

Magnetostratigraphy of the volcanic sequence of Río Grande de Santiago-Sierra de la Primavera region, Jalisco, western Mexico

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RESUMEN

Resultados paleomagnéticos nuevos del Cañón de Río Grande de Santiago (RGS), correspondientes a 13 sitios en unidades volcánicas de las secciones de Huaxtla, Paso de Guadalupe y Lazo, así como de 5 sitios de la Sierra de la Primavera, se utilizan con el fin de documentar la magnetoestratigrafía preliminar de las secuencias volcánicas del Cinturón Volcánico Transmexicano (TMVB). Los resultados magnetoestratigráficos se correlacionan con datos de 7 sitios cercanos del RGS, con 6 sitios de la SP y con fechamientos K-Ar disponibles. Un pozo geotérmico exploratorio de la Comisión Federal de Electricidad en la SP permitió la recuperación de muestras hasta los 1361 m, así como el estudio paleomagnético de 8 muestras de núcleo distribuidas entre 93 m y 1358-1361 m. En la secuencia volcánica de RGS de las secciones de Huaxtla, Paso de Guadalupe y Lazo, así como en los domos y secuencias lávicas de la SP, se documentan polaridades normales (N), intermedias (I) y reversas (R). Las tres secuencias estudiadas en el RGS son de alrededor de 800 m de espesor, incluyen una secuencia ignimbrítica basal (R), los basaltos San Cristóbal (principalmente R), riolitas y flujos de cenizas del grupo Guadalajara (principalmente R), la ignimbrita San Gaspar (N), flujos basálticos y un domo riolítico (N). La secuencia de la SP descansa sobre una secuencia andesítica e incluye una riolita, los basaltos San Cristóbal (R), riolitas y flujo andesítico del grupo Guadalajara (R), tobas de flujo de cenizas, riolitas de precaldera, la toba Tala (R, I) y los depósitos lacustres de intra-caldera. Los basaltos San Cristóbal representan la unidad más antigua de la TMVB, con edades entre 11 y 8 Ma. Este intervalo corresponde a un crón de polaridad normal en la escala de tiempo de polaridad geomagnética, lo que contrasta con la polaridad reversa dominante observada en el RGS y la SP. La polaridad normal de la ignimbrita San Gaspar ha sido fechada en 4.7-4.8 Ma y constituye un horizonte marcador en la región de Guadalajara. Esta ignimbrita y las unidades del grupo Guadalajara (con fechas de 5.2-5.5 Ma) son asignadas al crón reverso Gilbert, con la ignimbrita San Gaspar posiblemente correspondiendo al subcrón normal Thevera (4.59-4.79 Ma). La secuencia silíceo de la SP representa la reciente actividad volcánica en la región y se asigna al crón Brunhes.

PALABRAS CLAVE: Magnetoestratigrafía, Neógeno, rocas volcánicas, Sierra Madre Occidental, Cinturón Volcánico Transmexicano, oeste de México.

ABSTRACT

New paleomagnetic results for 13 sites in volcanic units from Huaxtla, Paso de Guadalupe and Lazo sections in the Río Grande de Santiago (RGS) canyon and for 5 sites in the silicic center of Sierra de la Primavera (SP) are used to document a preliminary magnetostratigraphy for the Trans-Mexican Volcanic Belt (TMVB) volcanic sequence. The magnetostratigraphic results are correlated with data for 7 nearby sites in the RGS and 6 sites in the SP, and with available K-Ar dates. A geothermal exploratory well drilled by the Federal Commission of Electricity in the SP allowed recovery of samples down to a depth of 1361 m, and 8 core samples were studied for paleomagnetism distributed between depths of 93 m to 1358-1361 m. Normal (N), intermediate (I) and reverse (R) polarities are documented in the volcanic sequence of RGS at Huaxtla, Paso de Guadalupe and Lazo sections, as well as in the domes and lava sequences of the SP. The three sections studied in the RGS are around 800 m thick, and include a basal rhyolitic ignimbrite (R), the San Cristóbal basalts (mainly R), rhyolites and ash flows of the Guadalajara group (mainly R), the San Gaspar ignimbrite (N), basaltic flows and a rhyolitic dome (N). The SP sequence rests on an andesitic sequence and includes a rhyolite, the San Cristóbal basalts (R), rhyolites and an andesitic flow of the Guadalajara group (R), ash flow tuffs, pre-caldera rhyolites, the Tala tuff (R, I), and intra-caldera lacustrine deposits. The San Cristóbal basalts represent the oldest TMVB units, with dates between 11 and 8 Ma. This interval corresponds to a normal polarity chron that contrasts with the dominant reverse polarity observed in RGS and SP. The normal polarity San Gaspar ignimbrite has been dated at 4.7-4.8 Ma, and provides a marker horizon in the Guadalajara region. This ignimbrite and the units of the Guadalajara group (with dates of 5.2-5.5 Ma) are assigned to the Gilbert R chron, with the San Gaspar ignimbrite possibly corresponding to the Thevera N subchron (4.59-4.79 Ma). The silicic sequence of SP represents the young activity in the region and is assigned to the Brunhes chron.

KEY WORDS: Magnetostratigraphy, Neogene, volcanic rocks, Sierra Madre Occidental, Trans-Mexican Volcanic Belt, western Mexico.

INTRODUCTION

Two major igneous provinces in Mexico, the Sierra Madre Occidental (SMO) and the Trans-Mexican Volcanic Belt (TMVB), intersect in western-central Mexico (Figure 1). The TMVB comprises most of the Quaternary and present-day volcanism and may be roughly described as an E-W elongated calc-alkaline magmatic province crossing central Mexico from the Pacific to the Gulf of Mexico. The SMO comprises older Late Mesozoic-Cenozoic calc-alkaline igneous products and shows a NW-SE orientation from the USA-Mexico border to the TMVB (Figure 1a). Both provinces are currently interpreted in terms of plate subduction processes, which occurred along the continental margin and constitute a record of ridge-trench-transform fault interactions and plate interactions (Atwater, 1989).

The volcanic stratigraphic and tectonic relationships of the volcanic sequences have been difficult to establish (e.g., Venegas-Salgado *et al.*, 1985; Allan *et al.*, 1991; Delgado-Granados, 1993; Moore *et al.*, 1994; Ferrari *et al.*, 1994; Righter *et al.*, 1995). The relatively abrupt topography and the scarcity of marker horizons within the thick volcanic successions in the area make it difficult to document age and regional correlations. In this paper we report the results of a magnetostratigraphic study of the volcanic sequences in two key areas west and north of Guadalajara, where the SMO and TMVB provinces intersect (Figures 1 and 2). The area has been selected for this study mainly because: (a) the volcanic sequences have been deeply cut by the Río Grande de Santiago to the north of Guadalajara City (Figure 1b), thus offering well-exposed sections, and (b) recent extensive geothermal exploration programs by the Federal Commission of Electricity in the Sierra de la Primavera immediately to the west of Guadalajara City (Figure 1b) have provided abundant subsurface data. The discussion concentrates on the Neogene volcanic stratigraphy of the Guadalajara region and the basal mafic igneous unit of the TMVB.

BASAL MAFIC SEQUENCE OF THE TMVB

Late Miocene volcanism is characterized by a basaltic unit widely distributed along the Tepic-Zacoalco rift which can be continued eastward to the state of Hidalgo (Ferrari *et al.*, 1994, in press). We refer to this widespread volcanism as the Basal Mafic Sequence of the TMVB. From a regional point of view, this basal sequence shows some differences among specific localities. Published isotopic ages constrain the emplacement of the sequence to a period between 11 and 8 Ma (Gastil *et al.*, 1979; Moore *et al.*, 1994; Rosas-Elguera *et al.*, 1997). In the Tepic area, the basaltic sequence is called Basaltos Cinco de Mayo with a thickness of about 600 m and an age of 9.9 to 8.9 Ma (Gastil *et al.*, 1979; Righter *et al.*, 1995). To the west, within the Punta Mita region, a pil-

low lava basalt yields an age of 10.2 Ma (Gastil *et al.*, 1979). Similar ages were obtained for several mafic dikes in two areas: one to the north of Punta Mita (13–10 Ma; Gastil *et al.*, 1979) and the other to the west of the SMO (11–12 Ma) in the Aguamilpa reservoir area (Damon *et al.*, 1979).

To the northwest of the study area, in the Ceboruco region, Federal Commission of Electricity drilled two geothermal wells. The Ceboruco well cuts a Plio-Quaternary succession of rhyolitic ash-flows intercalated with andesitic lava flows (Venegas-Salgado *et al.*, 1985; Ferrari *et al.*, in press). Below 530 m asl the well cut ~1800 m of andesitic to basaltic lava flows, which fill a narrow and deep graben structure (Romero and Pasquarè, unpublished data 1995), in similar rocks of the Jalisco block. A sample from the Ceboruco borehole has been dated by the whole-rock K-Ar method at 7.2, 7.7 and 8.2 Ma (Ferrari *et al.*, in press).

To the north of Guadalajara, Moore *et al.* (1994) described a widespread sequence of alkali olivine basalts and basaltic andesites with ages between 11 and 9 Ma (Watkins *et al.*, 1971; Damon *et al.*, 1979; Moore *et al.*, 1994). A distinctive silicic welded ash-flow is interbedded with the basalts in the lowest part of the exposed sequence where a heterogeneous silicic sequence of pumice flows, welded ash-flows, ash falls and reworked pyroclastics is also present in the uppermost part (Moore *et al.*, 1994). This sequence was named the San Cristobal basalts with a maximum thickness of about 600 m (Moore *et al.*, 1994).

Ferrari *et al.* (1994) referred to the Río Grande de Santiago mafic sequence as the basaltic unit to the east of Guadalajara City including Los Altos plateau. This mafic sequence is relatively primitive and covers ~8500 km² with a volume of about 3000 km³ (Ferrari *et al.*, 1994). According to published isotopic ages, the mafic sequence is between 9.5 and 12 Ma with calc-alkaline affinities and ~200–350 m thickness (Nieto *et al.*, 1985; Nixon *et al.*, 1987; Ferrari *et al.*, 1994). These data suggest a wide age range for the Río Grande de Santiago mafic sequence, though narrower than for the San Cristobal basalts.

To constrain the volcanic stratigraphy for the sequence of Los Altos plateau, samples of basalts and rhyolites from the northern Chapala graben have been dated by the K-Ar method (Rosas-Elguera and Urrutia-Fucugauchi, 1998). Following these and previous studies, in the northern Chapala graben area a sequence of basaltic lava flows with interlayered rhyolite and ash-flow tuff is found. The oldest unit yields isotopic ages 13.5 to 10.8 Ma, it is a 400 m thick sequence of basalts that overlies the ignimbrites of the SMO. Several basaltic dikes trending about 57° cut the basaltic sequence.

An ash-flow tuff with reworked material and lacustrine sediments at the bottom overlies the basalts. A sample of the

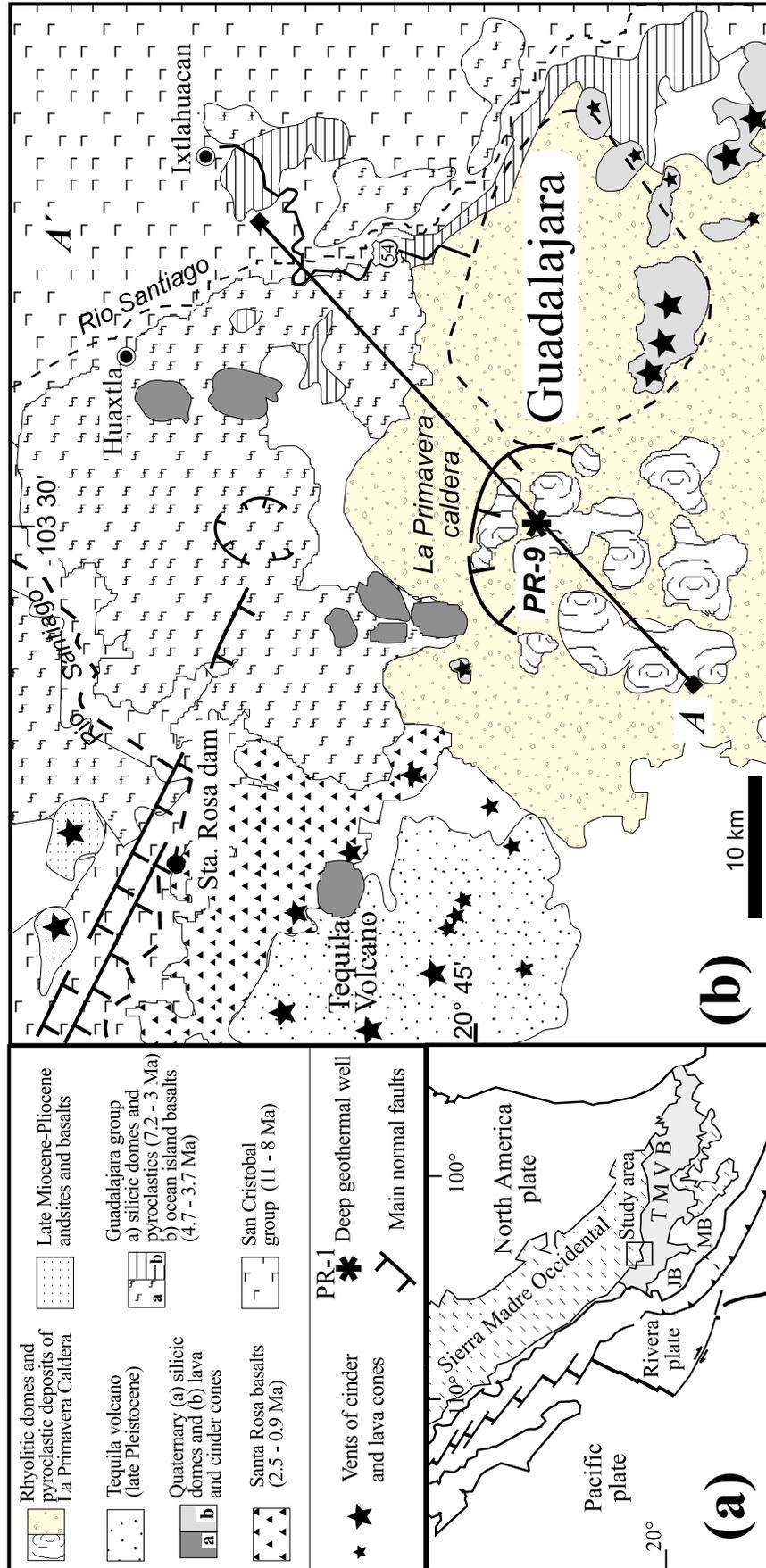


Fig. 1. (a) Location of study area at the intersection of the Sierra Madre Occidental and the Trans-Mexican Volcanic Belt (TMVB) in western Mexico. (b) Schematic geologic map of the study area showing the major volcanic features: stratovolcanoes (e.g., Tequila volcano), cinder cones, volcanic sequences and the silicic center of La Primavera caldera or Sierra de la Primavera. Sequences studied for magnetostratigraphy correspond to units in La Primavera and along the walls of the Río Grande de Santiago canyon (see Figure 2).

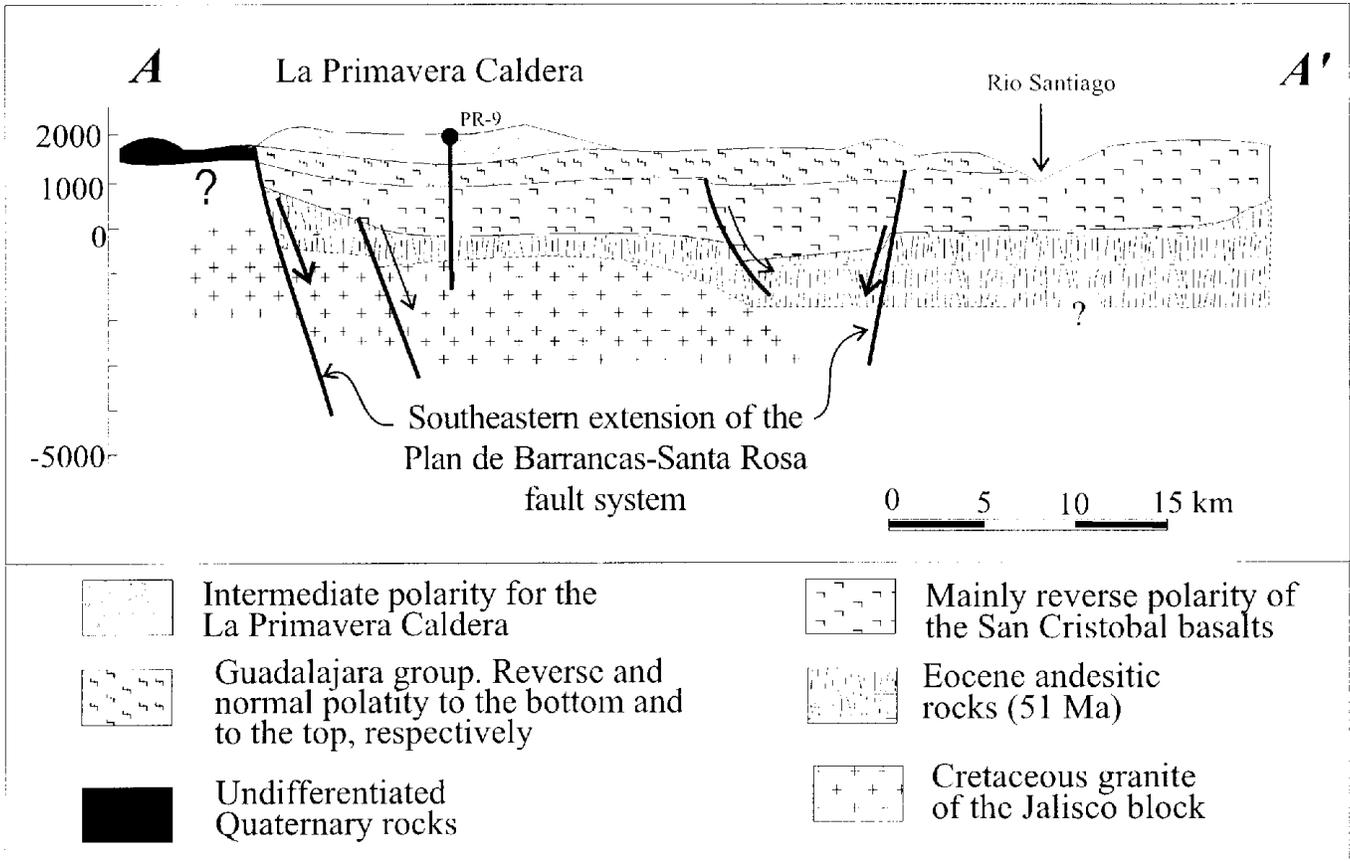


Fig. 2. Geologic section A-A' (see Figure 1b) across La Primavera caldera and Río Grande de Santiago showing the main volcanic units and structural features. Basement in La Primavera area is formed by granitic rocks.

ash-flow gives 10.3 Ma, which agrees with data for the reworked silicic member at the top of the San Cristobal basalts described to the north of Guadalajara by Moore *et al.* (1994). This ash-flow may be related to a rhyolitic volcanism between 10.3 and 8.6 Ma with basaltic lava flows at 9.3 Ma (Table 1 in Rosas-Elguera and Urrutia-Fucugauchi, 1998). Observations and K-Ar data have been interpreted in terms of a late Miocene lacustrine system called Jalisco paleo-lake by Rosas-Elguera and Urrutia-Fucugauchi (1998).

The age range for the San Cristobal group was given as 11 to 9 Ma by Moore *et al.* (1994), but the La Primavera geothermal wells cut a basaltic-andesite succession 800 m thick which gave a K-Ar whole-rock age of 12.5 ± 0.6 Ma (Ferrari *et al.*, in press). This result agrees with the new K-Ar age for Los Altos plateau and those reported for the Tepic area. Thus, we propose that the basal volcanism of the TMVB may have started earlier, in the middle Miocene (13 Ma). To the south of Los Altos plateau, the basalts gave slightly younger ages of 8.8–8.7 Ma and overlie a lacustrine succession (Rosas-Elguera and Urrutia-Fucugauchi, 1998).

Gastil *et al.* (1979) and Ferrari (1995) have proposed

that the late Miocene volcanism represents an important tectonic event related to the opening of the Gulf of California. Ferrari (1995) explains this volcanism in the Guadalajara region by WNW motion of the Jalisco block in a right-lateral transtensional zone along the boundary between the Sierra Madre Occidental and the Jalisco block.

PALEOMAGNETIC STUDIES

The paleomagnetic study concentrates on two critical regions around the City of Guadalajara (Figures 1 and 2). The region north of Guadalajara in the canyon of the Río Grande de Santiago (Figure 3) has been studied along federal highway 54 at three localities: Huaxtla, Paso de Guadalupe and Lazo. In the RGS canyon a thick succession of late Miocene basaltic units referred to as the San Cristobal basalts (Moore *et al.*, 1994) is extensively exposed. The San Cristobal basalts underlie a sequence of silicic rocks of the Guadalajara group (7.2–3.1 Ma). The second region lies immediately to the west of Guadalajara, in the silicic complex of Sierra de la Primavera (Figure 4).

The RGS canyon was initially studied by Watkins *et*

al. (1971), who reported results for seven sites in the volcanic sequence, as well as radiometric K–Ar dates and a stratigraphic interpretation. The volcanic units in Sierra de la Primavera have been studied from surface exposures (young Plio-Quaternary volcanics) and from cores recovered by drilling (young and older volcanics). Paleomagnetic results for the surface units have been reported in Urrutia-Fucugauchi *et al.* (1988); directional results are re-analyzed and combined with data from additional sites. Magnetic polarity data for the cores were obtained as part of a La Primavera geothermal exploration project by the Japan International Cooperation Agency (JICA-Report, 1989). Results are briefly

discussed below, together with the new paleomagnetic studies.

NEW STUDIES IN RIO GRANDE DE SANTIAGO

Seventy-seven oriented samples were collected from 13 sites distributed stratigraphically in the localities of Huaxtla, Paso de Guadalupe and Lazo (Figure 3). A total of 120 cylindrical specimens, 2.5 cm diameter and 2.1–2.2 cm high were available for the study. Their intensity and direction of natural remanent magnetization (NRM) were measured using a Molspin fluxgate magnetometer system.

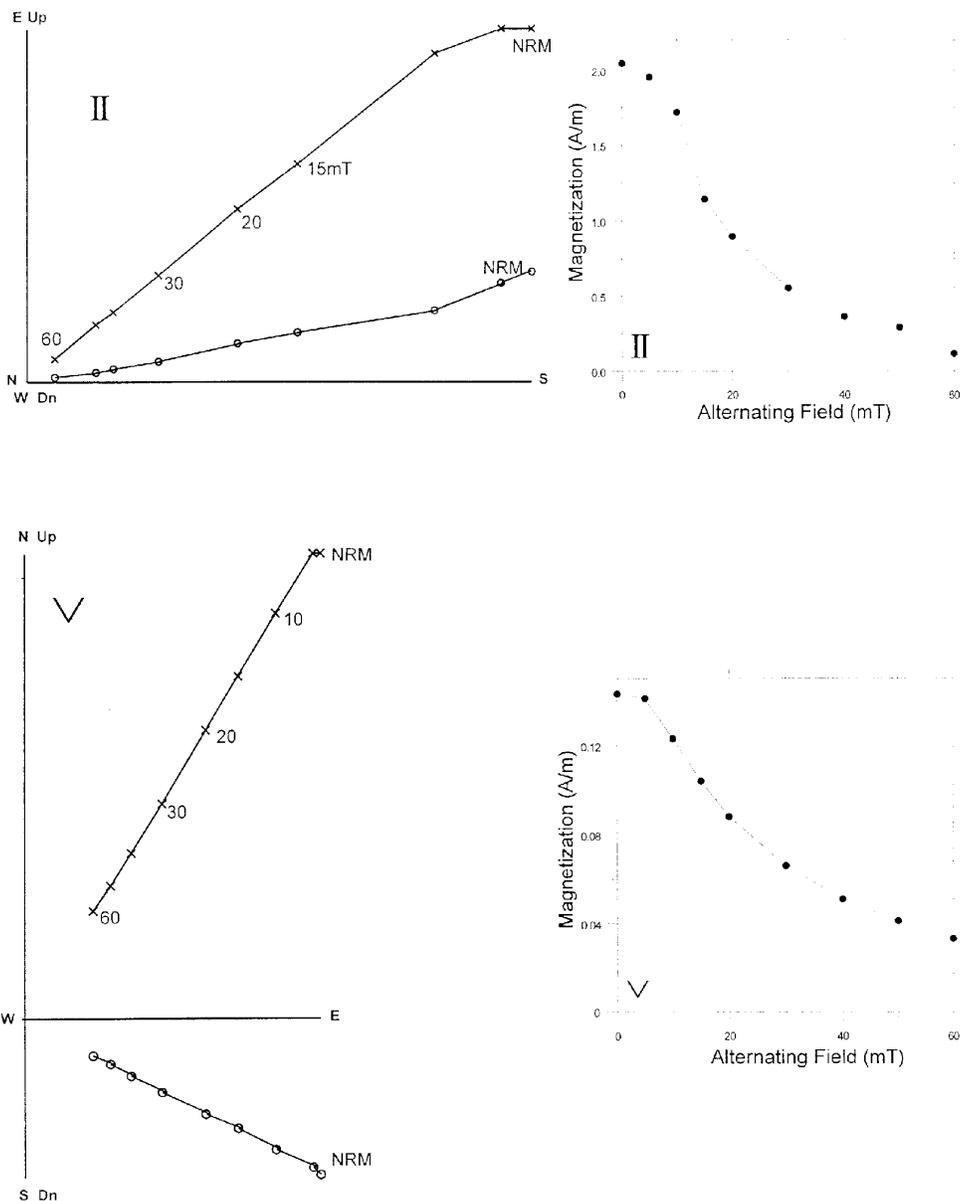


Fig. 5. Examples of demagnetization data in the form of vector diagrams for samples from the volcanic succession of the Río Grande de Santiago.

Table 1

Summary of magnetostratigraphic results for the Río Grande de Santiago

Site	Lithology	n/ns	Dec	Inc	k	α_{95}	Polarity	Ref.
I	Basaltic Andesite	6/4	134.1	-28.3	15.2	24.4	R	1
II	Basalt	8/6	159.6	-47.9	28.0	12.9	R	1
III	Basalt	3/3	174.9	-26.1	271.7	7.5	R	1
IV	Rhyolite	7/6	198.2	-32.6	9.0	24.1	R	1
V	Ignimbrite	7/7	139.3	-32.3	21.8	13.7	R	1
VI	Ignimbrite	7/4	6.4	25.01	19.4	24.2	N	1
VIIa	Andesite	4/4	153.6	-17.8	29.2	17.3	R	1
VIIb	Andesite	4/4	209.3	-46.9	26.2	18.3	R	1
VIII	Basalt	4/4	351.9	-45.1	107.0	8.9	R(I)	1
IX	Rhyolite	7/5	177.9	-26.5	20.1	17.5	R	1
XI	Andesite	5/5	208.6	-29.3	15.4	20.2	R	1
XII	Ignimbrite	9/7	350.1	38.7	12.1	18.1	N	1
XIII	Ignimbrite	6/4	7.6	19.7	33.8	16.0	N	1
7	Basaltic Ignimbrite	10	356.3	9.2	203.8		N	2
6	Basalt	6	330.3	46.9	69.2		N	2
5	Andesite Ignimbrite	8	186.1	-27.1	41.0		R	2
4	Basalt/Ignimbrite	17	178.7	-34.7	122.3		R	2
3	Basalt	8	358.6	45.0	33.5		N	2
2	Basalt	8	165.1	-21.0	284.5		N	2
1	Rhyolitic Ignimbrite	12	144.8	-58.1	167.5		R	2

Notes: n, number of samples; ns, number of samples for statistics; Dec and Inc, Declination and Inclination of characteristic remanent magnetization after demagnetization; k and α_{95} , Fisher statistical parameters: concentration parameter and 95% cone of confidence; Magnetic polarity: N, normal, I, intermediate and R, reverse; Reference: 1, this study and 2, Watkins *et al.* (1971).

Río Grande de Santiago volcanic succession
(Site-mean paleomagnetic directions)

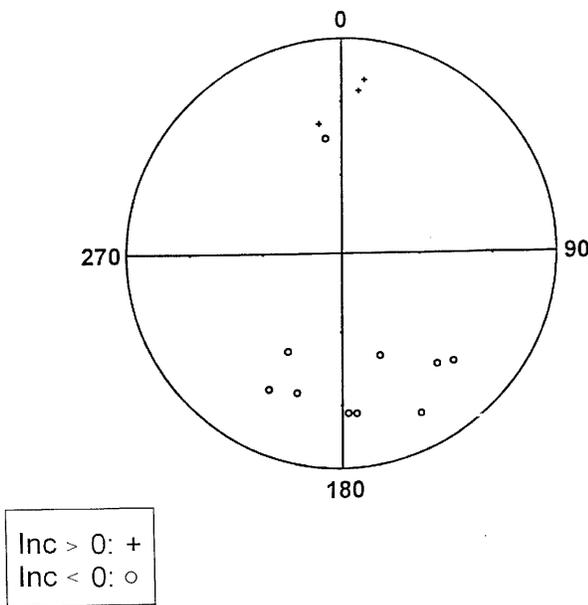


Fig. 6. Site-mean directions plotted in an equal-area stereographic projection for the volcanic units of the Río Grande de Santiago (data in Table 1).

The magnetic stability and vectorial composition of NRM were investigated by stepwise alternating field (AF) demagnetization. AF demagnetization was carried out in 8-12 steps up to 100 mT using a Schonstedt AF demagnetizer. Examples are shown in Figure 5, using demagnetization vector diagrams. The characteristic magnetization component (ChNRM) was calculated from end-points and by vector subtraction analysis. Site mean directions and associated Fisher statistics (Fisher, 1953) were then calculated for the NRM and the characteristic remanent magnetization (Table 1 and Figure 6). The within-site angular dispersion of most sites is high (Table 1). Analysis of the demagnetization data does not give evidence of multicomponent magnetizations (e.g., Figure 5), and the paleomagnetic record seems relatively simple. Because of the high angular dispersion, no tectonic implications are derived from the results. From the vector demagnetization data, we believe that the magnetic polarities are well defined and correspond to the primary TRM magnetizations. Virtual geomagnetic pole (VGP) positions were calculated for each site and magnetic polarity was assigned from the VGP latitude, with $\lambda_p < 45^\circ$ labelled as intermediate (I).

Watkins *et al.* (1971) reported paleomagnetic results for seven sites sampled along the canyon of the Río Grande

Table 2

Summary of K-Ar dates for the Río Grande de Santiago area

Rock Unit	Old date (Ma)	New Date (Ma)
a) Re-calculated from Watkins <i>et al.</i> (1971) study		
Basalt (site 2)	9.27 ± 0.12	9.52 ± 0.1
Basalt (site 3)	8.96 ± 0.10	9.20 ± 0.1
Ignimbrite (site1)	8.88 ± 0.12	9.12 ± 0.1
Basalt (site 4)	8.75 ± 0.20	8.98 ± 0.2
Andesite (site 5)	5.37 ± 0.07	5.51 ± 0.1
Ignimbrite (site 7)	4.65 ± 0.10	4.84 ± 0.1
Basalt (site 6)	4.71 ± 0.05	4.77 ± 0.1
b) Data from Moore <i>et al.</i> (1994)		
Basaltic andesite shield volcano at García de la Cadena		10.99 ± 0.23
Basalt Río Grande de Santiago		10.25 ± 0.82
Basalt Río Grande de Santiago		10.23 ± 0.34
Ignimbrite		10.23 ± 0.04
c) Data from Damon <i>et al.</i> (1979)		
Basalt andesite (same as Moore <i>et al.</i> , 1994)		10.05 ± 0.32

Note: The new dates have been re-calculated using the conversion table from Dalrymple (1992), which is based on the decay constants reported by Steiger and Jaeger (1977).

de Santiago (Figure 3). Methods used are similar to those just described. NRM intensity and direction of cylindrical specimens 2.5 cm diameter and 2.2 cm long were measured in a spinner magnetometer. Vectorial composition was investigated by AF demagnetization. Site-mean directions and associated Fisher statistics were calculated for the characteristic magnetizations (Table 1). K–Ar dating was used to estimate the age of the volcanic units and results are included in Table 2. The stratigraphic column reported in their study was based on the geochemical data, and has been subsequently improved by field reconnaissance, stratigraphic and petrographic studies carried out in the geothermal exploration program and in research academic projects.

SIERRA DE LA PRIMAVERA

Results for sixty-four oriented samples collected earlier (Urrutia-Fucugauchi *et al.*, 1988) and twenty one new samples from five domes and the Tala tuff in the Sierra de la Primavera were analyzed. The remanent magnetization for samples from the domes corresponds likely to a thermoremanent magnetization (TRM) (e.g., Figure 7). Nevertheless, a relatively high angular dispersion in directions is present at most sites. The high within-site dispersion observed in the data for the Tala tuff and the El Burro dome in the initial study led us to collect additional samples. Further, the reverse and intermediate polarities documented for those units

were crucial in the magnetostatigraphic correlations (Urrutia-Fucugauchi *et al.*, 1988). Median destructive fields (MDF) range between 25 and 35 mT, which probably points to PSD spinels as magnetic carriers. Microscopic observations show that the main magnetic mineral is Ti-poor titanomagnetite associated with ilmenite and titanohematite exsolutions.

Initial results for Tala tuff gave scattered directional results with a poorly defined mean direction of reverse polarity, with southward declination and upward inclination. The additional results for the Tala tuff show intermediate directions with downward and upward inclinations (Table 3). Secondary components observed in the demagnetization vector plots are relatively small or absent. The paleomagnetic record for the Tala tuff seems more complex than that observed for the dome units. The additional results show smaller within-site dispersions, but corresponding site-mean directions show considerable angular differences (Table 3; Figure 11).

The magnetic mineralogy and domain state of magnetic carriers have been further investigated by measuring the hysteresis properties using the MicroMag. Small pieces were cut from eleven selected unheated specimens and were measured to obtain the hysteresis loops and also the isothermal remanent magnetization (IRM) acquisition and back-field demagnetization curves (Figures 8 and 9). Domain state of

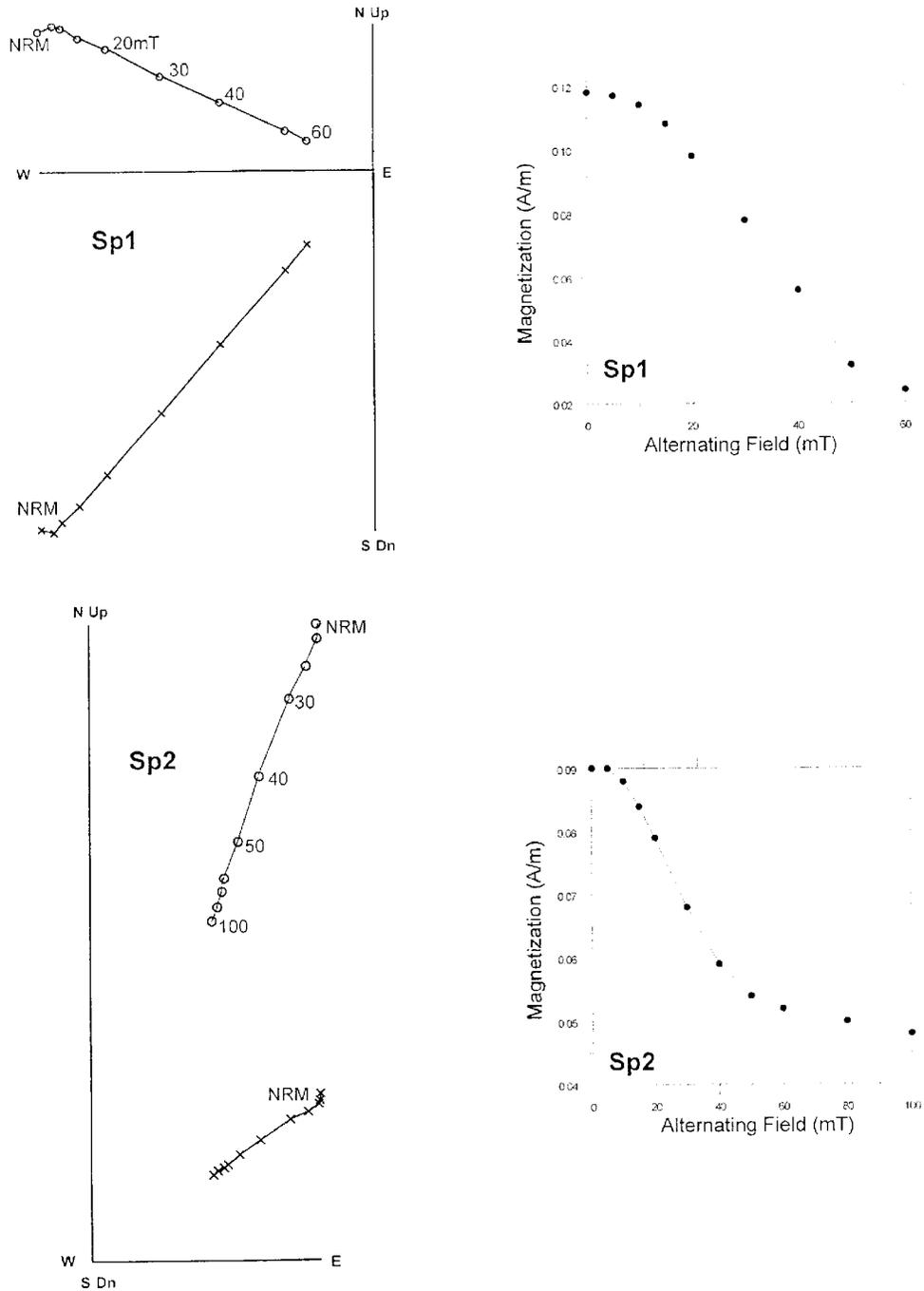


Fig. 7. Examples of demagnetization data in the form of vector diagrams for samples of the Sierra de la Primavera.

samples has been derived from the relationship between the magnetization ratio (M_r/M_s) and the coercivity ratio (H_{cr}/H_c), where M_r and M_s are the remanent and the saturation magnetization and H_{cr} and H_c are the coercivity of remanence and coercivity, respectively (Day *et al.*, 1977). Samples plot in the pseudo-single domain (PSD) state field, with no samples in the single domain (SD) and multidomain (MD) state fields (Figure 10).

Characteristic NRM directions for the domes are of normal polarity and have been assigned to the Brunhes chron (Figure 11). Mahood and Drake (1982) reported K–Ar dates which document the volcanic activity in the complex for the last 145–140 kyr. Site-mean ChNRM directions are relatively well grouped (Figure 11; Table 3). The stratigraphic relationships of the units studied are shown schematically in Figure 12. An exception was the site in the El Burro dome that

Table 3

Summary of magnetostatigraphic results for the Sierra de la Primavera

Site	Unit	n	Dec	Inc	k	α_{95}	Polarity	Reference
X	Tala tuff	20	180.0	-35.2	4.2	18.3	R	1
XIV	El Burro	6	0.2	-39.8	5.7	30.7	I	1
XV	La Cuesta	16	8.2	52.8	12.0	11.1	N	1
XVI	Las Canoas	16	6.3	28.7	23.5	7.7	N	1
XVII	El Tajo	3	4.8	54.4	67.7	15.1	N	1
XVIII	El Colli	3	337.0	29.3	115.4	11.5	N	1
PR-1	93m			-12.8			R	2
PR-4	300-301 m			40.8			N	2
PR-2	350 m			42.0			N	2
PR-5	350-353 m			42.8			N	2
RC-1	700 m			26.0			N	2
PR-1	910-915 m			19.7			N	2
PR-1	910-915 m			-17.7			R	2
PR-2	1358-1361 m			-57.0			R	2
SP-1	Tala tuff	4	293.9	53.9	60.7	11.9	I	3
SP-2	Tala tuff	4	18.9	-12.5	135.7	7.9	I	3
SP-3	Tala tuff	7	66.4	73.3	48.2	8.8	I	3
SP-4	El Burro	3	349.4	-53.5	119.2	11.3	I	3
SP-5	El Burro	3	271.1	-21.2	63.7	15.6	I	3

Note: n, number of samples; Dec and Inc, Declination and Inclination of characteristic remanent magnetization after demagnetization; k and α_{95} , Fisher statistical parameters: concentration parameter and 95% cone of confidence; Magnetic polarity: N, normal, I, intermediate and R, reverse; Reference: 1, Urrutia-Fucugauchi *et al.* (1988); 2, JICA Report (1989); and 3, this study.

gave a poorly defined intermediate direction with northward declination and upward inclination (Table 3). The additional paleomagnetic results for El Burro dome show intermediate directions, with improved precision and small within-site dispersion that are consistent with the initial data (Table 3). The K-Ar dates for El Burro dome are 96.7 and 127.7 kyr, which are within the range of dates for the Tala tuff of 95.2 and 96.7 kyr (Mahood and Drake, 1982). K-Ar dates for the other domes are younger. K-Ar dates for Las Canoas dome is 83.6 kyr, La Cuesta is 71.3 kyr, El Colli are 30.2 and 31.9 kyr, and El Tajo are 25.5 and 26.8 kyr (Mahood and Drake, 1982).

Samples from eight cores corresponding to geothermal exploration wells PR-1, PR-2, PR-4, PR-5 and RC-1 were studied for the JICA project (JICA-Report, 1989). Cubic 2.5 cm specimens were prepared and referred to the horizontal (cores were not oriented and azimuths were arbitrarily assigned for the measurement process). NRM was measured with a fluxgate magnetometer. Samples were AF demagnetized in 10, 20 and 30 mT steps. No secondary NRM components were observed and a characteristic remanence inclination was calculated from the AF demagnetized measurements. Results are summarized in Table 3. Both reverse and normal polarities were interpreted; note that polarity is assigned considering the magnetic inclination only (where, positive corresponds to normal and negative corresponds to reverse polarity).

DISCUSSION

For the magnetostatigraphic correlations, magnetic polarities are combined with field and petrologic observations and K-Ar dates. Results from the Paso de Guadalupe and Lazo sections are correlated with those reported earlier by Watkins *et al.* (1971). The combined results are then correlated with data for the Huaxtla section (Figure 13). According to Watkins *et al.* (1971) the basalt with normal polarity of site 6 is older than the San Gaspar ignimbrite of site 7, but our field observations confirm that the basalt flowed into a topographic low and is younger than the San Gaspar ignimbrite (Figure 13c).

Sites IV and V correspond to rhyolitic domes and an ash-flow tuff of the Guadalajara group, which in this section has an age range between 5.5 and 5.2 Ma. The flow directions of the ~3 m thick dark-coloured San Gaspar ignimbrite, which was dated at 4.7 Ma (Watkins *et al.*, 1971) and 4.8 Ma. (Gilbert *et al.*, 1985), were controlled by paleotopography. The San Gaspar ignimbrite provides a regional marker horizon in the Guadalajara region. A normal polarity was obtained for samples of this ignimbrite, site VI (site 7 of Watkins *et al.*, 1971) in the Lazo section. According to the magnetic polarities and K-Ar dates, we interpret sites IV, V, and VI as lying within the Gilbert Chron. The San Gaspar

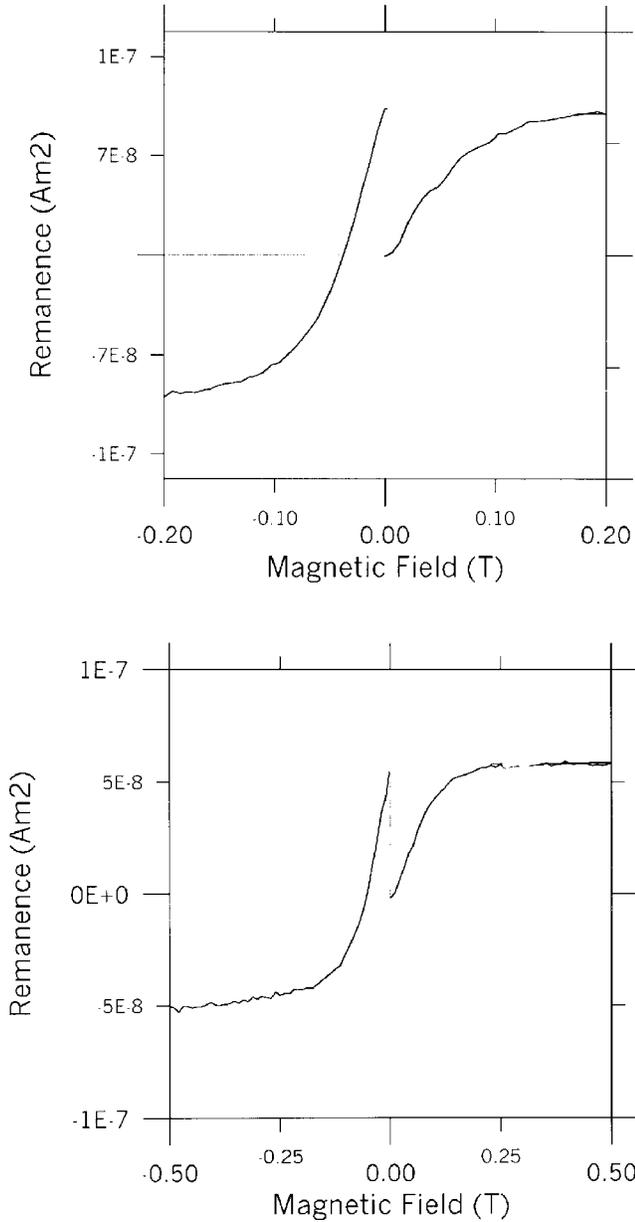


Fig. 8. Examples of hysteresis loops for representative samples of the Sierra de la Primavera (Tala tuff and central domes). Data measured in the MicroMag system.

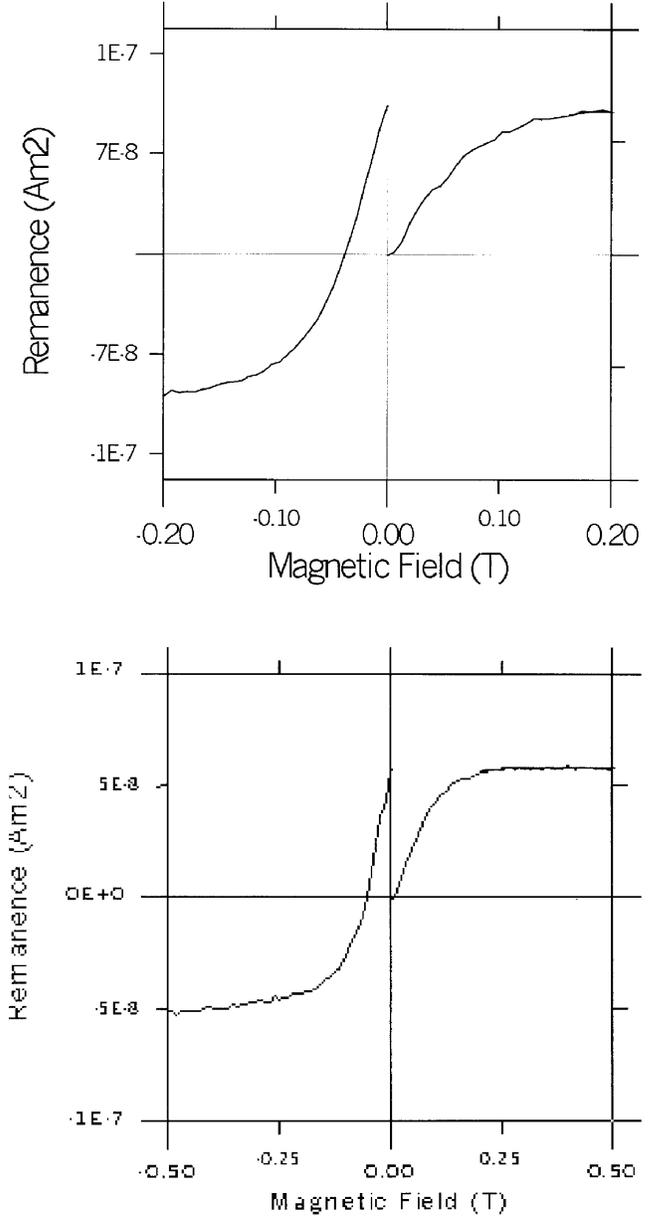
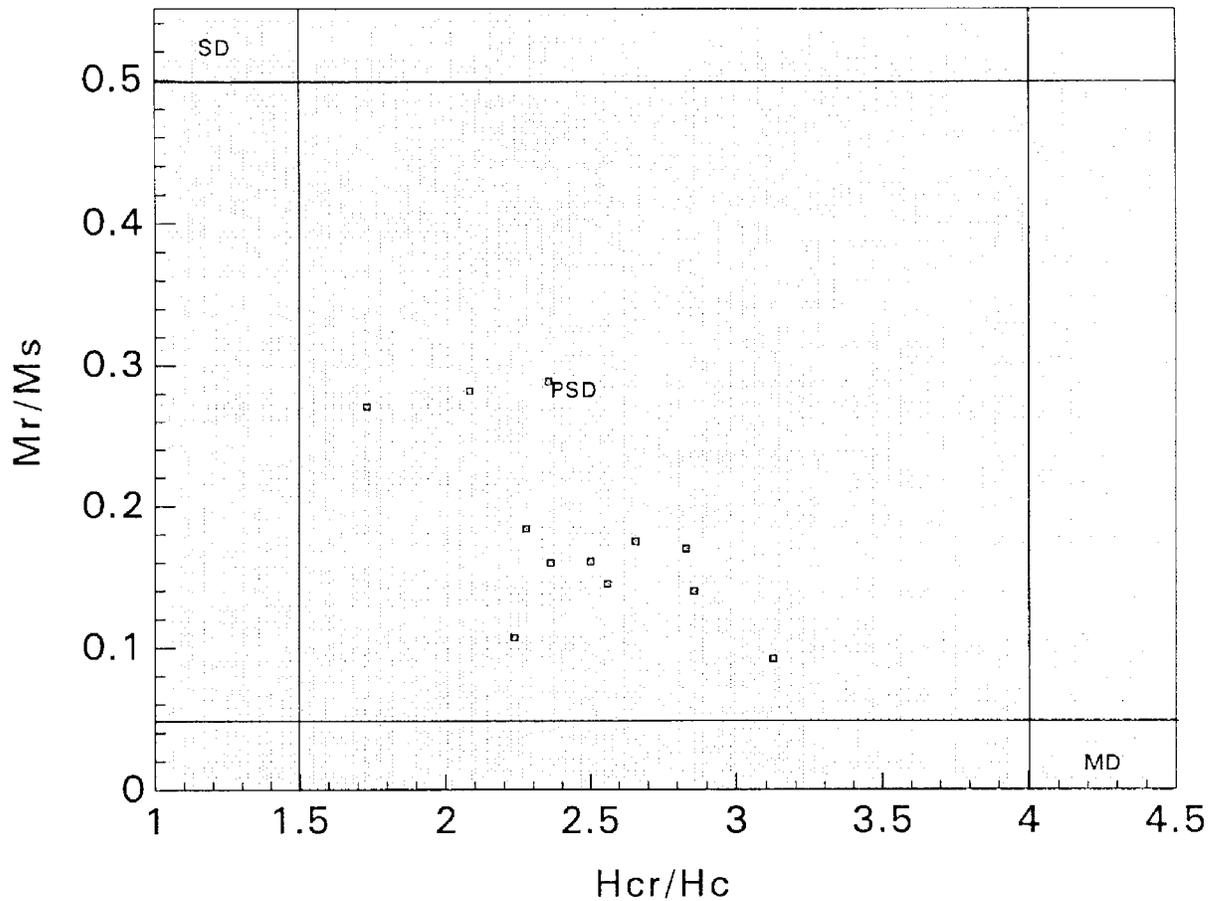


Fig. 9. Examples of isothermal remanent magnetization acquisition and back-field demagnetization curves for representative samples of the Sierra de la Primavera.

ignimbrite (site VI) thus lies within the normal polarity Thvera subchron (4.59–4.79 Ma), which is the oldest normal polarity interval of the reverse Gilbert Chron. The underlying rhyolitic domes were emplaced during the oldest reverse segment (4.79–5.3 Ma) of the Gilbert Chron, which agrees with the K–Ar dates and the stratigraphic position of the ignimbrite. The reverse polarity of a core of ash-flow tuff of the Primavera well and its relative stratigraphic position suggest a correlation with the volcanic units of the Guadalajara group (Figure 13).

The San Cristóbal basalts are the oldest sequence related to the TMVB, with ages between 11 Ma and 8 Ma (Watkins *et al.*, 1971; Gastil *et al.*, 1979; Damon *et al.*, 1979; Moore *et al.*, 1994; Rosas-Elguera *et al.*, 1997). A predominant normal polarity, with some reverse polarity subchrons is shown in the reference Geomagnetic Polarity Time Scale (GPTS) for this period (Harland *et al.*, 1990; Baksi, 1993). However, sites I-II, VII, IX of this study and sites 1, 2 and 4 of the Watkins *et al.* (1971) study show a reverse polarity (Figure 13), which may correspond with the short reverse



CALDERA LA PRIMAVERA, JALISCO

Fig. 10. Summary diagram for hysteresis parameters plotted in the Day diagram showing the fields for the single domain (SD), pseudo-single domain (PSD) and multidomain (MD) states. Note that samples fall in the PSD field.

subchrons documented in this interval. In addition, to the top of the volcanic succession sites VIII and 3 show intermediate and normal polarities, respectively (Figure 13).

Units of sites II and III are stratigraphically above the unit of Site IX and show different geologic and petrological characteristics, but they apparently correspond to the same late Miocene volcanic sequence. The unit at site I correlates with that of site VII; they both underlie the rhyolitic rocks of the Guadalajara group.

The magnetostratigraphy of Río Grande de Santiago area is correlated with the magnetostratigraphic information for the Sierra de la Primavera (Figure 13). The basal section of the PR-2 is formed by a sequence of basalts and andesitic basalts separated by a rhyolitic unit at the bottom of the well (Figure 13d). The reverse polarity for a core from this sequence suggests a correlation with the sequence represented by sites I, 2 and VII, exposed along the walls of the Río

Grande de Santiago canyon. The occurrence of reverse polarity ash-flows overlying the mafic sequence suggests a possible correlation with the oldest rocks of the Guadalajara group (Figure 13).

The intermediate polarity directions for the Tala tuff may be useful to constrain the apparently anomalous K–Ar stratigraphy for the Tala tuff and central domes and the Great Pumice Horizon (GPH), which are both above the Tala tuff (Figure 12). Dates for the Tala tuff are 95 ± 6.5 and 96.7 ± 3.8 kyr, whereas dates for central domes are 126, 111 and 102 ky and for the GPH are 122 and 104 kyr. That is, they are in inverse stratigraphic order. Mahood and Drake (1982) interpreted this anomaly in terms of anomalous dates for the central domes, which they considered to be younger. The intermediate polarity for the Tala tuff provides an alternative interpretation. The intermediate polarity may correspond to the Blake geomagnetic event whose age has been estimated around 110–116 kyr (Tarling, 1983). Short transitional events

Sierra de la Primavera
(Site-mean paleomagnetic directions)

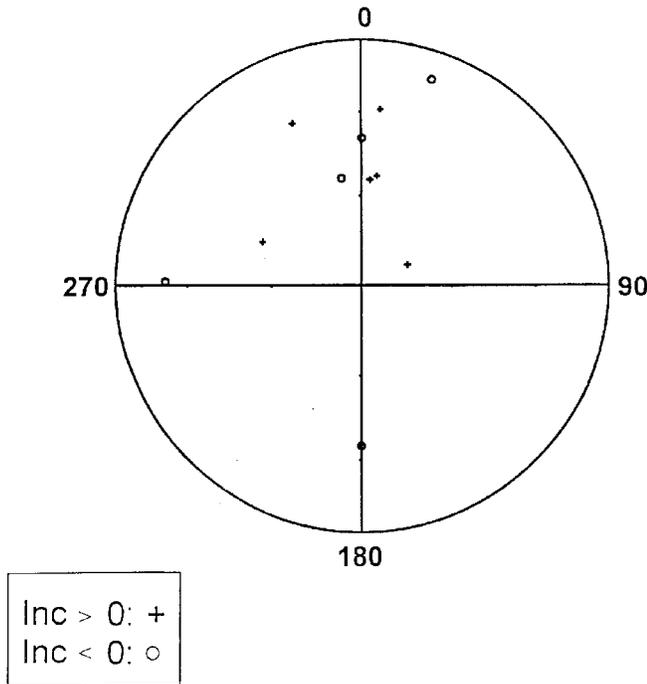


Fig. 11. Site-mean directions plotted in an equal-area projection for the volcanic units of the Sierra de la Primavera (data in Table 3).

within the Brunhes and Matuyama polarity chrons have been discussed (Champion *et al.*, 1988). The Laschamp and Blake events are among the best documented (Merrill and McFadden, 1994). This interpretation supports an older age for the Tala tuff than indicated by the K–Ar dates (Figure 12). A problem with this interpretation is the high angular dispersion observed in the results for the Tala tuff. The initial data presented high within-site angular dispersion. The new results show improved precisions, but with large between-sites angular dispersions (Table 3). This lack of agreement in the paleomagnetic site-mean directions may indicate a problem with the paleomagnetic record, which may have been affected by hydrothermal alteration. This agrees with the occurrence of high coercivity magnetic minerals (hematite?) observed in the Tala tuff, where hydrothermal processes partly reset the paleomagnetic and K–Ar systems (Urrutia-Fucugauchi *et al.*, 1988). Paleomagnetic data from three cores at various depths also indicate upward and downward inclinations (Table 3). On the other hand, the intermediate directions observed for El Burro dome, which has K–Ar dates (96.7 and 127.7 kyr) in the same range than those for the Tala tuff (95.2 and 96.7 kyr), provide support for the correlation of magnetostratigraphic results with the Blake subchron. In this case, the age range for the El Burro dome spans the age for the Blake subchron of around 110–116 kyr.

The tentative regional correlations in the Sierra de la

Primavera-Guadalajara-Río Grande de Santiago region are summarized in Figure 13. Results for Huaxtla, Paso de Guadalupe and Lazo sections in the Río Grande de Santiago canyon are first correlated using the geologic and magnetostratigraphic information. The vertical coordinates in the sections are given in meters above sea level. The basal units in the Huaxtla and Lazo sections belong to the San Cristobal basalts, which are characterized by predominant reverse polarities. In the Paso de Guadalupe section the basal units are formed by rhyolitic ignimbrites also of reverse polarity. The mafic San Cristobal sequence is overlain by rhyolites, and ash flow tuffs of the Guadalajara group, characterized by reverse polarity. In the Lazo section, they are overlain by the San Gaspar ignimbrite of normal polarity. The following unit is formed by OIB basalts of normal polarity, also present in the Paso de Guadalupe section. In the Huaxtla and Paso de Guadalupe sections, these OIB basalts are overlain by rhyolitic units. The San Cristobal basaltic sequence can be correlated to the subsurface sequence in the Sierra de la Primavera (here illustrated using the lithographic column for PR 2 well). Polarity is also reverse (upward inclinations). Units of the Guadalajara group can also be correlated using the dominant reverse polarity.

Polarities assigned to the subsurface sequence in Sierra de la Primavera are derived from the magnetic inclination measurements, except for the Tala tuff sampled at the surface and in the wells. Data for the Tala tuff sampled at the surface with fully oriented surface samples give intermediate polarity, with downward and upward inclinations (Table 3). The results from the cores at various depths, 99, 250 and 350 m in the exploratory geothermal wells, give also reverse, normal and normal polarities, respectively (Figure 13 and Table 3).

Castillo-Hernández and Vargas-Ledezma (1985) analyzed the lithologic column of cores recovered from drilling in the La Soledad area and correlated with the La Primavera PR-2 well. The well in the La Soledad area was 600 m deep and starts at an elevation of 900 m a.s.l., cutting exclusively an andesitic sequence. These andesites have been correlated with the unit Tomab of La Primavera, which is present at the middle section of La Primavera wells. In the area of Paso de Guadalupe, the basalt lies beneath unit IX, then is in agreement with the magnetostratigraphy derived for the volcanic sequence.

Volcanic activity in the Nayarit area was divided by Gastil *et al.* (1979) into Miocene 21–16 Ma volcanics (mainly rhyolites with related andesites and basalts), Late Miocene 11–8 Ma volcanics (mainly basalts) and Plio-Quaternary 5 Ma to Recent volcanics (basalts, andesites, dacites and rhyolites).

The age for the onset of volcanic activity of the TMVB has been a matter of discussion, and divergent estimates rang-

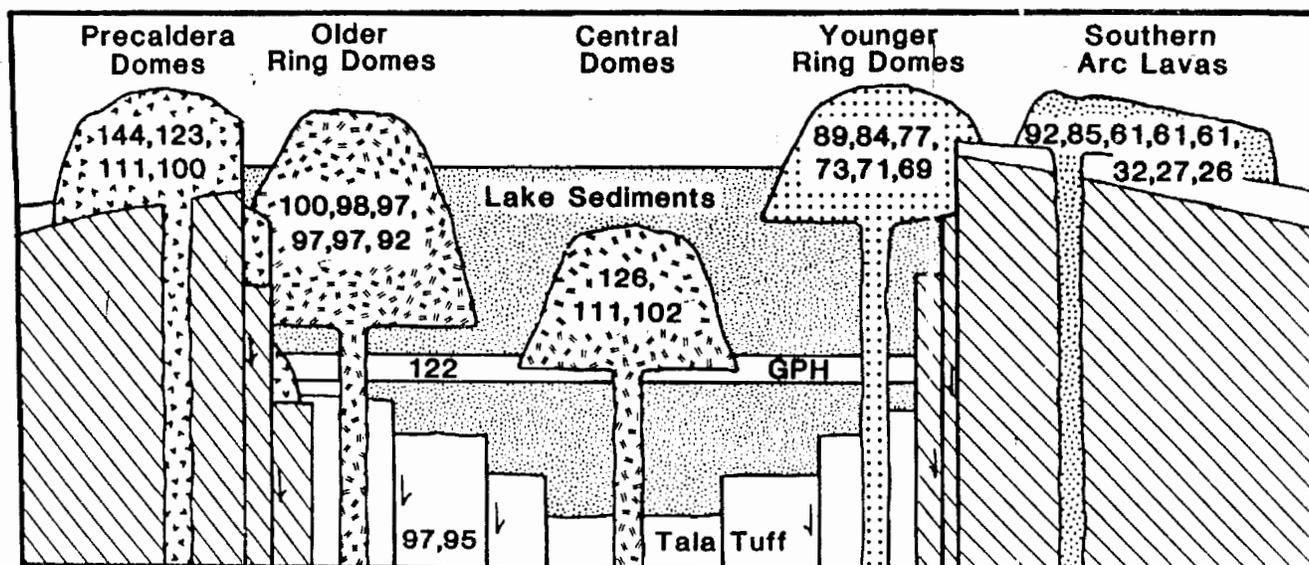


Fig. 12. Schematic diagram showing the relative stratigraphic relationships for volcanic units in Sierra de la Primavera (adapted from Mahood and Drake, 1983). Note the relationships between the Tala tuff and the central domes.

ing from the Oligocene (e.g., Mooser *et al.*, 1974) to the Pliocene and Pleistocene (e.g., Gastil *et al.*, 1979) have been discussed (Venegas-Salgado *et al.*, 1985; Ferrari *et al.*, 1994, in press). The difficulty in dating the onset of volcanism in the TMVB is partly due to the problem of definition of the province. If one assumes a Cocos plate subduction-related genesis for TMVB volcanics, then the onset and evolution of volcanic activity is related to the complexities and dynamic nature of plate motions of the (paleo-) Pacific realm and plate interactions along the continental margin. Volcanic activity of the SMO province significantly decreased about 27-21 Ma in response to changes in Farallon plate subduction (Atwater, 1989; Urrutia-Fucugauchi, 1978, 1986; McDowell and Clabaugh, 1979; Dickinson and Snyder, 1979). Neogene volcanism in the area reflects the evolving interactions of the Cocos, Rivera and North American plates, which developed in the present tectonic setting of the TMVB and subduction zone of the Middle America trench (MAT) (e.g., Delgado-Granados, 1993; Ferrari, 1995). Considering the complex magmatic arc sequences at given localities beneath the TMVB, a relationship with the southward migration of the Rivera triple junction along the paleo-trench system, formation of the Rivera and Cocos plates and development of the MAT may offer an age limit for the onset of TMVB volcanic activity. The mafic basaltic sequence observed in several areas in western and central Mexico that include the San Cristobal basalts studied paleomagnetically may constitute the basal volcanic unit of the TMVB (e.g., Ferrari *et al.*, 1994, in press). If this is the case, then volcanic activity related to the modern Cocos plate subduction started sometime around 13 to 8 Ma.

The within-site angular dispersions of most sites are

relatively high (Tables 1 and 3). Nevertheless, the magnetic polarity information appears well defined, and there is almost no evidence for secondary components in the demagnetization vectorial data (Figures 5 and 7). The magnetic record appears simple and the characteristic magnetizations correspond to primary TRM magnetizations. The magnetic carriers are likely low coercivity titanomagnetites with pseudo-single domain states (e.g., Figures 8, 9 and 10). Many volcanic units are characterized by reverse magnetic polarities and there is good agreement when units have been sampled at different localities. Because of the within-site dispersions, no attempt is here made to derive any tectonic implications from the paleomagnetic data. This important aspect requires further studies, which may permit to have a better comprehension of the paleomagnetic record and to define paleomagnetic directions for tectonic study. Paleomagnetic studies in adjacent areas have documented tectonic deformation occurring during the Neogene, e.g., the eastern Chapala region and for Los Altos plateau show overall mean directions deviated counterclockwise from the expected directions (Urrutia-Fucugauchi and Rosas-Elguera, 1994). Paleomagnetic results for volcanic units within the Jalisco block in contrast show concordant directions indicating the absence of significant tectonic movements (Nieto-Obregon *et al.*, 1992; Maillol *et al.*, 1997).

The Rivera triple junction may have migrated to off the tip of Baja California peninsula by 5 Ma and major spreading in the mouth of the Gulf of California by 4.5 Ma (e.g., Larson, 1972; Lonsdale, 1995). Establishment of Cocos plate subduction along the MAT could have been sequential or discontinuous, following along-margin displacements of terrane slivers. Paleoreconstructions of the past positions of

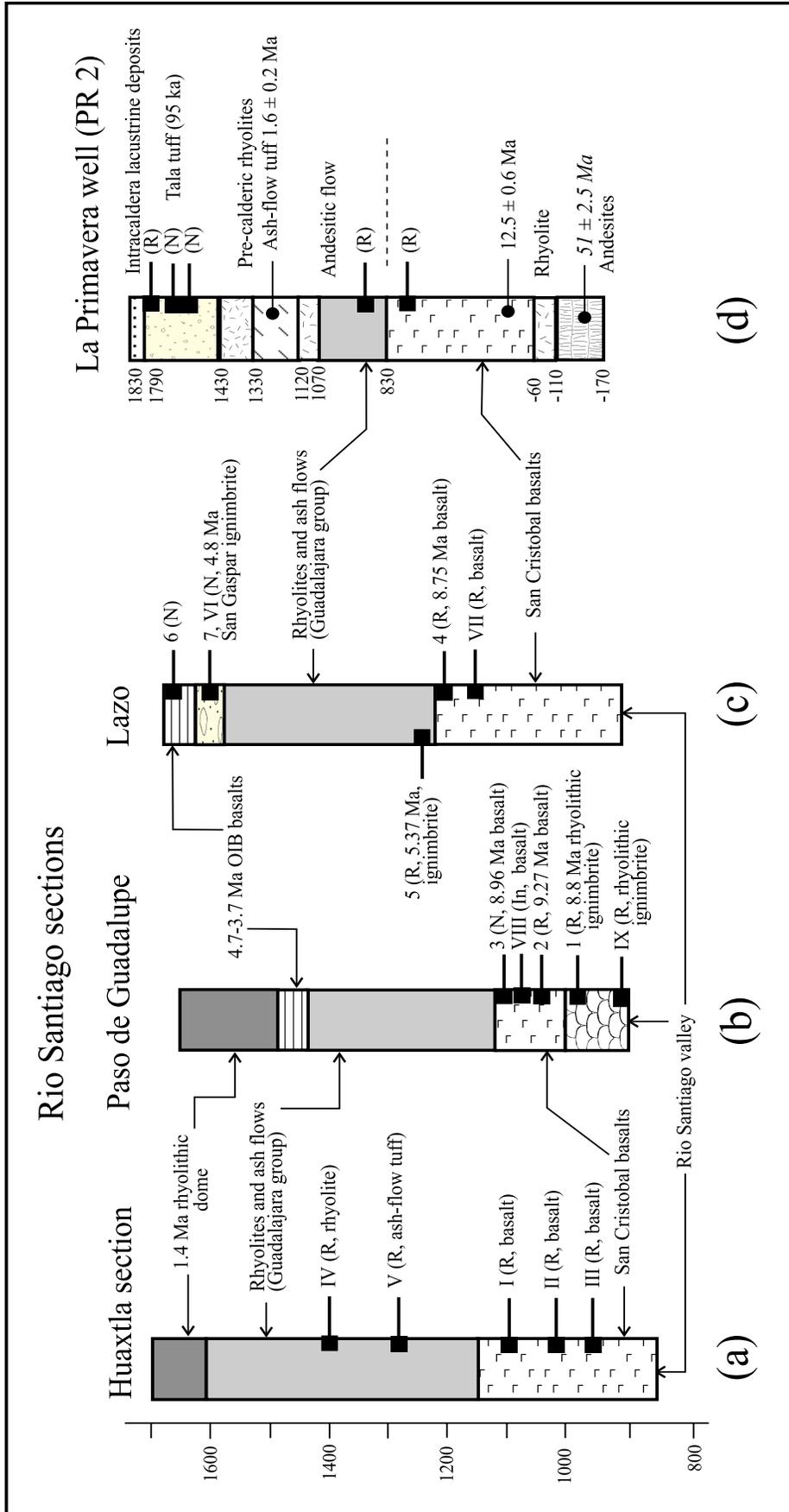


Fig. 13. Summary of the magnetostratigraphic results for this study with proposed correlations. The vertical coordinates are given in meters above sea level. Note the change in scale for the La Primavera well. Results are given in terms of the magnetic polarity for the three sections in the Río Grande de Santiago (Huaxtla, Paso de Guadalupe and Lazo) and the La Primavera well. The available K-Ar dates (see Table 2 and text) are included. The basal volcanic unit for the TMVB sequence is assumed to correspond to the mafic rocks referred in the area as the San Cristobal basalts. Magnetostratigraphic correlations are indicated by the arrows.

northern Central America or the Baja California peninsula imply complex processes and provide age constraints for the onset of plate subduction. For the western sector of the TMVB (Nayarit and Jalisco states) an age of 11 Ma might then be adequate, which correlates with the thick basaltic succession found to the north of Tepic (Gastil *et al.*, 1979) and in the Guadalajara and the Zacoalco-Colima-Chapala triple junction area (Allan, 1986; Moore *et al.*, 1994; Rosas-Elguera *et al.*, 1996).

CONCLUSIONS

The Oligocene-Miocene volcanic sequence of the SMO, and overlying younger volcanic units of the TMVB, are well exposed in the Río Grande de Santiago canyon to the north of Guadalajara region (e.g., Watkins *et al.*, 1971; Nieto-Obergon *et al.*, 1985; Moore *et al.*, 1994). Drilling for geothermal exploration by Federal Commission of Electricity in the Quaternary silicic center of Sierra de la Primavera, west of Guadalajara permits to investigate on the Miocene to Recent volcanic stratigraphy. Magnetic polarities derived from paleomagnetic studies have been used to construct a preliminary Miocene-Quaternary magnetostratigraphic correlation for the volcanic sequences of the Guadalajara region (Figure 13). Reference to the Geomagnetic Polarity Time Scale (Harland *et al.*, 1990; Baksi, 1993) and available K-Ar dates permit to estimate age ranges for the volcanic sequence in the Río Grande de Santiago, which extends from about 11 Ma to the Recent. K-Ar dates reported by Gilbert *et al.* (1985) for various units of the Guadalajara region range from about 7.7 Ma to 1.4 Ma. The K-Ar dates reported by Watkins *et al.* (1971) for the Río Grande de Santiago sequence range from 9.52 Ma to 4.77 Ma. The three sections of Huaxtla, Paso de Guadalupe and Lazo studied in the Río Grande de Santiago are around 800 m thick and include a basal rhyolitic ignimbrite (reverse), the San Cristobal basalts (mainly reverse), rhyolites and ash flows of the Guadalajara group (mainly reverse), the San Gaspar ignimbrite (normal), basaltic flows and a rhyolitic dome (normal). The Sierra de la Primavera sequence rests on an andesitic sequence and includes a rhyolite, the San Cristobal basalts (reverse), rhyolites and an andesitic flow of the Guadalajara group (reverse), ash flow tuffs, pre-caldera rhyolites, the Tala tuff (reverse, intermediate) and intra-caldera lacustrine deposits. The San Cristobal basalts represent the oldest TMVB activity in the region, with dates between 11 and 9 Ma. This interval corresponds to a normal polarity chron in the GPTS that contrasts with the dominant reverse polarity observed in the two volcanic sequences. The San Gaspar ignimbrite dated at 4.7–4.8 Ma has a normal polarity and represents a useful marker horizon in the Guadalajara region. This ignimbrite and the units of the Guadalajara group (with dates of 5.2–5.5 Ma) correlate with the Gilbert reverse chron, with the San Gaspar ignimbrite possibly correlating with the Thevera normal subchron (4.59–4.79 Ma). The silicic sequence of Sierra de la Primavera rep-

resents the young activity in the region and developed within the Brunhes chron. The Tala tuff has an intermediate-reverse polarity, which had been dated at 95-97 kyr (Mahood and Drake, 1982), and may correlate with the Blake subchron. Additional paleomagnetic study of the Tala tuff is required to investigate on magnetic carriers and nature of its paleomagnetic record. The K-Ar dates for the Tala tuff and for the central dome sequence are in inverse stratigraphic order (Mahood and Drake, 1982). If the correlation with the Blake subchron is adequate, then the Tala tuff is slightly older than the central dome sequence.

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