a building stone of many ancient buildings of the city. The ignimbrite is found at several outcrops in the northern part of the city and in some isolated spots within the study area. Particularly at La Mesita (Plate 1), the ignimbrite can be observed covering the Arroyo Mezcala basalt and the Cerro La Tortuga rhyolite. Strongly welded, light brown to light gray in color, the ignimbrite is also characterized by the presence of two distinct types of fiammae sustained by a fine matrix composed by light and brown shards and feldspar microcrysts. The brown shards are made of microporous trachytic glass containing feldspatic microphenocrysts. The clear shards, on the other hand, are rhyolitic peralkaline in composition and do not show phenocrysts (Gilbert *et al.*, 1985). Although it is always possible to distinguish the two types of glass, the fiammae are often devitrified, axiolithic with small cavities filled with quartz and feldspars. The presence of glass with two distinct compositions suggests, as in the case of the San Gaspar Ignimbrite, that its eruption was triggered by the arrival of a more mafic magma in a silicic chamber. The maximum size of the fiammae increases towards the south, pointing to a source in the Guadalajara city area. Gilbert *et al.* (1985) dated the ignimbrite at the Río Blanco and La Esperancia quarries obtaining K/Ar ages of 3.23 ± 0.08 Ma and 3.44 ± 0.1 Ma, respectively.

Cerro Chicharrón group

Widespread silicic volcanic activity occurred also after the emplacement of the San Gaspar and Guadalajara ignimbrites and produced many rhyolitic domes to the north of Guadalajara. We have informally grouped this silicic activity into the Cerro Chicharrón group, which consists of four geologic units.

San Lorenzo pyroclastics. Several pyroclastic flows and fall deposits crop out within the Arroyo San Lorenzo river basin (Plate 1). The sequence has a maximum thickness of 200 m and we estimated a volume of 4.1 km^3 (Table 3). The only clear contact at the base of the unit is with Cerro La Tortuga rhyolite that created a sort of barrier to the incoming pyroclastic flows. The unit is covered by the Cerro Los Bailadores rhyolite and the Mesa de Santa Rosa basaltic plateau. Starting from the lower part of the succession we found a pale gray ignimbrite with abundant brown pumices up to 10 cm in length, and fibrous bi-colored (black and light brown) pumice up to 3 cm in length. Also present are basaltic and rhyolitic lithic fragments, up to 10 cm and 6 cm long, respectively. A reworked and unsorted clastic deposit with fragments up to 2 cm in size follows the ignimbrite. This is covered, in turn, by a layer of reworked pumices 1 to 10 mm in size with a marked normal gradation. This is followed by another ignimbrite similar to the first one, covered by a clear, massive pumice layer up to 10 cm in thickness. The uppermost part of the sequence is formed by a dark gray to brown ignimbrite with sub-rounded brown flattened pumices up to 15 cm in length. Gilbert *et al.* (1985) obtained a K/Ar age of 3.07 ± 0.1 Ma for an oligoclase concentrate obtained from the pumice layer.

Cerro Los Bailadores rhyolite. Cerro Los Bailadores is a large dome complex that covers the pyroclastic deposits of the Arroyo San Lorenzo unit just to the northwest of Sierra La Primavera (Figure 2). The domes cover about 154 km^2 with maximum thickness of 500 m and an estimated volume of 30 km^3 (Table 3). The lavas are strongly welded and present well developed columnar joints. Silicic pyroclastic flows and pumice fall deposits are often observed at the base of the domes with a maximum thickness of 100 m. The domes are made of massive rhyolite lava with phenocrysts of quartz, feldspar and biotite 3 mm in size. Partially oxidized red and yellow bands are also observed within the rock. In thin section, the lava is porphyritic with a microcrystalline matrix. Phenocrysts are mostly made of euhedral, zoned and twinned plagioclase. Slightly altered rhombic pyroxenes and olivine xenocrysts are also found. The age of the unit is bracketed between the 3.07 ± 0.1 Ma of the Arroyo San Lorenzo unit and the 2.5 ± 0.06 Ma of the overlaying Santa Rosa basalt.

Cerro Chicharrón rhyolite. This unit consists of two well-preserved exogenous domes, Cerro Chicharrón and Cerro Jacal de Piedra, aligned in a NNW-SSE direction northeast of Tesistán (Plate 1). The domes sit on top of the Mesa de San Juan silicic flows (Espinazo del Diablo rhyolite) and form a 300 m thick, flat laying mesas. They cover an area of 19 km^2 with a volume of 5.7 km^3 (Table 3). The domes are made of welded columnar-shaped rhyolite overlying a 7 m thick pumice-rich deposit (described in detail in Figure 7) that we interpret as an initial fall deposit followed by reworked material. Spinnler *et al.* (2000) dated by the K/Ar method a sanidine separate from the Cerro Chicharrón rhyolite at 1.4 ± 0.5 Ma.

Los Pueblitos rhyolite. We included in this unit six rhyolitic flows that cover the Espinazo del Diablo unit in the central part of the study area on both sides of the Santiago River (Plate 1). The flows show a very well preserved morphology and cover an area of 1 to 8 km^2 each. The aggregate volume is estimated in about 16 km^3 (Table 3). Fine and relatively welded pumice layers are frequently observed at the base of the flows. These are probably pumice fall deposits related to the initial explosive activity that preceded the emplacement of the flows. The flows are made of low viscosity and porphyritic rhyolitic lava, light brown to cream in color

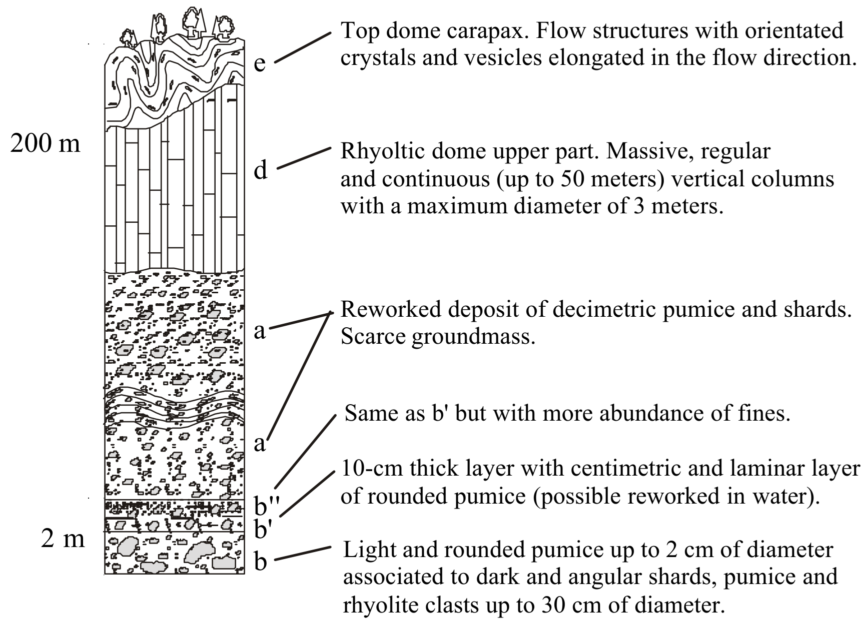

Figure 7. Stratigraphic section of Cerro Chicharrón rhyolitic dome.

and with a fine groundmass. Phenocrysts are white Carlsbad twinned feldspars, gray-blue quartz up to 3 mm in size and subordinate biotite. The flow passing through the Los Pueblitos village includes decimetric to metric basaltic enclaves mingled with the rhyolitic lava. This suggests that injection of the basaltic magma into the silicic magma chamber may have triggered the eruption. Although no isotopic age is available for the Los Pueblitos flows, the fact that they almost reach the present riverbed of the Santiago River suggests that they were emplaced in the late Pleistocene. They could be concurrent with the rhyolitic domes forming the base of Tequila volcano, about 20 km to the west, which were dated between 0.9 and 0.23 Ma by Wallace and Carmichael (1994).

Santa Rosa basalt

This is a succession of mafic lava flows mostly exposed to the west of the study area where they form the homonymous plateau comprised between the Tequila volcano to the south and the Santiago River to the north (Figure 2). Remnants of the flows also constitute hanging terraces to the north of the river. The flows are made of alkali-basalt with abundant plagioclase phenocrysts and rare olivine and augite. In thin section the groundmass consists of plagioclase, augite, olivine, iron oxides and, seldom, black-brown glass. The basaltic flows attain an aggregate thickness of over 150 m. Several authors have dated the Santa Rosa basalt by the K/Ar method. Apart from the age of 2.5 ± 0.06 Ma obtained by Nieto-Obregón *et al.* (1985) for one of the lowermost flows, the rest of the ages range between 1.34 ± 0.20 Ma and 0.91 ± 0.20 Ma (Damon *et al*., 1979; Nieto-Obregón *et al*., 1985; Nixon *et al.,* 1987).

Quaternary continental deposits

We differentiate three units: La Catarina, Nextipac, and soils and alluvial recent deposits. The first two are volcano-sedimentary deposits with an alternation of millimetric to centimetric pumice layers, supported by a fine pumice and ash matrix, and rounded pumice layers with no matrix. The third unit blankets the Tesistán area; this deposit is the result of superficial alteration of volcanic products.

TECTONICS

Faults

Although the study area is surrounded by several fault systems (Figure 2), only a few faults can be observed within it. At the southwestern corner of the area two WNW-ESE trending normal faults down drop the Cerro Los Bailadores dome complex to the SSW at least 250 m. The faults represent the eastern termination of the Santa Rosa normal fault system described by Ferrari and Rosas-Elguera (2000). West of the town of García de la Cadena (Plate 1), two E-W trending normal faults limit a 13-km long and 5-km wide graben structure. The normal faults cut the late Miocene San Cristóbal basalt and the early Pliocene Espinazo del Diablo rhyolitie and their scarps are 120 m high at most.

A major NNW trending lineament is observed for at least 40 km from Guadalajara to San Cristóbal (Plate

1). This lineament, however, is poorly understood because seismic and geologic data apparently give contradictory evidence. We infer a possible normal fault because historical and instrumental seismicity coincides to a marked and long rectilinear segment of the Santiago River. Indeed some large landslides of probable Holocene age are observed along the river canyon. In addition, the village of San Cristóbal was almost completely destroyed during an earthquake swarm in 1875, which was also felt in Guadalajara (Ordoñez, 1912). Another seismic swarm occurred in May-July, 1912, with a largest event of intensity VIII on July 20, 1912, located near Guadalajara (Ordoñez, 1912). Local seismic network set up temporarily by Comisión Federal de Electricidad between Guadalajara and San Cristóbal recorded many small seismic events consistently aligned along the inferred fault (M. Delgado-Vásquez, Depto. Sismotectónica de CFE, personal communication). In contrast, although the Espinazo del Diablo rhyolite appears bounded by the trace of the inferred fault, no fault planes were observed in these rocks and the San Cristóbal tuff, interlayered in the San Cristóbal basalt, outcrops at elevations no more than 50 m apart between the western and eastern side of the Santiago River canyon. We concluded that the fault could be an ancient feature reactivated in recent times. Failure to find the actual fault planes can be due to the unconsolidated fluvial deposits of the Santiago River, which largely cover the inferred fault zone.

Volcanic vents

Figure 2 shows the distribution of the late Miocene to Quaternary volcanic vents in the study area and its surroundings. Nakamura (1977) first proposed the general hypothesis that the vents of monogenetic volcanoes are usually aligned perpendicular to the minimum horizontal principal stress direction ($\sigma_{h\,min}$). The hypothesis has been validated in many different tectonic settings; furthermore monogenetic vent alignments have been used to construct the World Stress Map (Zoback, 1992). Here we have considered also the vents of the rhyolitic domes, since they are usually emplaced during a single volcanic episode, and, in a first approximation, they may be considered as monogenetic volcanic structures. We recognized at least two possible alignments of domes striking almost N-S (Figure 2). The longest alignment has a N14° direction, and involves 6 vents. If continued to the SSW it cuts the La Primavera caldera and reaches a length of 40 km. The other alignment crosses five vents and has a N344° trend. With these data alone we could conclude that the latest Miocene to Quaternary extensional direction strikes almost E-W in the study area. This result, which is in apparent contrast with the regional pattern of deformation depicted by Ferrari and Rosas-Elguera (2000), will be discussed in next section.

Dikes

Dike swarms were also assumed to be intruded perpendicular to the $\sigma_{h\,min.}$ Delaney *et al.* (1986), however, demonstrate that this is not always the case because dikes may also intrude pre-existing fractures not perpendicular to the $\sigma_{h\,min}$ under a variety of deviatory stress values. Furthermore, worldwide examples have shown that dikes are intruded radially in large volcanic edifices. In the study area, the radial collapses of the Cerro La Tortuga dome complex expose many rhyolitic dykes with dominant orientation N26°E, N140°E N240° E and N299°E (Figure 8). These preferential directions, however, appear to be the result of the present exposure only. In addition, the fact that the dykes converge to the center of the La Tortuga complex strongly suggests that their intrusion at shallow level was guided by the lithostatic load of the volcanic edifice and/or by the vertical pressure of a shallow magma chamber. Therefore, we consider these dykes as the expression of a local state of stress unrelated to the regional one.

DISCUSSION AND CONCLUSIONS

The boundary between the SMO and the TMVB

In the study area the ignimbrite succession of the SMO is overlain by the TMVB a few kilometers to the north of San Cristóbal (Plate 1). The southernmost ignimbrites of the SMO, however, are exposed at the Santa Rosa dam (Figure 2), about 10 km to the west of the southern boundary of our study area, where Nieto-Obregón *et al.* (1985) dated it at about 17 Ma. To the south of the TMVB, ignimbrites correlated to those of the SMO only outcrop about 35 km south of Lake Chapala, (Ferrari *et al.*, 2002), whereas in the Jalisco block all these silicic rocks are late Cretaceous to early Paleocene in age (Wallace and Carmichael, 1989; Righter *et al.*, 1995; Rosas-Elguera *et al.*, 1997). Furthermore, the geothermal wells drilled by CFE in the La Primavera caldera (location in Figure 2) encountered early Eocene andesites and a granite correlated to the Jalisco block just below the Río Santiago basalts at depth of 2,000 to 2,900 m (Ferrari *et al.*, 2000a). This led Ferrari *et al.* (2000a) to conclude that a major structural discontinuity must exists below the TMVB and, particularly, beneath the Tequila volcano. Although in the study area no faults bound the SMO ignimbrites, they are observed to dip southward beneath the San Cristóbal basalts south of the town of García de la Cadena. This suggests either that a) a south dipping oblique thrust, and/or b) a north dipping normal fault, is buried beneath the San Cristóbal basalt to the south. Since west of Tequila the tectonic contact between the SMO ignimbrites and the Cretaceous batholith of the Jalisco block is a middle Miocene left-lateral oblique thrust later reactivated by right-lateral transtension (Ferrari, 1995;

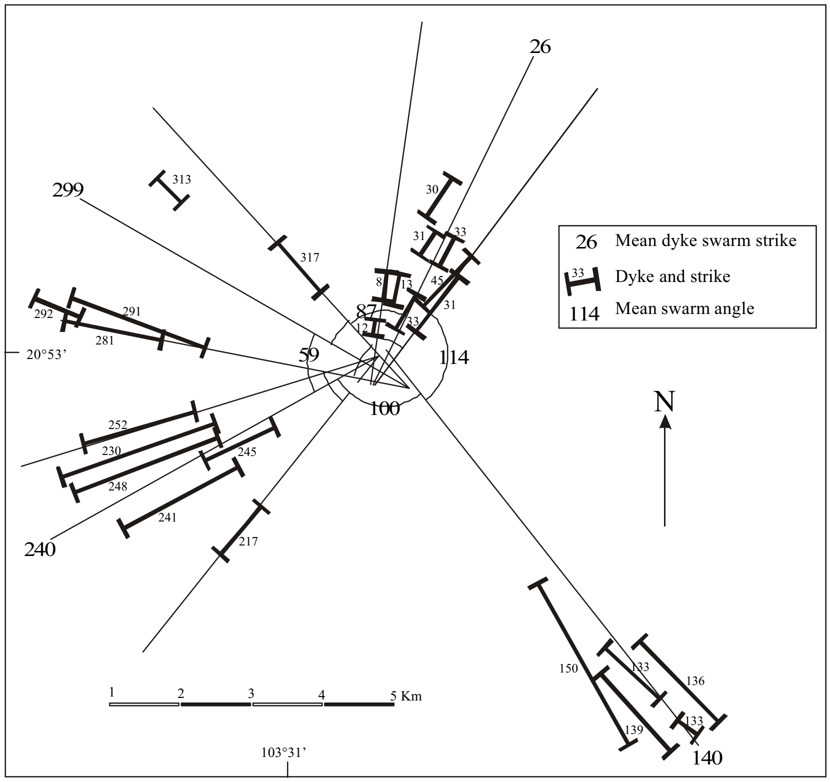

Figure 8. Details of the rhyolitic dykes swarm exposed at Cerro La Col and Cerro La Tortuga.

Ferrari *et al.*, 2000b) we think that both structures could be present beneath the late Miocene basalts.

Relations between magmatism and tectonics

On a regional scale, our study area lies at the intersection of the western and the central TMVB. To the west of the study area, the main fault systems trend WNW-ESE and are late Miocene to Quaternary in age (Ferrari and Rosas-Elguera, 2000) (Figure 2). To the east, Ferrari *et al.* (2000b) describe an ENE-WSW trending system of extensional faults. In this frame, the E-W trending normal faults of the northern part of the study area could represent a transition between the two deformation patterns. These faults, however, are located at the periphery of the area covered by the silicic volcanism, which seems to be characterized by absence of faulting. This area shows a rough N-S elongation and several silicic domes show a N-S alignment (Figure 2). The silicic volcanism covers more than 1,000 km^2 and has an aggregate estimated volume of 300 km^3, which is about nine times the volume of magma extruded by the late Pleistocene La Primavera caldera (Mahood, 1981). These features suggest that the silicic domes represent the surface expression of a long-lived silicic upper crustal chamber with the La Primavera caldera at its southern end. The chamber could coincide with an old buried structure similar to the inferred fault along the Santiago River.

By contrast, four alignments of monogenetic mafic volcanoes in the adjacent Tequila area show an average N125°E direction (Ferrari and Rosas-Elguera, 2000). According to Alaniz-Alvarez *et al.* (1998), monogenetic volcanoes are emplaced along high-strain rate, arc-parallel normal faults, whereas more evolved magmas correspond to arc-transverse, low strain rate, faults. Given the general NNE direction of extension in the western TMVB (Ferrari and Rosas-Elguera, 2000), N-S structures should have a low strain rate compared to the WNW-ESE structures and, therefore, magma ascending along them will undergo differentiation within the crust. This may explain the presence of a N-S elongated silicic magma chamber north of Guadalajara. This model may also explain the absence of faulting in the area covered by the silicic volcanism since even a limited amount of melt may prevent a brittle behaviour in the upper crust (Valentine, 1993).

Tectonic significance of the volcanic record

Our new volcanic stratigraphy indicates that the volcanism of the TMVB can be divided into two stages. The first part of the volcanic history, in the late Miocene, is characterized by the emplacement of abundant mafic lavas (Río Santiago group) and silicic domes and flows (Guadalajara group). This alternating mafic and silicic volcanism is changed by the arrival of alkali-basalts with an intra-plate affinity (Mirador de Ixcatán basalt) during the first extensional pulse in early Pliocene. These basalts are also concurrent with the emplacement of ignimbrites showing evidence of mixing between mafic and silicic magmas (San Gaspar and Guadalajara ignimbrites). This fact strongly suggests that the basalts triggered the eruption of the ignimbrites by providing the thermal input to an older silicic magma chamber. Concurrent silicic and mafic volcanism continues during the late Pliocene and the Quaternary but a main episode of alkali-basalts (Santa Rosa basalt) appear again concurrent with an extensional pulse observed in the region to the southwest of Guadalajara. Finally, Ferrari *et al.* (2001) noted that periods of silicic volcanism in the TMVB during latest Miocene and late Pliocene seem to match a period of stalling subduction of the Rivera plate, as estimated by DeMets and Traylen (2000). Considering all the above observations we conclude that the volcanic style is controlled primary by plate dynamics and it is modulated by the tectonics within the continental crust.

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