Paleomagnetic and rock-magnetic survey of Brunhes lava flows from Tancitaro volcano, Mexico

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Resumen

Este estudio presenta los resultados paleomagnéticos del Volcán Tancitaro, (perteneciente al Campo Volcánico Michoacán Guanajuato), en el oeste de México, como una contribución a la base de datos de promediados en el tiempo del campo global. Se realizó el estudio paleomagnético y de magnetismo de roca en once flujos de lava. Se colectaron 120 núcleos orientados en el volcán Tancitaro y sus áreas aledañas. Todos los sitios fueron previamente fechados por ^{40}Ar -^{39}Ar (Ownby *et al.*, 2007,) y van desde 793 ka hasta el presente. Se realizaron experimentos de magnetismo de roca, curvas de susceptibilidad e histéresis magnética y en la mayoría de los casos la remanencia magnética fue por la presencia de titanomagnetita pobre en Titanio con estructura magnética de pseudodominio simple. Ocho de los once flujos de lava dieron polaridad normal, mientras que los tres restantes produjeron paleodirecciones inconsistentes y no se tomaron en cuenta para el análisis y se debió probablemente por efectos de rayos. La paleodirección principal obtenida de los ocho flujos es Inc=39.5°, Dec= 356.4°, k=29, α_{95}=9.1° lo cual corresponde a la posición del polo con Plat=84.4°, Plong=219.9°, K=33 y α_{95}=8.5°. Esta dirección es prácticamente consistente con la paleodirección esperada del Plio Cuaternario, derivada del polo de referencia para el Craton Norteamericano. La variación paleosecular coincide con otros estudios de la misma latitud y con modelos estadísticos recientes. La inclinación media cae dentro de la incertidumbre del Eje Dipolar Geomagnético más 5% de contribuciones cuadrupolares.

Palabras clave: Paleomagnetismo, variación paleosecular, promedio de tiempo de campo, epoca Brunhes, Cinturón Volcánico Trans- Mexicano.

Abstract

This study presents paleomagnetic results from Tancitaro volcanism in the Michoacan Guanajuato Volcanic Field, western Mexico, as a contribution to the time averaged field global database. Detailed paleomagnetic and rock-magnetic studies were carried out on eleven independent lava flows; 120 oriented, standard paleomagnetic cores were collected from Tancitaro volcano and surrounding areas. All sites were dated by means of ^{40}Ar-^{39}Ar (Ownby *et al.*, 2007) as originating from 793 ka to present. Rock-magnetic experiments included continuous susceptibility and hysteresis measurements. Remanence is carried mostly by Ti-poor titanomagnetite of pseudo-single-domain magnetic structure. Eight out of eleven flows yield normal magnetic polarities while three sites yielded inconsistent paleodirections most probably due to lightning. Mean paleodirection from eight flows is Inc=39.5°, Dec=356.4°, k=29, α_{95}=9.1° which corresponds to a pole position with Plat=84.4°, Plong=219.9°, K=33 and A_{95}=8.5°, practically undistinguishable from expected Plio-Quaternary paleodirections, for the North American Craton. Paleosecular variation is compatible with other studies at the same latitude bands and with recent statistical models. The mean inclination falls within the uncertainties of the Geomagnetic Axial Dipole plus 5% quadrupolar contributions.

Key words: Paleosecular variation, time averaged field, Brunhes chron, Trans-Mexican Volcanic Belt.

Introduction

Fluctuations of the geomagnetic field with time are essential for understanding the geodynamo, and conditions in the Earth's liquid core and at the core-mantle boundary. Paleosecular variation may indicate modulation of geodynamo action in the core by the convective state of the lower mantle. Thus, determinations of these variations are decisive for understanding the processes in the core that give rise to the geomagnetic field and how and why the Earth's magnetic field reverses polarity.

The fundamental factors in the variability of the Earth Magnetic Field are the Time Averaged Field (TAF) and paleosecular variation (PSV). The TAF initiative has begun to update the database of geomagnetic observations over the last five million years (Mejia *et al.*, 2005; Tauxe *et al.*, 2004, Lawrence *et al.*, 2006; Lawrence *et al.*, 2009). A simple method to estimate the PSV consists in observing of the angular standard deviation (ASD) of virtual geomagnetic poles (VGPs) for a given locality. Several combinations of dipole and non-dipole components predict the ASD characteristic of PSV with latitude (McFadden *et al.*, 1988, 1991; Lawrence *et al.*, 2006; Johnson *et al.* 2008)).

Johnson *et al.* (2008) reported a detailed synthesis of a new generation of paleomagnetic data compilations. The latitudinal dependence of VGP (virtual geomagnetic poles) scatter for these data appears much less important. The data at low latitudes seems to be more scattered than those at high latitude. This issue depends critically on a set of data of latitude 20°N. Published directional data from Trans Mexican Volcanic Belt (TMVB) meeting some very basic selection criteria (Herrero-Bervera *et al.*, 1986; Ruiz-Martinez *et al.*, 2000; Osete *et al.*, 2000, Morales *et al.*, 2001, Alva-Valdivia *et al.*, 2001; Mejia *et al.*, 2005; Petronille *et al.*, 2005, Rodriguez-Ceja *et al.*, 2006) show an unusually high degree of scatter, which might be due to genuine geomagnetic field behavior.

The present study reports time averaged field global database and paleosecular investigations at low latitudes, based on a detailed rock-magnetic and paleomagnetic study of eleven lava flows associated to Tancitaro Volcano in the Michoacan Guanajuato Volcanic Field (MGVF). All sites were recently dated by means of Ar^{40}-Ar^{39} systematics (Ownby *et al.*, 2007). The available ages range from 793 Ka to present.

Available age and sampling

The Trans-Mexican Volcanic Belt contains stratovolcanoes, cinder cone fields and silicic caldera complexes. Volcanism in this region dates from late Miocene related to the subduction of Cocos and Rivera plates at the Middle America trench. The western TMVB is associated with subduction of ~ 9 Ma Rivera plate, whereas the 12-18 Ma Cocos plate subducts under North America to the east (Klitgord and Mammerickx, 1982).

The Michoacan-Guanajuato volcanic field is located in the west-central part of TMVB (Fig. 1), east of Chapala Lake. The geographic boundaries of the MGVF are 18°45' N to 20°15' N and 100°25' W to 100°45' W, with an area of 40,000 km², It contains over 2,000 small monogenetic volcanoes including cinder cones (90%), maars, tuff rings, lava domes and lava flows with hidden vents all are predominant calc-alkaline but some alkaline and transitional rocks are also found Silica content varies from 47% to 70% for olivine basalt and basalt-andesite rocks (Hasenaka, 1994; Hasenaka *et al.*, 1994).

Volcán Tancítaro (VT) is a large andesitic, composite volcano in the Michoacán–Guanajuato Volcanic Field in west-central Mexico. With a height of 3840 m (Ownby *et al.*, 2007), VT is the dominant feature in the MGVF. Twenty-six new Ar^{40}-Ar^{39} ages indicate that Tancítaro became active ≥793±22 ka and that the most recent effusive activity occurred at 237± 4 ka. Two catastrophic sector-collapse events are identified and dated; the first one on the west flank between 694 and 571 ka, and the second on the east flank between 261 and 238 ka (Ownby *et al.*, 2007).

Our sampling strategy was largely conditioned by Ownby *et al.* (2007) who gave 26 new Ar-Ar incremental heating ages for Tancitaro and adjacent sorounding areas. We sampled only sites with available radiometric dating information (Table 1 and Fig. 2 trough 4), of easy access and yielding fresh, apparently unanltered outcrops. In total, 120 oriented samples belonging to 11 individual lava flows were collected. The samples were distributed throughout each flow both horizontally and vertically. All lava flows sampled were horizontal (dip less than 4°). In general, samples were obtained at the bottom of flows with the hope of collecting samples with the finest grained material. Cores were sampled with a gasoline-powered portable drill, and oriented in most cases with both magnetic and sun compasses.

Summary of magnetic experiments

In order to obtain the directions of characteristic remanent magnetization and to identify the principal magnetic carriers, following experiments were carried out: a) Thermal and alternating field demagnetizations, b) measurements of continuous thermomagnetic curves (low field susceptibility versus temperature), and c) hysteresis experiments.
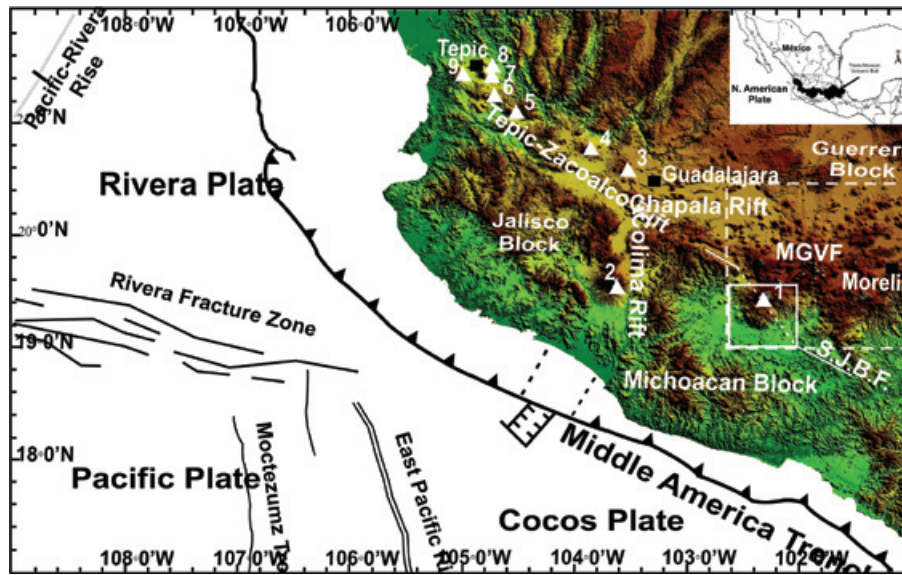
Fig. 1. Tectonic setting of western Mexico, adopted from Delgado-Granados (1993) and Ownby *et al.* (2007). Numbered triangles refer to volcanic centers: (1) V. Tancítaro, (2) V. Colima, (3) Sierra La Primavera, (4) V. Tequila, (5) V. Ceboruco, (6) V. Tepetiltic, (7) V. Sangangüey, (8) V. Las Navajas, (9) V. San Juan. S.J.B.F. = San Juanico–Bueanavista Fault. The dashed box represents the Michoacán Guanajuato Volcanic Field (MGVF).

Table 1

Flow-mean paleodirections of characteristic remanence, location and available isotopic age determinations (Ownby *et al.* 2007) for Tancitaro volcanics. N, number of treated samples; n, number of specimens used for calculation; Inc, Inclination; Dec, Declination; k and α_{95}: precision parameter and radius of 95% confidence cone of Fisher statistics.

| Site	n/N	Inc (°)	Dec (°)	k	a95	Lat (°)	Long (°)	Age (Ka)
Tan1 (TV)	3/9	23.8	7.8	56	16.5	N 19° 24' 58.3"	W 102° 18' 17.5"	209± 41
Tan2 (TV)	8/8	43.5	353.5	199	3.9	*idem*	*idem*	209± 41
Tan3 (UR-4)	8/8	60.9	339.9	242	3.6	N 19° 22' 27.7"	W 102° 05' 03.3"	429 ±64
Tan4 (San Fco)	0/8	-	-	-	-	N 19° 22' 08.8"	W 102° 21' 54.2"	339 ±23
Tan5 (Tan 28)	2/8	41.2	348.5	-	-	N 19° 23' 40.2"	W 102° 24' 43.8"	269± 22
Tan6 (Tan 26)	7/8	58.6	17.9	41	9.6	N 19° 25' 32.6"	W 102° 26' 07.9"	256 ±18
Tan7 (Tan 10)	6/8	28.1	348.6	115	6.3	N 19° 18' 32.0"	W 102° 32' 22.5"	373 ±61
Tan8 (Tan 43')	8/8	27.7	2.5	359	2.9	N 19° 15' 42.7"	W 102° 33' 50.6"	612 ±41
Tan9 (Tan 43)	8/8	31.3	352.7	39	9.2	N 19° 16' 05.5"	W 102° 34' 08.44"	612 ±41
Tan10 (NI 19)	7/8	32.8	1.2	69	7.3	N 19° 09' 52.4"	W 102° 12' 56.7"	82 ±24
Tan11 (NI 18)	7/8	43.6	349.3	198	4.3	N 19° 00' 36.9"	W 102° 04' 03.5"	163± 37
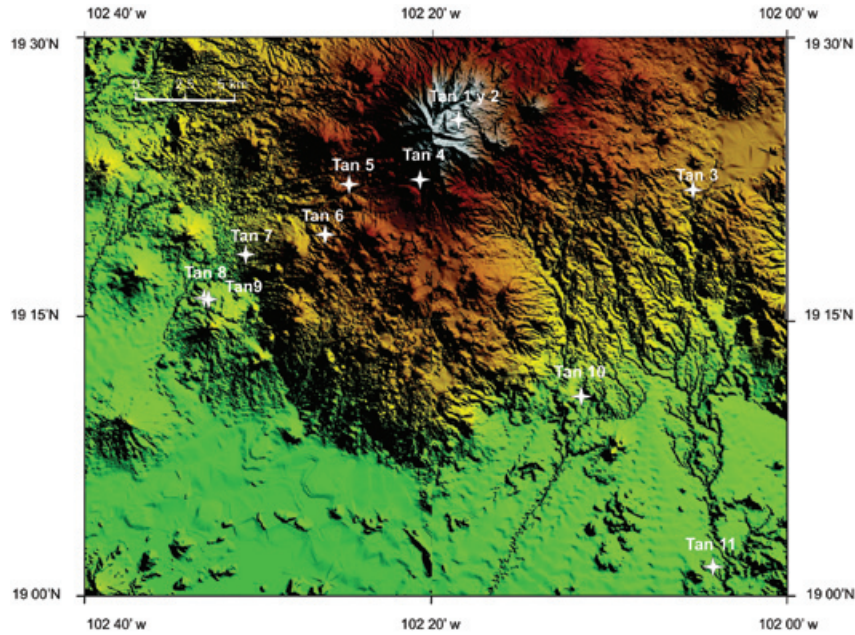
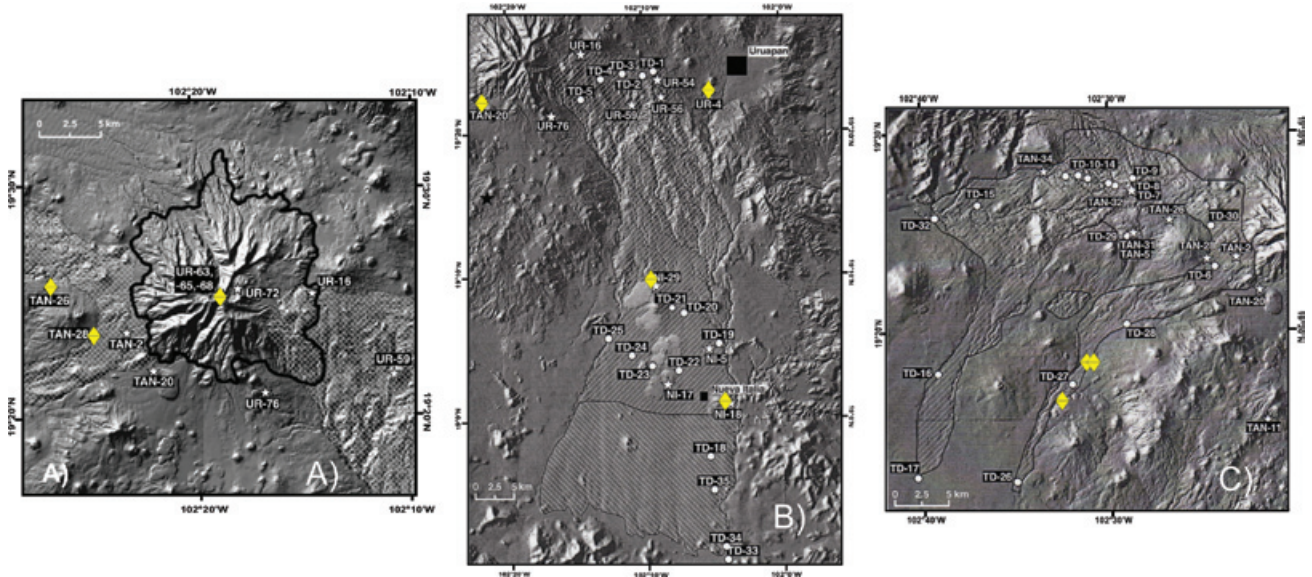Fig. 2. Digital elevation model for Tancitaro area showing the location of sites.

Fig. 3. Greater details of sampled site location (adopted from Ownby *et al*. 2007).

Remanence Properties

The remanent magnetizations of seven to nine samples from each lava flow (Table 1) were measured with a JR-6 (*AGICO LtD*) spinner magnetometer (nominal sensitivity ~ 10^{-9} Am^2) at the Laboratorio Interinstitucional de Magnetismo Natural (LIMNA) in Morelia (Mexico). Both

alternating field (AF) demagnetization (using a *molspin* AF-demagnetizer) and stepwise thermal demagnetization up to 560 °C (using a *ASC TD-48* furnace) were carried out. During thermal demagnetization, the low-field susceptibility at room temperature was measured after each step with a Bartington susceptibility meter.

Two-component magnetizations were systematically recognized for most of studied units (Fig. 4). The secondary components are sometimes much stronger than primary ones (samples 08T012A, 08T012B and 08T093A). The characteristic magnetizations components are isolated after applying 40 mT peak alternating field. It should be noted that AF treatments proved to be more efficient than thermal demagnetization. This is illustrated at Fig. 4. Samples 08T012B and 08T012A belong to the same core. While thermal treatment is unable to isolate primary remanence, the alternating fields could reveal the primary, characteristic magnetization at last steps of demagnetization procedure. We believe that the origin of this strong secondary overprint is due to the lightning effect. This is in agreement with the fact that the NRM (natural remanent magnetization) directions show huge dispersion on the equal-area projection. We note that no ChRM directions were obtained from sites TAN1, TAN4 and TAN5.

For remaining sites, relatively small, secondary components, probably of viscous origin were detected and were easily removed applying 10 mT (Fig. 4, sample 08T107A). The greater part of remanent magnetization, in most cases was removed at temperatures between 520 and 560°C, which indicate to low-Ti titanomagnetites as responsible for magnetization. The median destructive fields (MDF) range mostly from 20 to 40 mT, suggesting pseudo-single domain grains as remanent magnetization carriers (Dunlop and Özdemir, 1997).

A characteristic magnetization direction was determined by the least squares method (Kirschvink, 1980), 4 to 10 points being taken in the principal component analysis for this determination. The obtained directions were averaged by unit and the statistical parameters calculated assuming a Fisherian distribution.

Susceptibility vs. Temperature

Low-field susceptibility measurements (k-T curves) under air were carried out using *Agico-Kapabrdige* susceptibility meter equipped with furnace in Saint Maur (France) IPGP laboratory. One sample from each site were heated up to about 630°C at a heating rate 20°C/min and then cooled at the same rate. Curie temperature was determined by the Prévot *et al*'s (1983) method. Alternatively, low-temperature (from about –185°C to room temperature) susceptibility was recorded using the same apparatus.
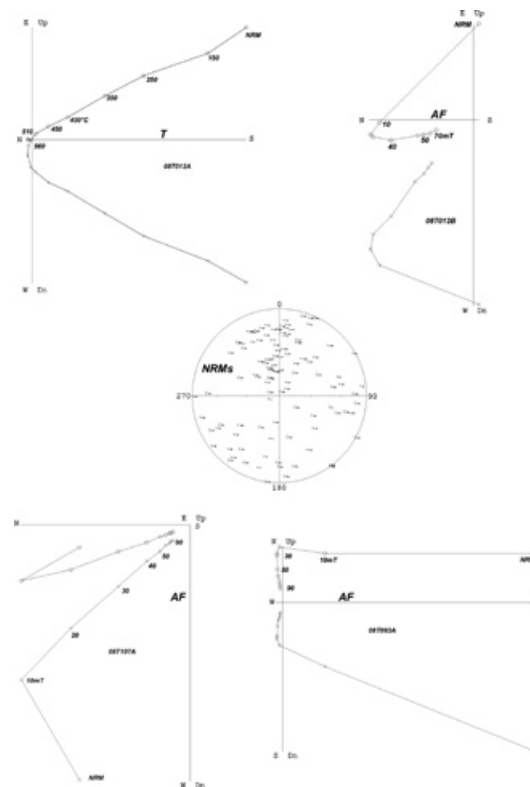

Fig. 4. Orthogonal vector plots of stepwise thermal or alternating field demagnetization of representative samples. The numbers refer either to the temperatures in °C or to peak alternating fields in mT. o - projections into the horizontal plane, x – projections into the vertical plane. Also shown (middle) is the equal area projections of NRM directions before magnetic treatments.

Low-T susceptibility experiments (Fig. 5) show a rather monotonic increase from about -185°C to room temperature with no indication of Verwey transition. Some titanium-poor titanomagnetite may be responsible for remanent magnetization. As showed by Özdemir *et al.* (1993), the Verwey transition may be largely suppressed for the titanomagnetites with variable titanium content. Alternatively, similar behavior may also belong to non-stoichiometric (partially oxidized) magnetite. Corresponding high-T susceptibility experiments (Fig. 6) also indicate the presence of Ti-poor titanomagnetites. However, the cooling and heating curves are not perfectly reversible, probably because of low initial value of magnetic susceptibility. This may also be due to some **moderate mineralogical alteration at high** temperatures. Both Ti-rich and Ti-poor titanomagnetites seem to co-exist in few lava flows (samples 08T107 and 08T004A). These curve yields apparently two different thermomagnetic phases during heating. The lower Curie point ranges between 300-400°C, while the highest one is about 570°C.

Hysteresis

Magnetic hysteresis measurements were performed at room temperature on a specimen from all sampled sites at IPGP (Saint Maur) laboratory apparatus in fields up to 0.8 Tesla. The histeresis parameters were calculated after correction for the paramagnetic contribution. The coercivity of remanence (H_{cr}) was determined by applying progressively increasing backfield after saturation. Typical hysteresis plot are reported in Fig. 7a. The representative curve is simple, symmetrical and reflects very restricted ranges of the coercivities (Tauxe *et al.*, 1996). Judging from the ratios of hysteresis parameters (Fig. 7b), it seems that all samples fall in the pseudo-single domain (PSD) grain size region (Day *et al.*, 1977). This may also indicate a mixture of multidomain (MD) and a significant amount of single domain (SD) grains (Dunlop and Özdemir, 1997; Dunlop, 2002).

Results and discussion

Beside strong lightning effect, the average unit directions are rather precisely determined for 8 independent lava flows out of 11 collected (Table 1, Fig. 8a). All α_{95} are less than 10°. All flows yielded normal polarity magnetization as may be expected for the Bruhnes age rocks. We consider the paleodirections determined in this study to be of primary origin. Thermomagnetic curves show that the remanence is carried in most cases by Ti-poor titanomagnetite, resulting of oxy-exsolution of original titanomagnetite during the initial flow cooling, which indicates that the primary magnetization is a TRM (thermoremanent magnetization). Moreover, unblocking temperature spectra and relatively high coercivities point to pseudo-single domain magnetic structure grains as responsible for remanent magnetization. The mean paleodirection obtained from eight flows is Inc=39.5°, Dec=356.4°, k=29, α_{95}=9.1° which corresponds to the pole position Plat=84.4°, Plong=219.9°, K=33 and A_{95}=8.5°. These directions are practically undistinguishable (Fig. 8a and b) from both the spin axis and the expected Plio-Quaternary paleodirections, as derived from reference poles for the North American craton (Besse and Courtillot, 2002). This may indicates that no major regional tectonic rotation occurred in the area since about 1 My. The mean inclination overlaps within the uncertainties to those derived from the GAD (Geomagnetic Axial Dipole) and GAD plus a 5% quadrupolar contributions.
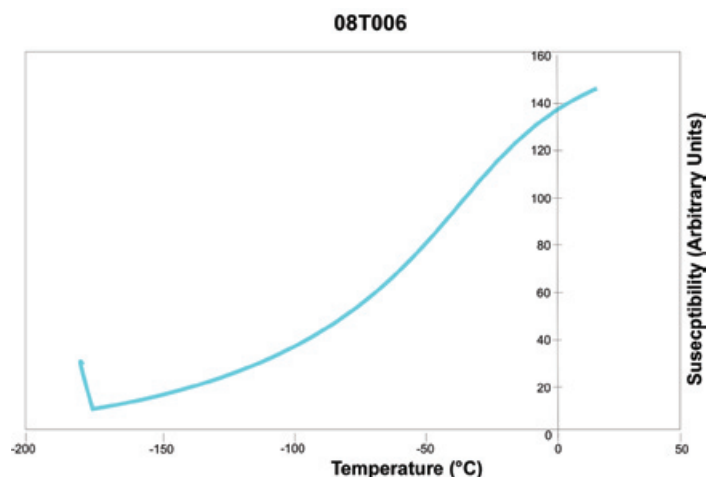

Fig. 5. representative curve of susceptibility vs. temperature curve recorded from -185°C to room temperature.
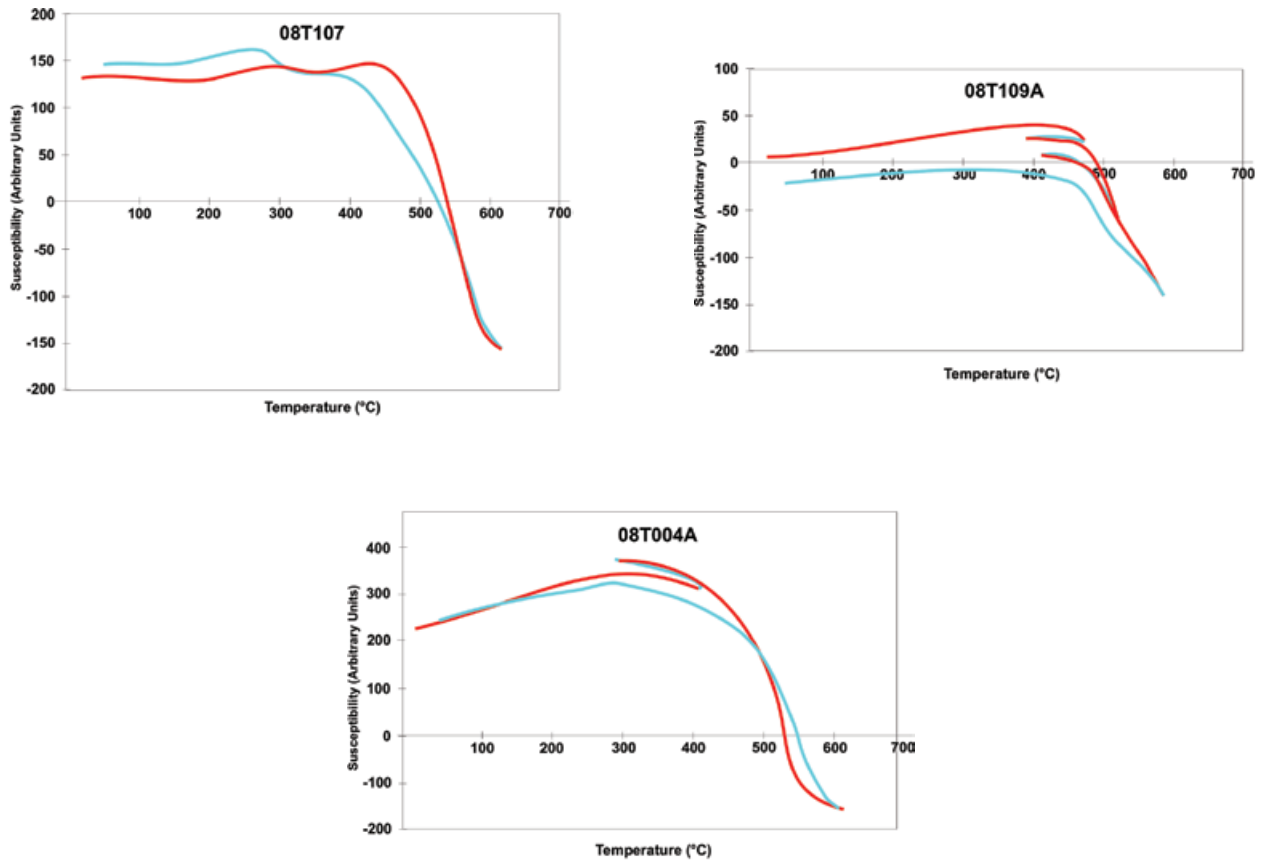
Fig. 6. Susceptibility versus temperature (in air) curves of representative samples at high temperatures.
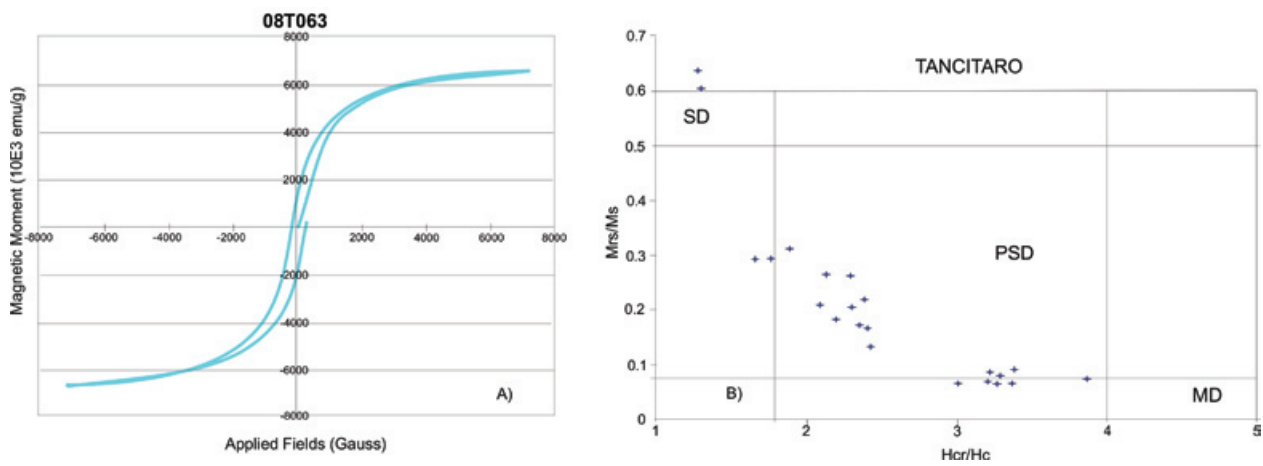

Fig. 7. Typical examples of hysteresis loops (uncorrected) and Day (Day *et al.* 1977) plot.

The formula $S_F^2 = S_T^2 - S_W^2/n$ was used for estimating paleosecular variation in this study where, S_T is the total angular dispersion $S_T = \left[(1/N-1)\sum_{i=1}^{N} \delta i^2\right]^{1/2}$ [*Cox*, 1969], N the number of sites used in the calculation, δ_i the angular distance of the *i*th virtual geomagnetic pole (VGP) from the axial dipole, S_W the within site dispersion (following McEllhinny and McFadden, 1997) and, *n* the average number of sample per site. All new VGPs obtained on this study yield lesser colatitudes (maximum value is 28.3°) than generally adopted 45° cut-off angle (Johnson *et al.*, 2008). We obtained S_F=16.0 with S_U=25.5 and S_L=8.1 (upper and lower limits respectively) which reasonably agree to the model G of McFadden *et al.* (1988, 1991) fit to the McElhinny and McFadden (1997) and Johnson *et al.* (2008) databases for the last 5 Myr (Fig. 8b and 9).

The combination of our data with previously published results from Central and Western Mexico (Conte, 2004) yields that the amplitude of the secular variation is consistent with values obtained from other worldwide scattered sites. Thus, the hypothesis of the Pacific dipole window (Doell and Cox, 1971) may be rejected. This supports the findings of McElhinny *et al.* (1996) and Ruiz-Martínez, (2004). **Within the uncertainties, the** results obtained in this study agree with the PSV values for Hawaii (+20° latitude) and Reunion (-20° latitude). However, the amplitude of dispersion found is much higher in Mexico with respect to other places at the same latitude bands in agreement with findings of Lawrence *et al.*, 2006. More high quality studies and reevaluation of old sites are needed in order to estimate whether this is a genuine characteristic of geomagnetic field.
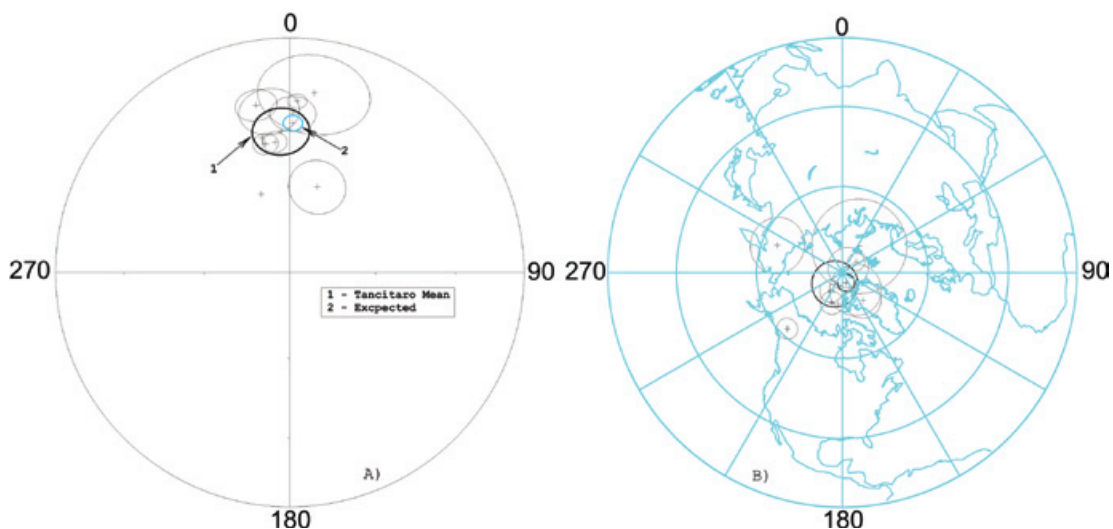

Fig. 8. A) Equal area projections of the flow-mean characteristic paleodirections for the Tancitaro volcanics and B) corresponding virtual geomagnetic pole positions.
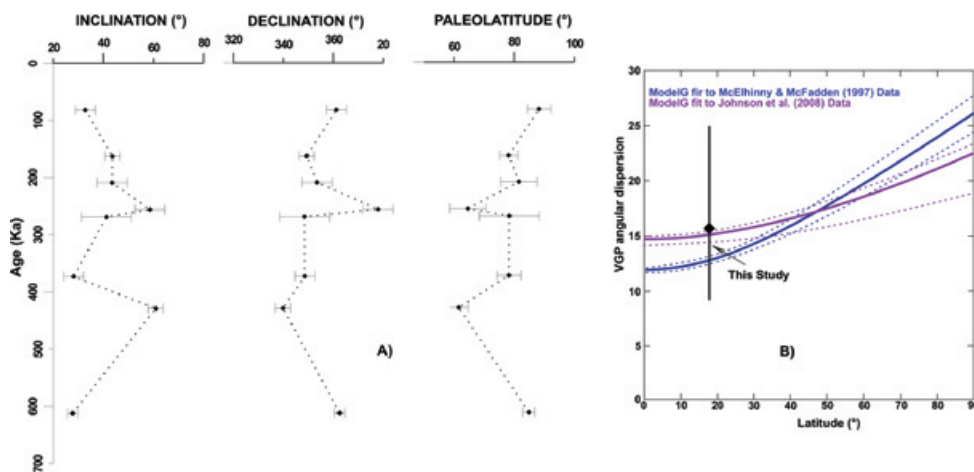

Fig. 9. A) Flow-mean magnetic declination, inclination and paleolatitude of virtual geomagnetic poles against age, B) Paleosecular variation of lavas (PSVL) for the last 5 Ma. (Adopted from McFadden *et al.*, 1988 and 1991 and Johnson *et al.* 2008).

Acknowledgements

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