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Paleomagnetic data from the Trans-Mexican Volcanic Belt: implications for tectonics and volcanic stratigraphy

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We report a paleomagnetic and rock-magnetic study of Miocene volcanic rocks from the Trans-Mexican Volcanic Belt. A total of 32 sites (238 oriented samples) were collected from three localities: Queretaro, Guadalajara and Los Altos de Jalisco basaltic plateaux, which span from 11 to 7.5 Ma. Several rock-magnetic experiments were carried out in order to identify the magnetic carriers and to obtain information about their paleomagnetic stability. Microscopic observation of polished sections shows that the main magnetic mineral is Ti-poor titanomagnetite associated with exsolved ilmenite. Continuous susceptibility measurements with temperature yield in most cases reasonably reversible curves with Curie points close to that of magnetite. Judging from the ratios of hysteresis parameters, it seems that all samples fall in the pseudo-single domain (PSD) grain size region, probably indicating a mixture of multidomain (MD) and a significant amount of single domain (SD) grains. Based on our paleomagnetic and available radiometric data, it seems that the volcanic units have been emplaced during a relatively short time span of 1 to 2 My at each locality. The mean paleomagnetic directions obtained from each locality differ significantly from that expected for the Middle Miocene. The mean paleomagnetic direction calculated from 28 sites discarding those of intermediate polarity is $I = 32.46^\circ$, $D = 341.2^\circ$, $k = 7.2$ and $\alpha_{95} = 11.6^\circ$. Comparison with the expected direction indicates some 20° anticlockwise tectonic rotations for the studied area, in accordance with the proposed left-lateral transtensional tectonic regime already proposed for this period.

1. Introduction

The Trans-Mexican Volcanic Belt (TMVB), one of the largest continental volcanic arcs built on the North America plate, spans about 1000 km and crosses central Mexico from the Pacific to the Atlantic coast (Fig. 1). Subduction-related volcanism in Mexico resumed in the Eocene after Laramide deformation and formed the Sierra Madre Occidental silicic volcanic province (Fig. 1). During early to middle Miocene time, the volcanic arc rotated counterclockwise and, in the late Miocene, began to form the TMVB as a result of subduction of the Cocos and Rivera plates (Ferrari *et al*., 1999). The initial stage of the TMVB is marked by widespread basaltic volcanism, emplaced from the Pacific coast to the longitude of Mexico City, to the north of the modern volcanic arc (Fig. 1). This volcanism is characterized by plateau-like structures resulting from the coalescence of shield volcanoes and fissure lava flows, which have an estimated aggregate volume ranging between 3200 and 6800 km^3 (Ferrari *et al*., 2000). Geologic and stratigraphic studies have shown that these basaltic lavas were emplaced in a period between about 11 and 8 Ma (Ferrari *et al*., 1994a and 2000; Moore *et al*., 1994; Righter *et al*., 1995), which is also concurrent with the initial opening of the Gulf of California.

Several authors have suggested that during this period the TMVB, to the west of Guadalajara, experienced left-lateral transtensional tectonic deformation (Pasquaré *et al*., 1988; Garduño *et al*., 1993; Ferrari *et al*., 1994b and 2000; Urrutia-Fugugauchi and Rosas-Elguera, 1994). However, due to the poor behavior of basaltic rock for recording slickensides on fault planes, left-lateral oblique faulting has been directly observed at only a few sites. On the other hand, their well-established stratigraphic position and the easy access of these basalts makes them a good target for paleomagnetic studies, with the purpose of determining to what extent this succession has been affected by tectonic rotation about a vertical axis. In this paper we present the results of a regional paleomagnetic study of the basaltic sequences, which also provides better constraints on the age of the rocks.

2. Geologic Setting and Sampling

We carried out systematic sampling at sites located in upper Miocene basaltic lava flows in four areas in the states of

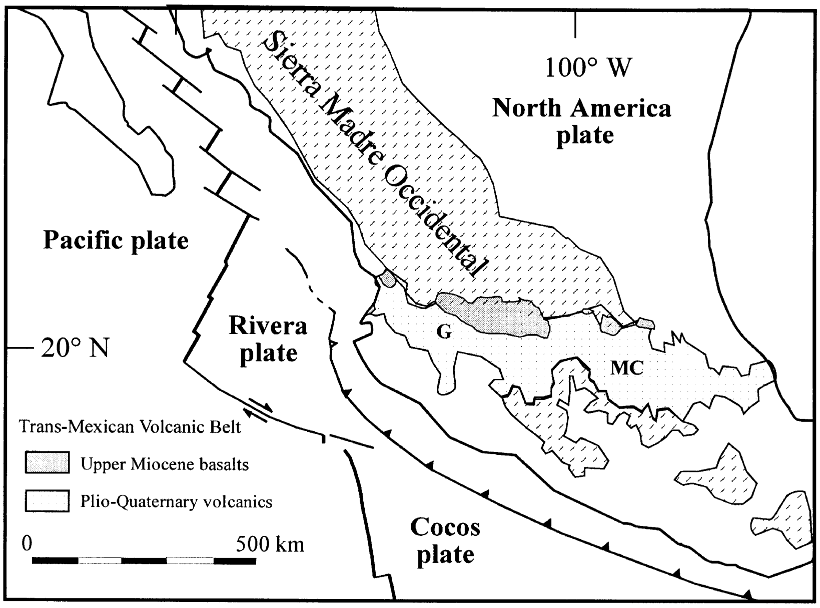

Fig. 1. Plate tectonic setting of central Mexico, showing the Cenozoic volcanic provinces and outcrops of upper Miocene mafic lavas. G = Guadalajara, MC = Mexico City.

Jalisco, Guanajuato, Queretaro, and Hidalgo (Figs. 1, 2, 3, 4). We focussed on sites where an isotopic age was available (Table 3) or that might be unambiguously correlated with dated sites.

The largest exposure of the upper Miocene basalts is along the Rio Grande de Santiago river canyon, north of Guadalajara (Figs. 2 and 3) where it has been informally named the *San Cristobal basalt* by Moore *et al.* (1994). The exposed volcanic succession is over 700 m thick and filled a pre-existing depression cut into lower Miocene ash-flow tuffs belonging to the Sierra Madre Occidental silicic volcanic province. We sampled this succession along two transects running along both riverbanks. The first one crosses the succession in a north-south direction at about 35 km north of Guadalajara (Fig. 2). Site BGC is located in an eroded basaltic shield volcano, dated at 11 Ma (Moore *et al.*, 1994), and represents the oldest rock of the succession. Two sites located to the south (AM) were later dated as early Miocene (Ferrari, unpublished data) and were therefore discarded from our paleomagnetic analysis. The rest of the sites (BM, and SCB series) are located at different elevations in the river canyon; where the succession was dated *ca.* 10 Ma (Damon *et al.*, 1979; Moore *et al.*, 1994; figure 2). The second transect is located immediately east of Guadalajara, about 20 km south of the site of a previous paleomagnetic and geochronologic study by Watkins *et al.* (1971). Rocks sampled are not dated at this location but can be correlated with those dated by these authors between 9.5 and 9.0 Ma (Table 3).

East of Guadalajara, in the *Los Altos de Jalisco* region, the basalts exposed in the Rio Grande de Santiago river form a 130 km long, 60 km wide plateau, with a mean elevation of 1900 m. In the Rio Verde valley, 25 km northwest of Tepatitlán (Fig. 3) the basalts are about 220 m thick and are affected by a left-lateral transtensional fault system running from Ixtlahuacán to San Miguel el Alto in a ENE-WSW direction (Ferrari *et al.*, 2000, see also Fig. 3). The southern part of the *Los Altos de Jalisco* plateau is disrupted by an extensional fault system, which runs from Ocotlán to Cuerámaro (Fig. 3) and shows a left-lateral component of motion. In this area the basalts crop out in tilted blocks partly covered by younger volcanic rocks (Rosas-Elguera and Urrutia-Fucugauchi, 1998). We sampled several blocks disrupted by transtensional fault system (LC, LR, AC, CM, LP). Another three sites were sampled to the north, inside a less disturbed plateau (SJG, AR, CP) (Fig. 3). The available dates indicate that at all these sites the basalts were emplaced between 10.2 ± 0.3 and 8.7 ± 1.0 Ma (Nieto-Obregon *et al.*, 1981; Nixon *et al.*, 1987; Rosas-Elguera *et al.*,1989; Rosas-Elguera and Urrutia-Fucugauchi, 1998).

East of Penjamo (Fig. 3), about 10 km north of Salamanca, upper Miocene basalts crop out as a tabular succession north of the *Bajio fault* (Nieto-Samaniego *et al.*, 1999, figure 4). They range between 100 and 200 m in thickness, and overlie lower Miocene ash flows and Oligocene rhyolitic lava domes (Fig. 4). Other outcrops of mafic lava flows emerge from the alluvial filling of the *Bajio* depression are found north of Celaya (Fig. 4). The lavas of Salamanca and Celaya yield dates ranging between 9.5 and 10.5 Ma (Hasenaka *et al.*, 1994; Cerca-Martínez, 1998), suggesting that they represent fragments of a unique tabular volcanic structure. We sampled the site dated as 10.2 ± 0.1 Ma by Hasenaka *et al.* (1994) (site TH), which represents one of the youngest lava flows in the succession.

The most widespread outcrops of upper Miocene lavas are around the city of Queretaro (Fig. 4), where several isolated tabular volcanic structures likely represent remnants of an old plateau-like structure at a mean elevation of 1950 m (Fig. 4). The lava flows cap a fluvio-lacustrine succession and exhibit a total thickness of about 80 m. Site AE is located in one of the uppermost lava flows exposed near the Queretaro airport,

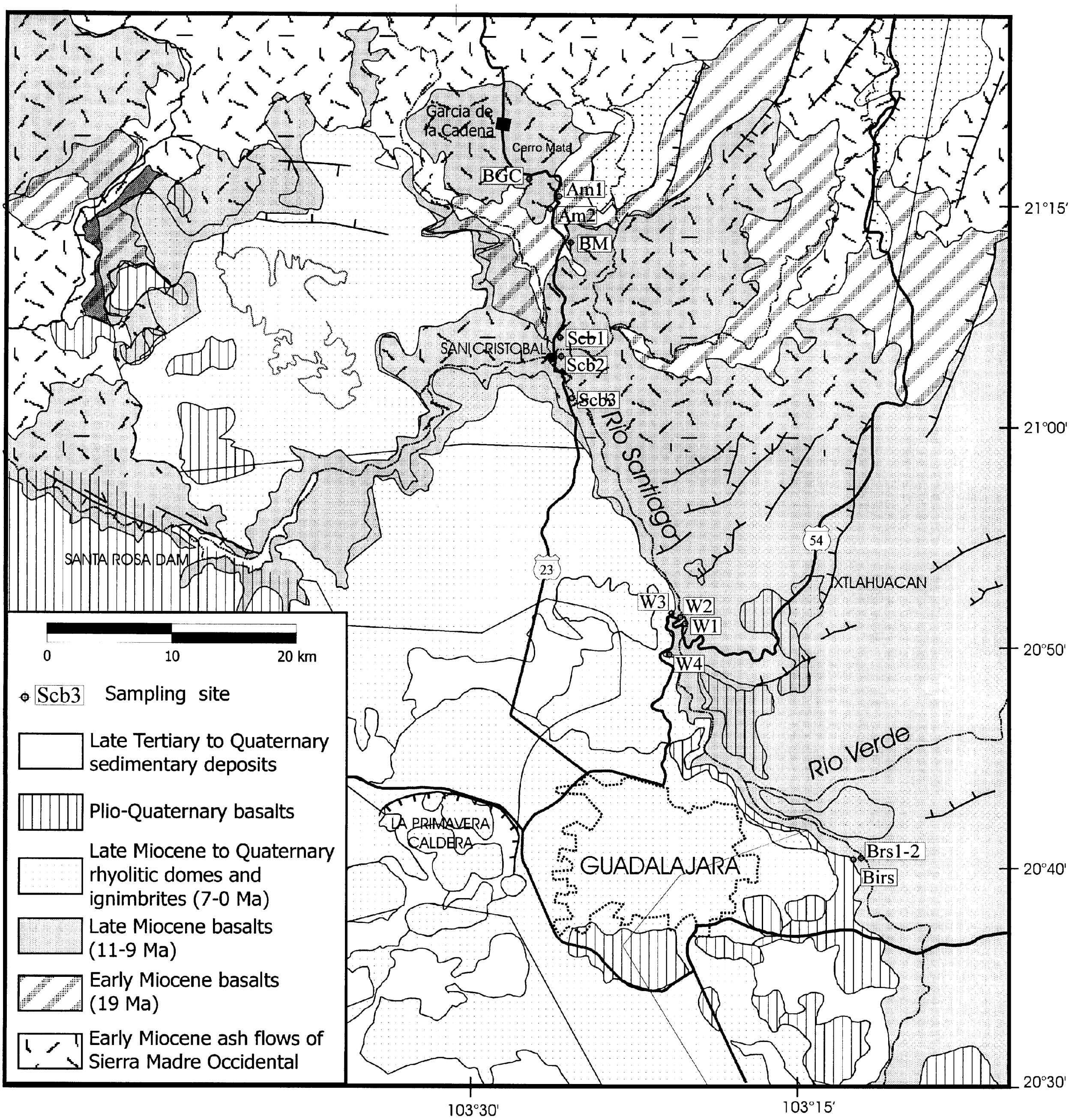

Fig. 2. Geologic map of the Rio Grande de Santiago and Guadalajara region with locations of sampling sites. Sites marked W1 to W4 are from Watkins *et al.* (1971).

having date of 8.1 ± 0.8 Ma (Pasquarè *et al.*, 1991). Site VC was in a basaltic andesite from the bottom of the succession, with an age of 9.6 ± 1.0 Ma (Murillo-Muñeton and Torres-Vargas, 1987). The other sites in the Queretaro area are in lava flows inferred to be bracketed between these dates (CA, LSE, LNE), except site CI, located in the Cerro Cimatario shield volcano, that caps the tabular basaltic succession and could be younger than the flows sampled at the Queretaro airport.

The easternmost exposure of upper Miocene basalts is in the state of Hidalgo around the Pathé geothermal area, ∼50 km east of Queretaro City (Fig. 4). The *Pathé* succession is defined by 80 to 300 m of sub-horizontal lava flows, interbedded with several spatter and scoria cones, which partly fed the basaltic succession. One of the uppermost lava flows was dated by Suter *et al.* (1995) at 7.7 ± 0.1 Ma, using $^{40}Ar/^{39}Ar$ systematics. We sampled two flows at the base of the succession in the northwestern part of the lava field, which were dated by Jacobo-Albarrán (1986) at 9.3 ± 0.5 Ma (Fig. 4).

In total, 238 oriented samples belonging to 32 flows were collected. Commonly, the outcrops extend laterally over a few tens of meters and in these cases we drilled typically 8–10 cores per flow. The samples were distributed throughout each flow both horizontally and vertically in order to minimize effects of block tilting and lightning. In general,

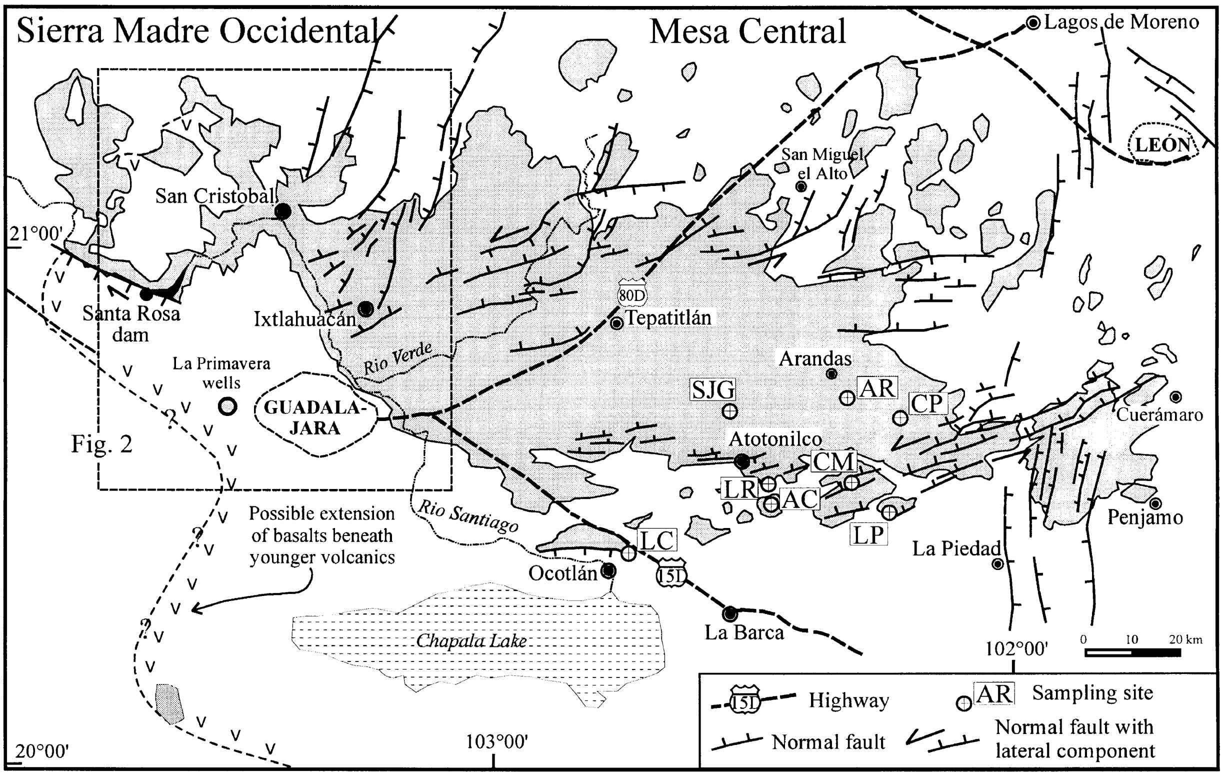

Fig. 3. Simplified geologic map of upper Miocene mafic lavas (in gray) and main fault systems of the *Los Altos de Jalisco* region (from Ferrari *et al.*, 2000) with location of studied sites. The area covered by Fig. 2 is also indicated.

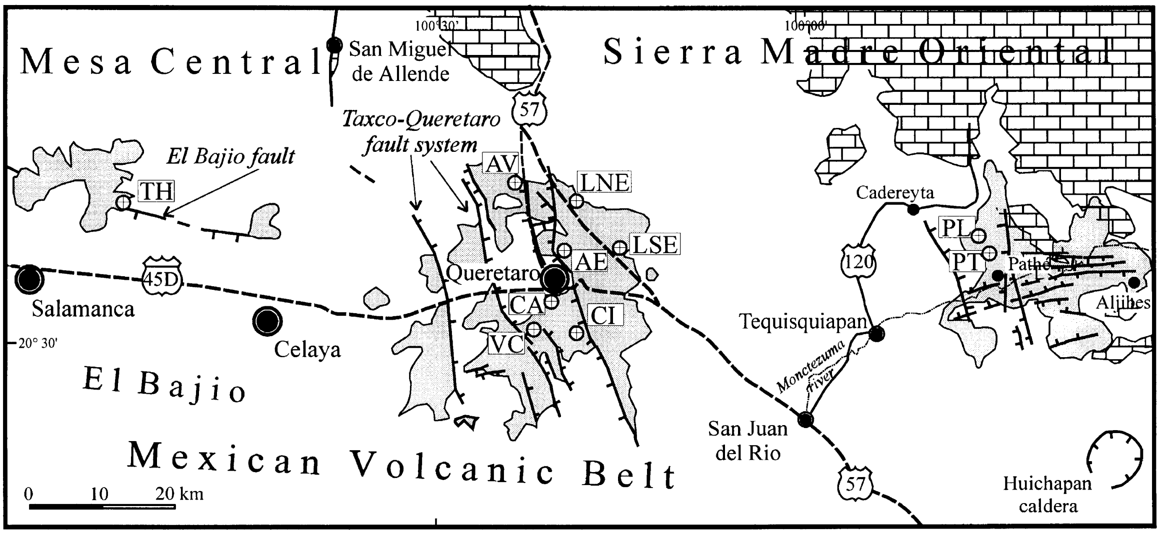

Fig. 4. Geologic sketch map of outcrops of upper Miocene mafic lavas and main faults in the Guanajuato, Queretaro and Hidalgo states (from Ferrari *et al.*, 2000). Boxed pattern indicates the Mesozoic sedimentary succession of the Sierra Madre Oriental.

samples were obtained at the very bottom of flows with the hope of collecting samples with the finest grained material. At a few, small outcrops, only 4–6 samples were collected. Three samples were taken from the apparently altered part of the unit PL. Due to their distinct paleomagnetic directions, we decided to identify this result as a different unit PL (bis). Cores were obtained with a gasoline-powered portable drill, and then oriented in most cases with a magnetic compass (after testing that it was not affected by the remanent magnetization of the outcrop).

3. Rock Magnetic Properties

3.1 Continuous thermomagnetic curves

Low-field susceptibility measurements (using Bartington MS2 system), performed on one sample per flow, yield two different types of behavior. More than half of the curves show the presence of a single magnetic/ferrimagnetic phase with Curie point compatible with relatively low-Ti titanomagnetite (Fig. 5A, sample BRS-7a). However, the cooling and heating curves are not perfectly reversible. Microscopic observations on polished sections also show that the main

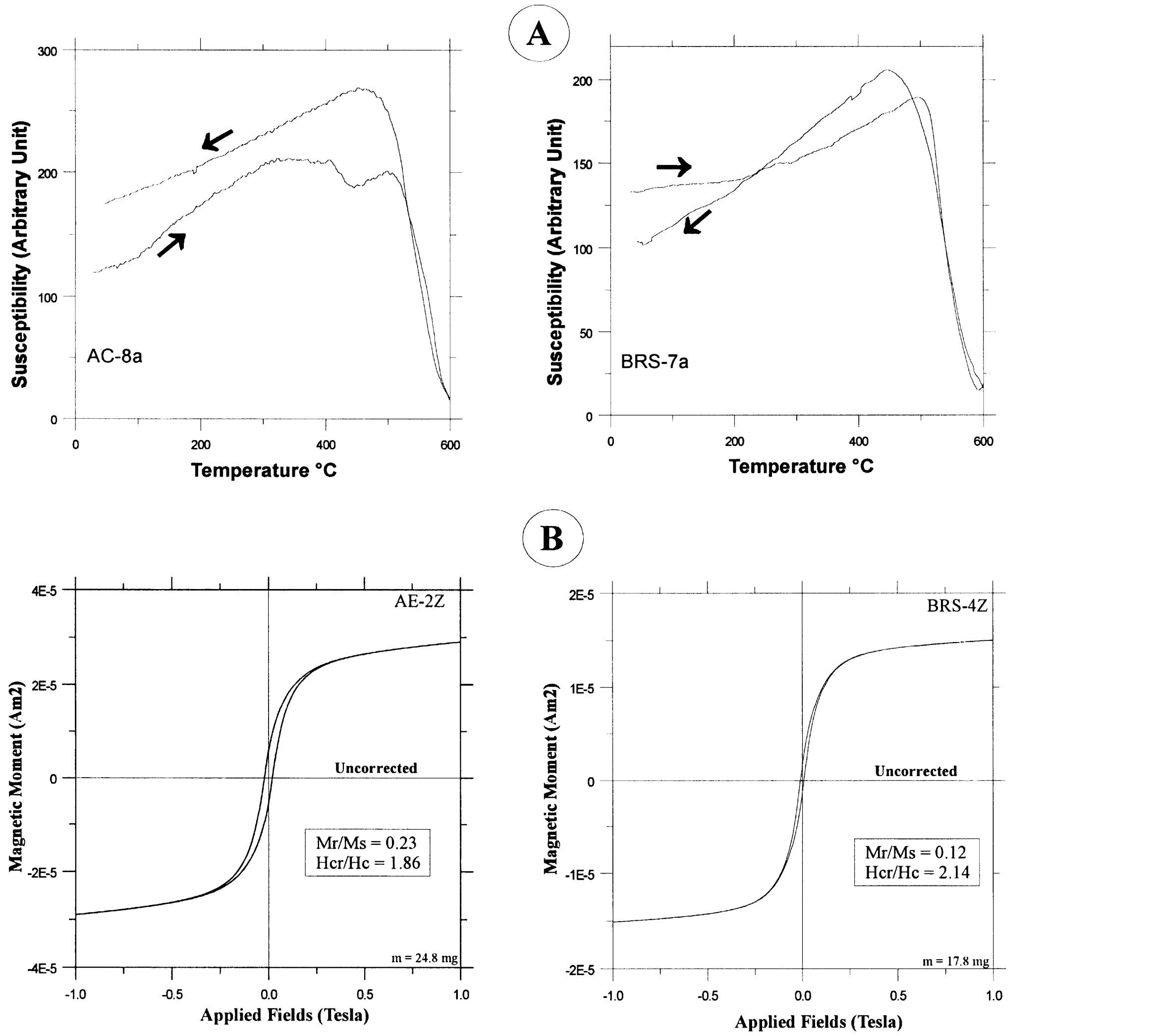

Fig. 5. A) Susceptibility versus temperature (in air) curves of representative samples. The arrows indicate the heating and cooling curves. B) Typical examples of hysteresis loops (uncorrected) of small chip samples from the studied volcanic flows.

magnetic mineral is low-Ti titanomagnetite associated with exsolved ilmenite, probably formed as a result of oxidation of titanomagnetite during initial cooling. These intergrowths typically develop higher than 600°C (Haggerty, 1976) and consequently, the NRM (natural remanent magnetization) carried by these samples should be a thermoremanent (TRM) magnetization.

In other cases, mainly flows from the Los Altos region, yield two different thermomagnetic phases during heating (Fig. 5A, sample AC-8a). The lower Curie point ranges between 380–420°C, and the highest one is about 580°C. The cooling curve shows only a single phase, with a Curie temperature close to that of magnetite. Such irreversible curves can be explained by titanomaghemite, which probably transformed into magnetite (Readman and O'Reilly, 1972; Özdemir, 1987) during heating. Both experimental and theoretical studies (Heider and Dunlop, 1987; Nishitani and Kono, 1989; Özdemir and Dunlop, 1989; Goguitchaichvili *et al.*, 2000) show that chemical remagnetization by maghemitization records have the same direction as the original TRM. Consequently, paleodirections were most probably unaffected by alteration.

3.2 Hysteresis experiments

Hysteresis measurements were performed on samples from all flows using an AGFM 'Micromag', in fields up to 1 T. Curves were rather symmetrical in all cases (Fig. 5B). Near the origin, no potbellied and wasp-waisted behavior (Tauxe *et al.*, 1996) was detected, which probably reflects very restricted dual ranges of the opaque mineral coercivities. IRM (isothermal remanent magnetization) acquisition curves (not shown) were found very similar for all samples. Saturation is reached in moderate fields of the order of 100–150 mT, which reveals that a cubic phase is principal remanence carrier. Based on the ratios of hysteresis parameters, all samples fall in the pseudo-singledomain (PSD) grain size region, probably indicating a mixture of multidomain (MD) and a significant amount of singledomain (SD) grains.

4. Paleomagnetism

4.1 Methods

Remanence measurements were made using a Molspin spinner magnetometer (sensitivity $\sim 10^{-8}$Am^2). Stepwise alternating field (AF) demagnetization used a home made AF demagnetizer providing fields up to 200 mT. Stepwise

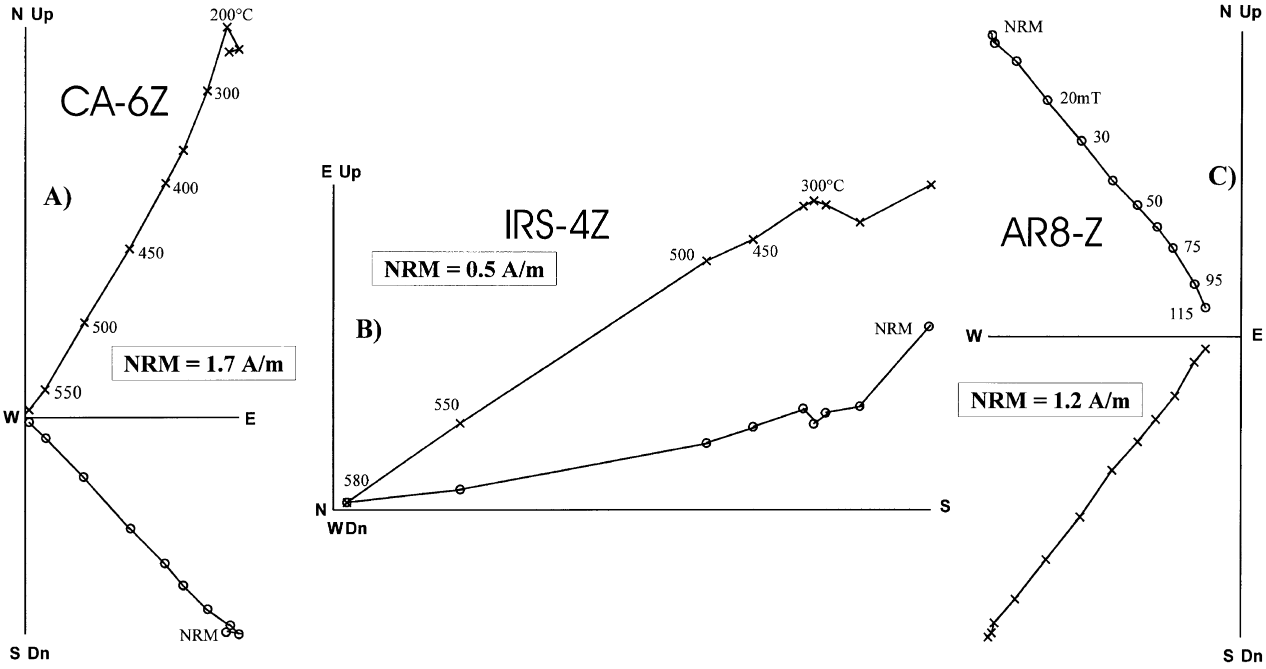

Fig. 6. Orthogonal vector plots of stepwise thermal or alternating field demagnetization of representative samples yielding mainly one component magnetization (stratigraphic coordinates). The numbers refer either to the temperatures in °C or to peak alternating fields in mT. O-projections into the horizontal plane, x-projections into the vertical plane.

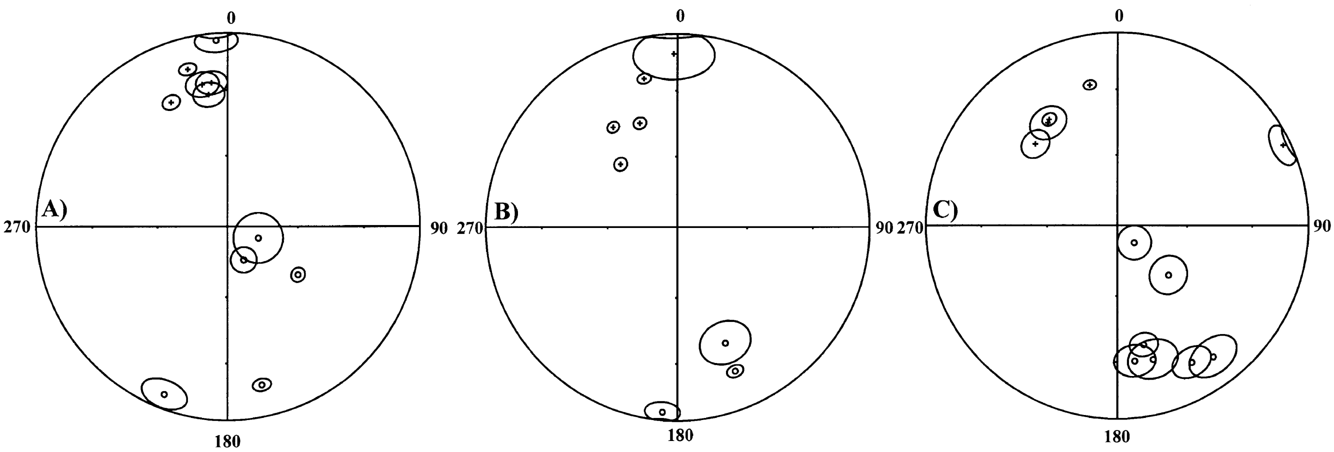

Fig. 7. Equal area projections of the flow mean characteristic paleodirections for three localities (A: Queretaro, B: Los Altos, C: Guadalajara). Circles/Crosses denote upper/lower hemisphere projections.

thermal demagnetization to 600°C was carried out using a Schonstedt furnace with a residual magnetic field of 20 to 25 nT. Heatings were performed in air. After each heating step, the low field susceptibility at room temperature was measured using a Bartington MS2 susceptibility meter.

A characteristic magnetization was determined by the least squares method (Kirschvink, 1980), with 4 to 9 points used for this determination. The directions were averaged by flow and the statistical parameters calculated assuming a Fisherian distribution.

4.2 Demagnetization

All 238 samples (i.e. one specimen per sample) were progressively demagnetized. Typically, 4 to 10 samples per flow were subjected to thermal or AF demagnetization, except unit PL (bis), for which we had only 3 oriented samples. Most samples carry essentially a single component magnetization, observed both upon thermal or alternating field treatment (Fig. 6). A generally small secondary component, probably of viscous origin, is sometime present and easily removed (Figs. 8A and B). The majority of the remanence was removed at temperatures between 500 and 550°C, which is common for Ti-poor titanomagnetite resulting from oxyexsolution. These observations are compatible with thermomagnetic experiments. The median destructive fields (MDF) range mostly from 30 to 40 mT pointing to single-domain (SD) magnetic grains as remanence carriers (Dunlop and Özdemir, 1997). Higher coercivity components (MDF more than 100 mT) were found for unit AE. Few samples showed

Table 1. Unit mean directions of remanence and corresponding VGP positions for all flows. N, number of treated samples; n, number of specimens used for calculation; Dec, Declination; Inc, Inclination. k and α_{95}: precision parameter and radius of 95% confidence cone of Fisher statistics, δ: angular distance from the normal dipole direction. Pol, Magnetic polarity, Plat/Plong: Latitude/Longitude of VGP position.

Flow	Location	Lat	Long	$n\backslash N$	Dec	Inc	k	α_{95}	δ	Pol	Plat	Plong
					Queretaro							
AE	Queretaro airport	20°37.130	100°22.952	8\8	335.3	30.1	263.1	3.4	21.2	N	66.1	163.7
AV	Sta. Rosa Jauregui, Qro	20°43.708	100°26.501	10\10	345.6	17.2	237.3	3.1	20.4	N	71.9	131.9
CA	Queretaro toll house	20°34.181	100°29.005	10\10	124.4	−53.4	418.6	2.4	136.1	I	−39.3	17.3
CI	Cerro Cimatario, Qro.	20°31.217	100°19.932	6\8	200.9	−8.1	100.1	7.7	148.5	R	−64	205.6
LNE	Highway to S.M. Allende	20°43.061	100°21.714	8\8	349.8	26.3	87.4	6.1	11.1	N	78.3	137.5
LSE	Highway to S.M. Allende	20°40.857	100°18.645	8\8	351.8	31.6	84.6	5.9	7.1	N	81.6	148.1
PL	North of Pathé, Hgo.	20°40.599	99°41.965	5\5	356.4	−4	132.2	6.7	37.2	N	67.3	89.9
PL (bis)	North of Pathé, Hgo.	20°40.599	99°41.965	3\3	110.8	−76.1	139.1	10.5	126.3	I	−27.4	52.7
PT	North of Pathé, Hgo.	20°39.909	99°41.920	8\8	167.7	−17.4	254	3.2	160.9	R	−73.5	308.3
TH	N of Juventino Rosas	20°42.168	101°02.584	8\8	353.6	26.1	94.7	5.7	8.9	N	80.9	122.4
VC	Villa Corregidora	20°39.965	100°25.606	6\6	154.1	−74.3	155	5.4	136.8	R	−46	62.3
					Los Altos							
AC	Atotonilco, Jal.	20°29.880	102°27.450	8\8	157.8	−20.7	339.5	3	156.8	R	−66.6	326.9
AR	W of Arandas, Jal.	20°42.130	102°19.660	9\9	326.9	38.2	445.8	2.4	27.3	N	59.1	176.8
CM	Ayotlán, Jal.	20°33.060	102°18.770	10\10	317.5	53.6	302.7	2.8	36.4	N	50.1	197.2
CP	Cerro Pelon quarry	20°40.530	102°13.900	9\9	157.2	−35.2	32.2	9.9	161	R	−68.6	349.3
LC	Ocotlán toll house, Jal.	20°24.100	102°44.140	8\8	184.7	−4.7	99.4	5.6	151.4	R	−71.5	243.6
LP	Presa Huascato, Jal.	20°29.310	102°14.000	10\10	339.9	42.2	360.3	2.5	18.3	N	71	184.1
LR	Atotonilco, Jal.	20°31.410	102°26.140	8\8	347.2	22.2	736.1	2.1	15.6	N	74.9	134.2
SJG	N of Atotonilco	20°41.200	102°32.660	8\10	358.8	11.1	15.4	13.5	21.9	N	75.1	82.3
MB*	Mesa del Burro	20°40.500	103°25.500	6\7	5	33.8	59.1	8.8	4.3	N	79.1	50.8
					Guadalajara							
AM2	El Malacate	21°09.670	103°25.740	7\7	167.4	−36.8	122.1	5.5	169	R	−78.2	342.3
AM1	El Malacate	21°09.330	103°26.110	6\8	164.9	−28.9	66.9	9.4	166.4	R	−74.3	325
BGCS1	Cerro Mata, Zac.	21°11.160	103°27.280	4\4	135.6	−79.8	165.8	7.2	129.9	I	−34.4	60.1
BGCS2	Cerro Mata, Zac.	21°11.160	103°27.280	5\5	151.1	−20.1	110.2	7.3	151.2	R	−60.1	330
BIRS	Rio Santiago canyon	20°40.420	103°11.370	4\4	325.8	35.8	157.4	7.3	28.2	N	58.1	171.9
BM	N of San Cristobal	21°07.890	103°25.180	5\6	133.9	−59.5	90.1	8.1	139.9	R	−46.4	24.1
BRS	Road to Ixtlahuaca	20°40.550	103°10.230	8\8	348.7	26.6	586.6	2.3	11.7	N	77.5	138.2
BRS1	Road to Ixtlahuaca	20°40.040	103°10.830	6\6	143.4	−16.4	55.4	9.1	143.1	R	−53.6	306.4
IRS	Road to Ixtlahuaca	20°40.300	103°11.160	4\5	172.6	−29.9	144.4	7.7	173	R	−81.7	316.3
ISG	San Gaspar	20°41.500	103°10.530	8\10	64.3	4.2	83.6	6.6	66.3	I	24.8	354.3
SCB1	San Cristobal	21°02.540	103°25.540	9\9	327.1	34.8	336.2	2.8	27.3	N	59.1	170.4
SCB2	San Cristobal	21°03.400	103°25.640	6\6	314.7	39.7	188.7	5.9	36.7	N	47.9	178.3

*Site MB represent very young (most probably late Bruhnes) lava flow and yielded paleodirections close to the present day field.

more complex or 'unstable' remanence and no primary magnetization was determined.

4.3 Directions of characteristic remanent magnetization

The flow mean paleodirections are overall well-determined (Table 1, Fig. 7). Almost all α_{95} values are less than 10°, except the unit PL (bis) where we had only 3 samples and SJG, which seems to be affected by lightning.

Six normal, three reverse and two intermediate polarity flows were recognized for *Queretaro* volcanic field (Table 1). Their correlation with geomagnetic polarity time scale (GPTS) is discussed below. In this paper, we formally use the paleolatitude of 45° as a cut-off angle to separate the paleosecular variation and intermediate geomagnetic regime (McElhinny and McFadden, 1997). In absence of more detailed paleomagnetic coverage, we are not sure that the in-

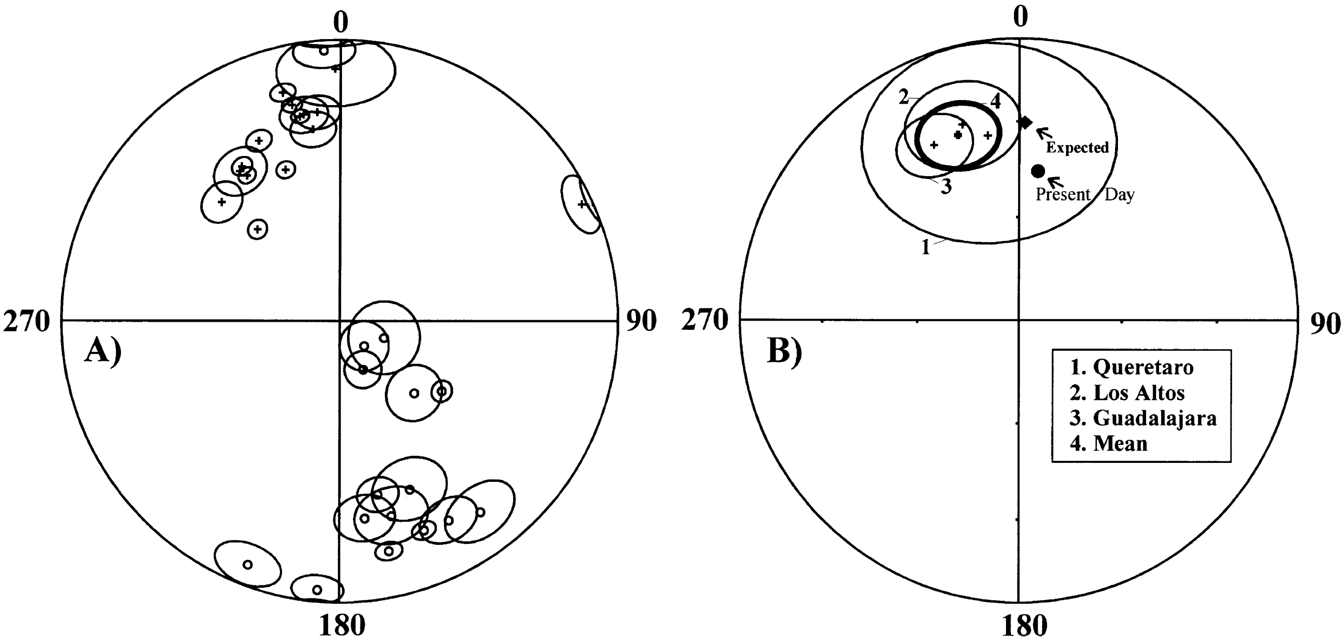

Fig. 8. Equal area projection of the mean directions for all flows and for the three groups of sites as indicated in Table 3.

Table 2. Between flow average directions and VGPs for the Queretaro, Los Altos and Guadalajara sites. S is the total between flow dispersion of average flow VGP. S_u and S_l are 95 per cent confidence limits for S after Cox (1969). Intermediate directions (flows: CA, PL (bis) and BGCS1) are discarded (see text). In addition, four units (AM1, AM2, MB and ISG) were also discarded for the analyses because their inadequate ages (see text and Table 3).

Locality	N	Inc	Dec	k	α_{95}	Plat	Plong	K	α_{95}	S	S_l	S_u
Queretaro	9	33.7	350.8	3	33.2	80.6	140	14	14.2	21.7	16.6	31.2
Los Altos	8	29.2	343.5	15	14.8	72.5	159	20	12.6	18.1	13.7	26.8
Guadalajara	8	33.5	330.7	21	12.4	63.4	164	18	13.5	19.2	14.5	28.4
All	25	32.4	341.2	7	11.6	72.7	158	16	7.5	20.3	17	25.2

termediate VGP's found in this study have a geomagnetic significance. *Los Altos* region yielded mostly normal polarity magnetization except flows AC, CP and LC, which are reversely magnetized. Six reversed, four normal and two intermediate polarity flows were recognized in *Guadalajara* volcanic field (Fig. 7 and Table 1)

5. Discussion and Conclusions

In general the polarity obtained for the flows studied is consistent with their stratigraphic position and with absolute age determinations for each site (Fig. 9). Combining the available geochronologic data with the polarity of the paleomagnetic samples obtained in this study, better constraints of the age of emplacement can be achieved (Table 3, Fig. 9).

Lava flows sampled in the northern transect of the Rio Grande de Santiago (BGC, BM and SCB series) may all be put into Anomaly 5. The older part of the sequence, sampled in the northern side of the valley, was reversely magnetized, and, in accordance with the age provided by Moore *et al.* (1994), should correspond to chron C5r.1r (10.94–11.05; Cande and Kent, 1995). The polarity of the rest of the succession was normal, and coincides with chron C5n.2n (9.92–10.94 Ma). The second transect along the Rio Santiago valley (BRS and BIRS samples) is less well dated but if one consider the ages provided by Watkins *et al.* (1971), recalculated with the constants of Steiger and Jäger (1977), the observed polarity appear to belong to anomaly 4A and to chron C4Ar.1r to C4Ar.2r (9.02–9.58 Ma) with samples BIRS and BRS corresponding to the short events of normal polarity C4Ar.1n.

Sites sampled in the *Los Altos de Jalisco* region also span Anomaly 4A and 5 (Table 3). The large experimental error ($2\sigma = 1 - 2$ Ma) of some of the available ages suggests that they are probably not very reliable. The real age may be inferred from the obtained polarity. Sites AC and CP were dated at 13.5 ± 1.3 Ma and 12.0 ± 2.0 Ma by Castillo-Hernandez and Romero-Rios (1991) and Verma *et al.* (1987); however, according with the stratigraphic position and the obtained polarity the real age probably fall within chron C5r, in the range 10.94–11.93 Ma. Similarly, site SJG, dated at 11.0 ± 2.0 Ma by Verma *et al.* (1987), could belong to chron C5n.2n (9.92–10.94 Ma) as most of the other sampled sites. The basaltic flow sampled north of Salamanca (TH) also belongs to chron C5n.2n (Table 3). However, the basalts exposed to the east, in the Queretaro and Pathé areas are distinctly younger, being emplaced within Anomaly 4 and,

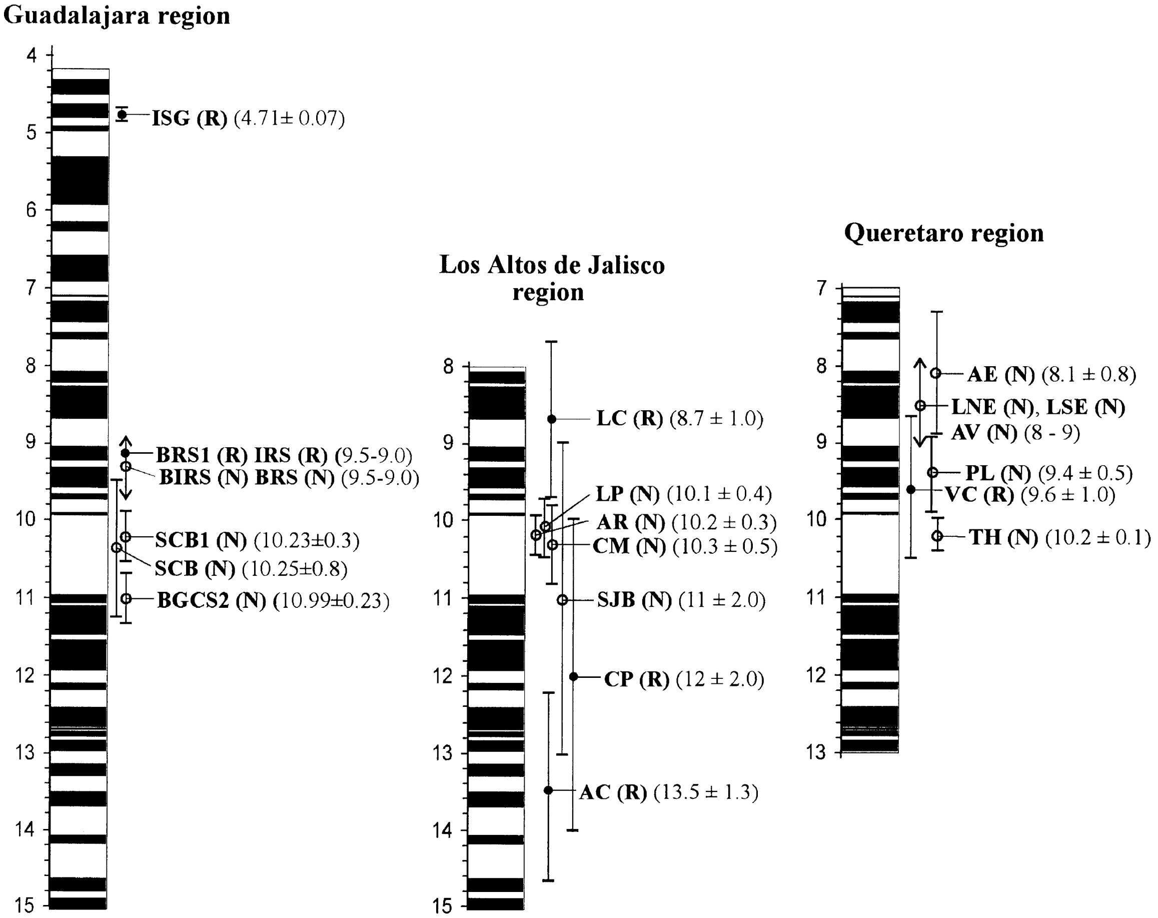

Fig. 9. Summary of the results from the three studied regions with possible relation with the geomagnetic scale of Cande and Kent (1995). Absolute ages are reported with error bar. Arrows indicate the possible age range of some sample based on correlation of geologic units.

likely between chron C4n and C5n.1n.

In conclusion, combining the magnetostratigraphic and isotopic age data set, the volcanic activity in the *Rio Grande de Santiago* and *Los Altos de Jalisco* regions appears to have taken place between 9 and 11 Ma and the volcanism in the Queretaro and Pathé areas took place between 7.4 and 9.8 Ma, thus revealing a marked eastward migration of volcanism with time.

Our paleomagnetic data has an unfortunately large dispersion (Fig. 8 and Table 2). We calculated mean directions in several ways. In order to omit transitional directions in the calculation, a cut-off angle is used to separate assumed paleosecular variation and intermediate field periods. Using of a correct cut-off angle is still controversial. Camps and Prévot (1996) showed that, if the angular distance from the dipole direction (δ on Table 1) exceeds 40°, the directions should be regarded as intermediate. McElhinny and McFadden (1997), analysing worldwide paleomagnetic data, used VGP paleolatitude of 45° as a limit of paleosecular variations. This cut-off angle was used in this study. *Queretaro* volcanic field yield the mean directions of $I = 33.7°$, $D = 350.8°$, $k = 3.4$, $\alpha_{95} = 33.2$. *Los Altos* region provide $I = 29.2°$, $D = 343.5°$, $k = 15$, $\alpha_{95} = 14.8$ and *Guadalajara* region $I = 33.5°$, $D = 330.7°$, $k = 20.8$, $\alpha_{95} = 12.4$. Using all data (25 flows), we obtained mean inclination of 32.4° and mean declination of 341.2°. The mean inclination (Fig. 8 and Table 2) is, in each determination, in good agreement with the expected inclination for the late Miocene, as derived from reference poles given by Besse and Courtillot (1991) for North America. The declination, however, is significantly different from that expected ($D = 1.2°$). The results from *Guadalajara* region shows the highest deviation in declination (Table 2). The mean direction calculated from all data suggest a mean tectonic counterclockwise rotation of about 20°. The declination deviation could be the consequence of local block rotations. However, our data set presents apparently large dispersion (Table 2) and is not sufficiently robust to enable an accurate determination of the variations in the magnitude of the rotations within the studied area. Counterclockwise rotations in central Mexico were previously recognized by Urrutia-Fucugauchi (1976) and later supported by additional studies (Urrutia-Fucugauchi, 1981; Urrutia-Fucugauchi and Böhnel, 1988). More recently, Urrutia-Fucugauchi and Rosas-Elguera (1994) reported about 15° counterclockwise rotation for latest Miocene to Quaternary lavas in the Lake Chapala area, south of the *Los Altos de Jalisco* region (Fig. 3).

These available paleomagnetic data, altogether with our new results may be explained by rotations of shallow crustal blocks by variable left-lateral shear across the studied region. Most sites along the Rio Grande de Santiago north of Guadalajara and in the *Los Altos de Jalisco* region lie

Table 3. Summary of the available isotopic age determinations for the studied volcanic flows and their possible relation to the Cande and Kent (1995) geomagnetic polarity time scale.

Sample age					
Site	Published age (Ma)	Ref.	Polarity	Possible Chron	Age (Ma)[(1)]
Guanajuato, Queretaro and Hidalgo					
AE	8.1±0.8	1	N	C4n–C4r.1n	7.43–8.25
AV	~ 8–9	*	N	C4n–C4r.1n	7.43–8.25
CA	~ 8–9	*	I	—	—
CI	undated		R	C3Br–C4n.1r	< 7.65?
LNE	~ 8–9	*	N	C4n–C4r.1n	7.43–8.25
LSE	~ 8–9	*	N	C4n–C4r.1n	7.43–8.25
PL	9.4±0.5	2	N	C4Ar.1n–C5n.1n	9.23–9.88
PL'	9.4±0.5	2	I	—	—
PT	9.4±0.5	2	R	C4n.1r	7.56–7.65
TH	10.2±0.1	3	N	C5n.2n	9.92–10.94
VC	9.6±1.0	4	R	C4Ar.1r–C5n.1r	9.02–9.92
Los Altos de Jalisco					
AC	13.5±1.3	6	R	C5r.1r–C5r.3r?	10.94–11.93
AR	10.2±0.3	6	N	C5n.2n	9.92–10.94
CM	10.3±0.5	5	N	C5n.2n	9.92–10.94
CP	12.0±2.0	7	R	C5r.1r–C5Abr	10.94–11.93
LC	8.7±1.0	8	R	C4r.1r–C4Ar.3r	8.07–9.74
LP	10.1±0.4	5	N	C5n.2n	9.92–10.94
LR	~10–11	*	N	C5n.2n?	9.92–10.94
SJG	11.0±2.0	8	N	C5n.2n?	9.92–10.94
MB*	—		N	—	—
Rio Grande de Santiago (Guadalajara)					
AM2	21.6±0.3	9	R	C6Ar	21.32–21.76
AM1	21.6±0.3	9	R	C6Ar	21.32–21.76
BGCS1	10.99±0.23	10	I	—	—
BGCS2	10.99±0.23	10	R	C5r.1r	10.94–11.05
BIRS	9.5–9.0	11	N	C4Ar.1n–C4Ar.2n	9.23–9.64
BM	~ 10–11	*	R	C5r.1r?	10.94–11.05
BRS	9.5–9.0	11	N	C4Ar.1n–C4Ar.2n	9.23–9.64
BRS1	9.5–9.0	11	R	C4Ar.1r–C4Ar.2r	9.02–9.58
IRS	9.5–9.0	11	R	C4Ar.1r–C4Ar.2r	9.02–9.58
ISG	4.71±0.07	12	I	—	—
SCB1	10.23±0.34	10	N	C5n.2n	9.92–10.94
SCB	10.25±0.82	10	N	C5n.2n	9.92–10.94

References: 1 Pasquaré *et al.*, 1991; 2 Jacobo-Albarrán, 1986; 3 Hasenaka *et al.*, 1994; 4 Murillo-Muñeton and Torres-Vargas, 1987; 5 Castillo and Romero, 1991; 6 Nixon *et al.*, 1987; 7 Verma *et al.*, 1987; 8 Rosas and Urrutia, 1998; 9 Ferrari, unpublished; 10 Moore *et al.*, 1994; 11 Watkins *et al.*, 1971; 12 Gilbert *et al.*, 1985. * inferred from stratigraphic relations, [(1)] Based on Cande and Kent, 1995.

close to two ENE-WSW trending left-lateral transtensional fault zones (Figs. 2 and 3) (Ferrari *et al.*, 2000). The first system runs from Ixtlahuacán to San Miguel el Alto and is characterized by several NNE trending *en echelon* splays, indicative of a left-lateral component of motion (Figs. 2 and 3). The second transtensional fault system runs from Ocotlán to Cuerámaro through Atotonilco (Fig. 3) and fault planes with a left-slip component of offset were observed at many sites (Ferrari *et al.*, 2000). The westward continuation of this system could be responsible for the counterclockwise rotation observed also in the Chapala area (Urrutia-Fucugauchi and Rosas-Elguera, 1994). Block rotation associated to these transtensional fault systems is probably responsible for the observed declination discrepancies. The relative scatter of the observed rotations in the three regions may be explained by considering that the fault system affects a rather wide belt that is fractured in several small blocks with variable internal rotation.

In the case of the Queretaro area the counterclockwise rotation with respect to that expected for North America is relatively small. This may be related to a minor left-lateral component of motion along the NNW-SSE trending Taxco-Queretaro and Pathé faults system (Fig. 4), which could be expected if these faults were reactivated by arc normal extension. Alternatively, it can be due to the left-lateral transtension along the ENE-WSW faults of the Cuitzeo lake region (Pasquaré *et al*., 1991), which continue to the ENE up to the Queretaro and Pathé areas (Fig. 4).

In conclusion, we propose that the paleomagnetic data reported here are consistent with an increasing counterclockwise rotation of upper Miocene rocks in central Mexico, from the Pathé area to the west, which could be related to intra-arc left-lateral transtension. In any case, more comprehensive work on these areas is required to understand the details of the shearing tectonics, which accompanied the early development of the Mexican Volcanic Belt.

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