



PALEOMAGNETISM AND TECTONICS FROM THE LATE PLIOCENE TO LATE PLEISTOCENE IN THE XALAPA MONOGENETIC VOLCANIC FIELD, VERACRUZ, MEXICO

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ABSTRACT

The Xalapa monogenetic volcanic field, Veracruz, Mexico is located at the eastern end of the Trans-Mexican Volcanic Belt. This study uses 196 specimens collected from 20 sampling sites in, 0.8 ka to 5.96 ± 0.156 Ma, Xalapa lavas and 34 specimens from 3 sampling sites in, 4.5 ± 0.028 Ma, La Concha Ignimbrite. For the lavas, the study (1) identifies the magnetic mineralogy by reflected light microscopy, thermomagnetic curves and UnMix curves; and (2) defines the magnetic domain size distribution by hysteresis plots, day diagrams, and First Order Reversal Curves. For the basalts and the ignimbrite: (1) characteristic remanent directions and virtual geomagnetic poles are calculated; (2) paleosecular variation is defined, which is coherent with the expected values; (3) net rotation experienced, at each site, since the emplacement is calculated.

The results are used to improve some of the already published radiometric dates. Calculation of net rotation allowed the identification of the rotation domains, active since past ~ 2.5 Ma, due to a major system previously proposed by other authors in the region. This, in-turn, supports the identification of new strike-slip faults system, in the previously known normal faults. The study establishes a relationship between the translational fault systems and the distribution of volcanoes. Finally, a caution is raised for the future studies and the importance of analyzing the site-specific paleomagnetic information with respect to the local geological setting is emphasized.

Keywords: Paleomagnetism, tectonics, Xalapa, volcanic field, Mexico

1. Introduction

Due to oblique convergence and different subduction angles along the Middle America trench, there are different crustal blocks delimited by active fault systems (Andreani *et al.*, 2008a; Ferrari *et al.* 2012). In the north, these blocks are delimited from the North American plate by active rifting along the Trans Mexican Volcanic Belt (TMVB). The study area is part of the southern Mexico block.

The NNW trending Pliocene -Quaternary strike-slip Veracruz fault system in the Veracruz Basin is important because it connects two major structural provinces, the sinistral strike-slip faults province in the south and the central part of the TMVB affected by the sinistral transtensive faulting. The area, thus, represents the transition between the strike-slip and the normal faulting, and has therefore, experienced $N110^\circ$ to $N130^\circ$ trending sinistral strike-slip faults (Andreani *et al.*, 2008b) and normal faulting striking $\sim N072^\circ$ (Andreani *et al.*, 2008b). The fault system reveals wrenching in some parts (Andreani *et al.*, 2008b). The master fault is associated with E-W to NE-SW trending secondary synthetic Riedel shears (Andreani *et al.*, 2008a).



2. Local Geology

The study area is located in a region of Quaternary scoria cones, stratovolcanoes and shield-like volcanoes between the Cofre de Perote-Pico de Orizaba volcanic range, and the south Gulf of Mexico Coastal Plain. The present study aims at applying rock- and paleomagnetic techniques on the basalts of the XMVF and the La Concha Ignimbrite to calculate the characteristic remanent magnetization (ChRM) directions. Paleosecular variation (PSV) is calculated for the basalts. The ChRM directions are used to establish a magnetostratigraphic sequence of different flows. The magnetostratigraphic column aids in refining the radiometric dates of some lava flows. The ChRM directions are compared with the Apparent Polar Wander Path (Torsvik *et al.*, 2012) to calculate the rotation suffered due to the strike-slip faulting in the area. This allows the identification of synthetic and antithetic faults and small transpressive zones. A relation between the faults and volcanism is established.

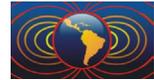
3. Methodology

Samples were obtained with a portable gasoline powered drill. One polished section was prepared from each site and was studied through a reflected light microscope. Furthermore, temperature dependent low-field magnetic susceptibility (χ -T) experiments were carried out at high temperatures on a Highmoore Susceptibility Bridge equipped with a furnace. Magnetic domain type distribution of the ferrimagnetic minerals was determined from hysteresis, acquisition of isothermal remanent magnetization (IRM) curves, and backfield using AGFM Micromag apparatus in fields up to 1.2 Tesla. The First order reversal curves (FORC) were calculated for one standard sample per site. The UnMix curves were calculated to reveal the coercivity distribution.

All specimens were demagnetized in an AF Molspin demagnetizer and non-inductive Schonstedt furnace, and measured using a JR-5 spinner magnetometer in the magnetically shielded room at the Paleomagnetic Laboratory of the Geophysics Institute, UNAM, Mexico. Alternating field (AF) demagnetization was performed in peak fields up to 100 mT. Prior to demagnetizing of samples, first two pilot specimens from each site, were demagnetized by AF and thermal with 10–12 steps to analyze and determine the best laboratory strategy to obtain the ChRM directions. The ChRM directions are determined as line or plane data using principal component analysis, and in some cases, the sites were treated with the combined analysis on remagnetization circles (planes) and directions (lines).

The PSV was obtained from the dispersion of the angular standard deviation, SB, considering that the angle Θ_i is of the directions with respect to the average of the N sites (see eq. 9 of Johnson and McFadden, 2015). Its upper and lower limits (Su and Sl) were obtained from the relationship proposed by Cox (1969). However prior to this calculation, all sites (normal and reversal polarities) were combined in normal polarity, for the best statistic, and a cut off was decided based on the algorithm of Vandamme (1994). The dispersion between-site, SB, was compared with Model G and model TK03.GAD of the PSV. Additionally, the A95 confidence envelopes criteria proposed by Deenen *et al.* (2011) was calculated to decide if the number of sites studied represents an optimal population for understanding the variations of the geomagnetic field.

Combining the radiometric dates with the virtual geomagnetic pole and comparing them with the known geological polarity time scale (GPTS; Cande and Kent, 1995) permitted the construction of the magnetostratigraphic column and improve the published radiometric dates at 6 sites. The net rotation since emplacement of the basalts, was calculated using the ChRM directions, and the Apparent Polar Wander Path (APWp), by Torsvik *et al.* (2012).



4. Characteristic remanent magnetization (ChRM) directions results.

The basalts present two magnetization components with distinct coercivity. The low coercivity component is removed by an alternating field lower than 10 mT or a temperature in the range of 250 – 300 °C (Fig. 1). This component, attributed to viscous remanent magnetization, contributes between 10 - 20%, and in some cases up to 25% of the total remanent magnetization. The high coercivity component is stable up to 100 mT, and accordingly all sites provide reliable ChRM as for most sites $\alpha_{95} < 10$, and only few sites present $10.3 < \alpha_{95} < 15.5$. The ChRM was used to calculate the virtual geomagnetic poles. The general mean ChRM directions of the La Concha Ignimbrite is Dec = 169.07, Inc = -27.92, $k = 44.0$, and $\alpha_{95} = 6.3$.

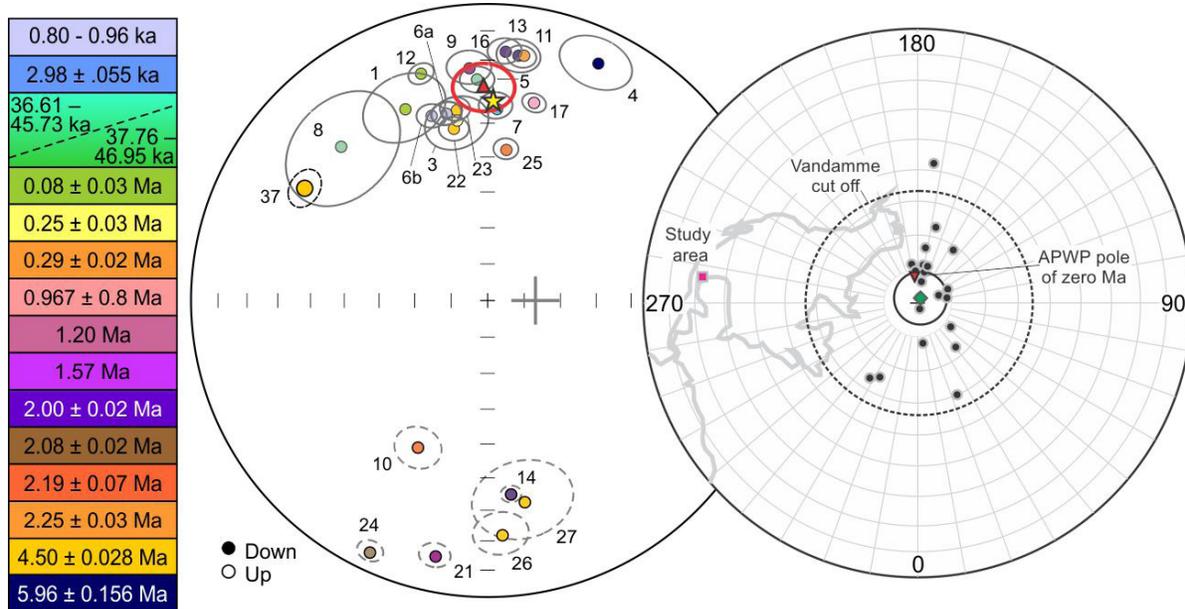


Figure 1. In a stereonet, depending on the age of the lava, color coded ChRM is plotted. The virtual geomagnetic poles are plotted using PuffinPlot (Lurcock and Wilson, 2012).

5. Discussion

The stratigraphically underlying El Castillo Ignimbrite shows a mean counter-clockwise rotation of $16^\circ \pm 5.8$ (Alva-Valdivia *et al.*, 2017). A similar uniformity was, thus, expected from the basalts, however, they are rotated 44.8° counter-clockwise to 31.7° clockwise. They do not show any system either chronologic or spatial, with respect to the Río Actopan fault (Fig. 2). The unsystematic rotation of the basalts is owed to the sampling locations. The sampling sites of the ignimbrite and the basalt are not identical except in two cases, sites 30 and 4 (Fig. 2). Probably the rocks at some sampling sites of basalts suffered rotation due to local faults. This is further supported by the fact that basalts of the same age, but different location, present different rotations, for example, sites 1 and 12; 13, 14 and 16; and 22 and 23 (Fig. 2). However, the rotation allows the identification of local rotation domains and demarcation of the translation in faults near the sampling sites. Rotation due to faulting at sampling sites of the El Castillo Ignimbrite is calculated from the results published in Alva-Valdivia *et al.* (2017) and is provided in the Figure 2. The geometry of the domains depends upon the rotation of the nearby sites, the trend of the faults in vicinity and distribution of volcanoes.

Along the Río Actopan fault, all sites of basalts and the El Castillo ignimbrite reveal an anti-clockwise rotation of 6° to 45° (Fig. 2). This rotation suggests that the Río Actopan fault has a sinistral translational component that agrees well with that of the Veracruz fault system and along the TMVB on a regional scale.



Morales-Barrera (2009) and Rodríguez *et al.* (2010) observed and inferred faults ‘B’, ‘E’, ‘H’, ‘J’, and ‘K’ (Fig. 2). They considered these faults as normal because of a clear scarp or other evidence of down-throw. Rotation at sites near to these faults is anticlockwise indicating a sinistral strike-slip component. These faults were, therefore, affected by normal and strike-slip faulting and are synthetic to the major Río Actopan fault (Fig. 2). Notably, the site 28 of the El Castillo ignimbrite is on the footwall of the fault ‘B’ and shows a clockwise rotation of 3° , antithetic to the Río Actopan fault. However, site 26 on the hanging wall has an anti-clockwise rotation of 26° . The minor antithetic 3° rotation is therefore considered insignificant. Morales-Barrera (2009) and Rodríguez *et al.* (2010) observed strike-slip faulting at ‘C’, ‘D’ and ‘I’, but did

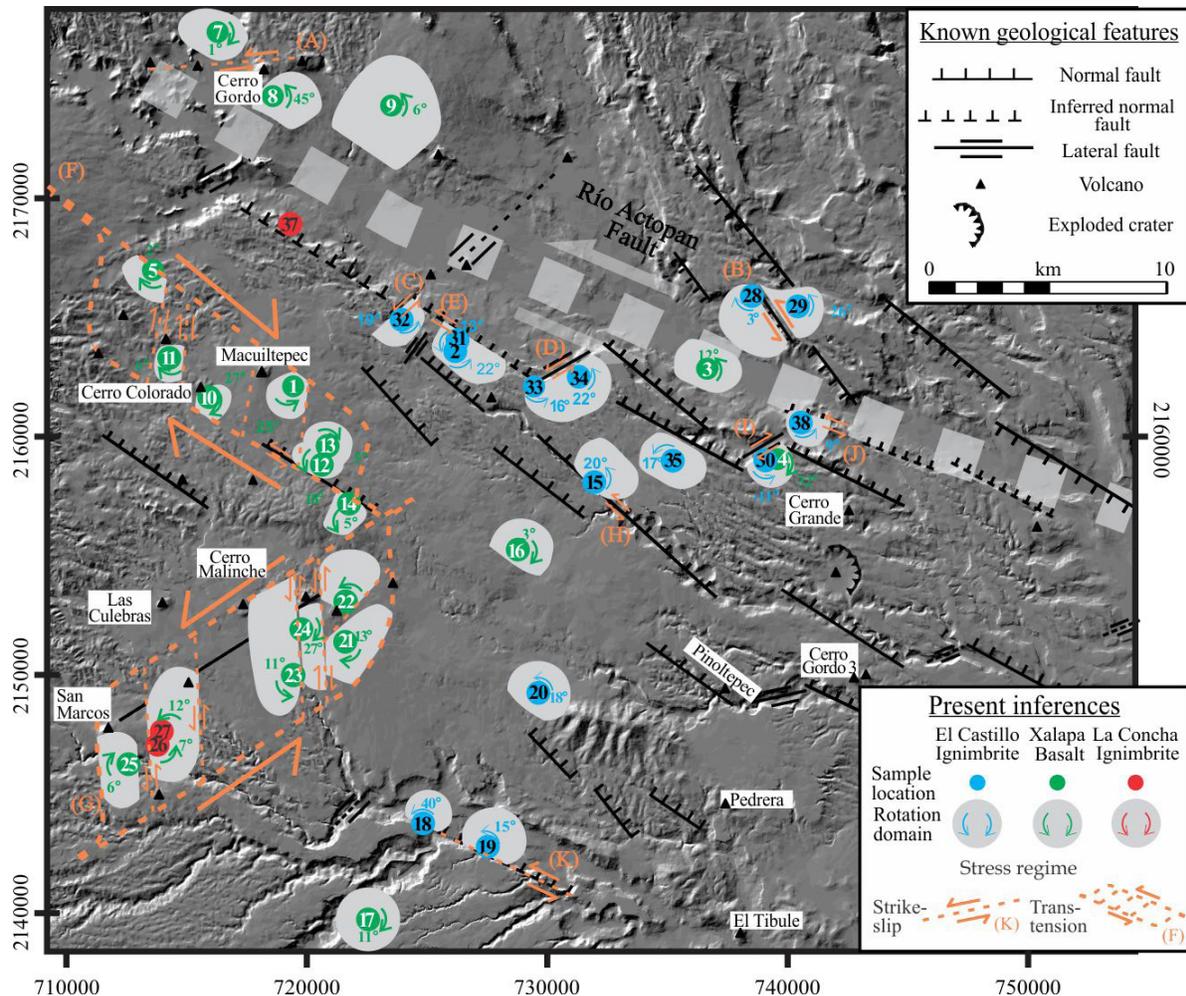
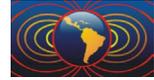


Figure 2. The Digital elevation map shows earlier published geological features in the area (modified after Morales-Barrera, 2009; Rodríguez *et al.*, 2010; Alva-Valdivia *et al.*, 2017). Also shown are sampling sites, calculated rotation and inferred rotation domain. Note that the site 6 lies to the far west (Fig. 1), and the information on the local faults is not available. This site is, thus, omitted from the map. The rotations in decimal points are rounded off to the nearest whole number.

not decipher the sense of translation. The sites near strike faults ‘C’ and ‘D’ show 16° to 22° anti-clockwise rotation (Fig. 2). These faults are, therefore, sinistral and synthetic to the Río Actopan Fault (Fig. 2).

Fault ‘I’ is an interesting case. Here, the site 4 of Chiconquiaco basalt coincides with site 30 of the El Castillo ignimbrite. The basalt (5.96 ± 0.156 Ma) and the ignimbrite (2.2 – 2.5 Ma) show clockwise and anti-clockwise rotation of 32° and -10.6° , respectively. Before the deposition of the ignimbrite the basalt



was, therefore, rotated $\sim 42.6^\circ$ due to the dextral rotation at fault 'I'. However, after the emplacement of the ignimbrite, the fault changed its sense to sinistral and inflicted a -10.6° rotation. Fault 'I' is linking two normal faults (Fig. 2). Its sense of shear would, thus, depend upon the throw and heave of these faults. It is, therefore suggested that the change in the sense of rotation at fault 'I' is due to differential movement at the two normal faults throughout the past ~ 5.96 Ma.

In the NW part of the study area, four volcanic vents, including Cerro Gordo, are distributed linearly ENE-WSW. This trend is similar to some of the strike-slip faults observed in the area, such as the one in the SE part of the study area near Pinoltepec. In the vicinity of the volcanoes, to the SE is the site 8 and to the NW is site 7 (Fig. 2), which are rotated 44.8° anti-clockwise and 0.7° clockwise, respectively. The linear alignment of the volcanic vents is, thus, suggested to be due to a strike-slip fault 'A'. Coherent predictions were made by Andreani *et al.* (2008a), which that in part of the TMVB faults control the alignment of the volcanoes.

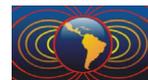
Several volcanoes, including Macuiltepec and Cerro Colorado, are concentrated in the W part of the study area. In this part, Morales-Barrera (2009) inferred an NW-SE striking north-down normal fault. Anti-clockwise rotation at sites 12 and 14 reveal a sinistral component in this fault, making it an oblique fault. The rotation of the basalts, at sites 1, 5, 10, 11, 12, 13 and 14, indicates the presence of mostly dextral smaller strike-slip faults almost perpendicular to the oblique fault. When joined the faults take-up a form similar to a typical dextral transtensional fault. It is, therefore, very likely that the concentration of the volcanoes and the clockwise rotation is due to a dextral transtensional fault 'F'. The fault 'F' is, thus, antithetic to the Río Actopan Fault. However, such faults are common in dominantly sinistral TMVB (*e.g.*, Suter *et al.*, 1995; García-Palomo *et al.*, 2000; Prost and Aranda, 2001; Espinoza-Nava and Toriz-Gama, 2005).

Similarly seven volcanoes, for example, San Marcos are distributed almost linearly in the SW part of the study area. This linearity inspired Morales-Barrera (2009) and Rodríguez *et al.* (2010) to infer an NE-SW trending strike-slip fault. However, the variable degree of dominantly anti-clockwise rotation suggests the occurrence of four parallel sinistral faults and a dextral fault. The distribution of anti-clockwise rotation domains and the parallel sinistral faults may be part of a larger sinistral transtensional fault 'G'. Such a fault would successfully explain the concentration and alignment of volcanic vents. The fault is synthetic to the Río Actopan fault. Similar, sinistral transtension is reported from the central part of the TMVB and is known to control the distribution of the volcanoes in Los Tuxtlas volcanic field (Andreani *et al.*, 2008a, 2008b).

6. Conclusions

The Xalapa basalts present, 5 to 50 μm large, low-Ti titanomagnetite cubic and skeletal grain that sporadically have fine trellis type ilmenite lamellae. The magnetic domain type represents a mixture of single and multi-domain without superparamagnetic particles. These properties reveal that magma rise forming the Xalapa basalts was faster than that of the Deccan basalts. Furthermore, the Xalapa lava flows were emplaced on highly irregular topography leading to variable thickness of the flows. Finally, Xalapa basalts cooled slower than the El Castillo Ignimbrite but faster than the Deccan basalts. Based on the confident evidence, the study recognizes numerous smaller, dextral and sinistral, lateral faults in the area. These faults have not been observed before, either due to inaccessibility or absence of outcrops. The study reports dextral and sinistral transtensional faults in the W part of the study area. In the entire area, the blocks have mainly moved left lateral wise (sinistral) along the Río Actopan fault and there are smaller, mostly synthetic faults. Few antithetic faults, such as 'F' are observed (Fig. 2). These smaller antithetic and synthetic faults reveal a sinistral Riedel shear zone in the area (*e.g.*, Wolcox *et al.*, 1973; Davis, 1999). Andreani *et al.* (2008a) report similar secondary Riedel shear in the Veracruz Basin, which is further east of the study area.

Earlier studies predicted that in spatial and temporal sections of the TMVB the distribution of volcanoes may be restricted by fault localization and rise of magmatic fluids due to small pull-apart basins (transtensional faults) and/or small block rotation. This study provides evidence coherent with such hypothesis. The



present study is unique in a way because it analyzes the mean ChRM directions and PSV vis-à-vis site-specific rotation. Such correlation emphasizes on a major possible problem with the paleomagnetic studies, which base their conclusion on the average values, disregarding the importance of spatial distribution and associated geological heterogeneities, such as local deformation. It is, therefore, imperative to analyze the paleomagnetic information with a local and regional point-of-view.

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