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RESEARCH ADVANCE

MAGNETIC DATING OF VOLCANIC ERUPTIONS: CASE STUDY OF XALNENE TUFF AND TOLUQUILLA VOLCANO IN CENTRAL MEXICO

Dataciones magnéticas de erupciones volcánicas: estudio de la toba Xalnene y el volcán Toluquilla en el centro de México

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ABSTRACT. *Dating volcanic eruptions, a central aspect of stratigraphic and geochronological studies, increasingly requires multiple techniques. Archaeomagnetic and paleomagnetic studies provide high resolution records, when referred to paleosecular variation and magnetic polarity time scales. Here, we review the use of archaeomagnetic and magnetic anomaly studies in dating a volcanic eruption. A case study in the Valsequillo Basin, in central Mexico, permits evaluation of different approaches. The paleomagnetic data on lavas and pyroclastics provide spot readings, whereas the volcanic conduit system covers a slightly longer temporal scale. The distinct cooling records provide additional constraints on the magnetization records for correlation and dating.*

KEYWORDS. *Archaeomagnetism; magnetostratigraphy; dating; volcanic eruptions; magnetic anomalies.*

Figure 1. View of the Valsequillo Basin, with the reservoir, surrounding hills and volcano-sedimentary sequence (E. Tellez, A. Trigo).

RESUMEN. *La datación de erupciones volcánicas es un aspecto central de los estudios estratigráficos y geocronológicos que precisa de estrategias multitécnicas. Los datos arqueomagnéticos y paleomagnéticos proporcionan registros de alta resolución que requieren referirse a las curvas de referencia de paleovariación paleosecular y escala de polaridad magnética. Aquí revisamos el uso de análisis arqueomagnéticos y anomalías magnéticas en la fechación de erupciones volcánicas. Las secuencias volcano-sedimentarias de la cuenca de Valsequillo, en el centro de México, permiten evaluar los métodos y enfoques. Los datos paleomagnéticos en lavas y piroclásticos proporcionan registros puntuales, mientras que los modelados de anomalías magnéticas del sistema de conductos volcánicos cubren un rango temporal de mayor duración. La correlación de los distintos registros de enfriamiento provee elementos adi-*

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cionales en la interpretación de los registros de magnetización y en las correlaciones y datación.

PALABRAS CLAVE. *Arqueomagnetismo; magnetoestratigrafía; datación; erupciones volcánicas; anomalías magnéticas.*

INTRODUCTION

Dating volcanic eruptive history is essential for stratigraphic, volcanological, and archaeological studies, but this remains challenging even for recent eruptions. In the case of hominid evolution and migration, chronology takes central stage, requiring high precision (Zhu *et al.* 2003; Calvo-Rathert *et al.* 2008). This is generally approached by applying different dating methods. Here we discuss the potential use of magnetic methods – magnetostratigraphy, archaeomagnetism, paleosecular variation and ground magnetics – in providing additional constraints to radiometric and stratigraphic studies. Studies of the Xalnene tuff and Toluquilla volcano in the Valsequillo Basin (Figure 1) provide an interesting case study, including contrasting chronologies and their association to early human occupation in central Mexico.

The basin contains a Quaternary sedimentary sequence that preserves Late Pleistocene vertebrate fossils, including human remains (Irwin-Williams 1969, 2011). The sequence has been dated using U-Th, fission tracks and radiocarbon, with dates spanning a large range (Szabo *et al.* 1969; Steen-McIntyre *et al.* 1981; Pichardo 2000). Correlation of Valsequillo tephras with the eruptive record of La Malinche volcano have been inconclusive. Difficulties in dating the sequence opened a debate on the age of early human presence in the area (Szabo *et al.* 1969; Steen-McIntyre *et al.* 1981; Irwin-Williams 2011).

Recently, the tuff was dated at 38 ka by OSL and 1.3 Ma by Ar/Ar, with contrasting implications for the nature of the prints and peopling of the area (González *et al.* 2006; Renne *et al.* 2005). Paleomagnetic analyses on the tuff and lavas were interpreted in terms of a young and an old age (Goguitchaichvili *et al.* 2007, 2009; Feinberg *et al.* 2009). To these studies, a ground magnetic survey over the cinder cone was added, which provided constraints linking the volcano to the Xalnene tuff (Urrutia-Fucugauchi *et al.* 2012). These studies illustrate the capacity of the methods for construing the age of a geologic event, but also show the uncertainties involved in interpretation. Here we summarize the studies and discuss the potential and challenges for stratigraphic studies.

XALNENE TUFF

The Valsequillo volcanic and sedimentary sequences have been long studied (e.g., Szabo *et al.* 1969; Steen-McIntyre *et al.* 1981), but interest in them was renewed following the study on possible human footprints in the Xalnene tuff by González *et al.* (2006), supporting a human presence. Challenging this interpretation, Renne *et al.* (2005) documented a reverse polarity magnetization for the Xalnene tuff, which they correlated to the Matuyama C1r.2r reverse chron. González *et al.* (2006) rejected the results considering that the lapilli was reworked or it contained inherited material. They referred to the heterogeneous composition of the tuff and that the reverse polarity was due to a self-reversal mechanism or correlated to the Laschamp subchron.

The correlation to the Laschamp excursion was supported by Gogichaishvili *et al.* (2007), who reported transitional paleomagnetic directions for Xalnene tuff and low paleointensities on lavas from Cerro Toluquilla volcano.

Feinberg *et al.* (2009) showed that Xalnene tuff and Toluquilla lavas record similar reverse polarity magnetizations and that the Ar/Ar dates of 1.28 and 1.3 Ma are indistinguishable from the Xalnene tuff date. Feinberg *et al.* (2009) concluded that association of Cerro Toluquilla as the source of the Xalnene tuff is based on a) aerial thickness distribution of the ash, decreasing with distance from the cone, b) agreement of Ar/Ar dates and c) similar paleomagnetic records for tuff and lavas. Examples of the paleomagnetic and rock magnetic data are shown in Figure 2. The chronology presents implications for early human migration and peopling of the Americas (Urrutia & Urrutia 2011).

MAGNETIC ANOMALY MODELING

The magnetic survey of Cerro Toluquilla volcano documented a dipolar anomaly, with a ~3250 nT high and ~1500 nT low (Figure 3). As mentioned, the inverse polarized dipole indicates a source with reverse polarity remanent magnetization. Modeling of the anomaly permitted to constrain the source and quantify magnetization parameters.

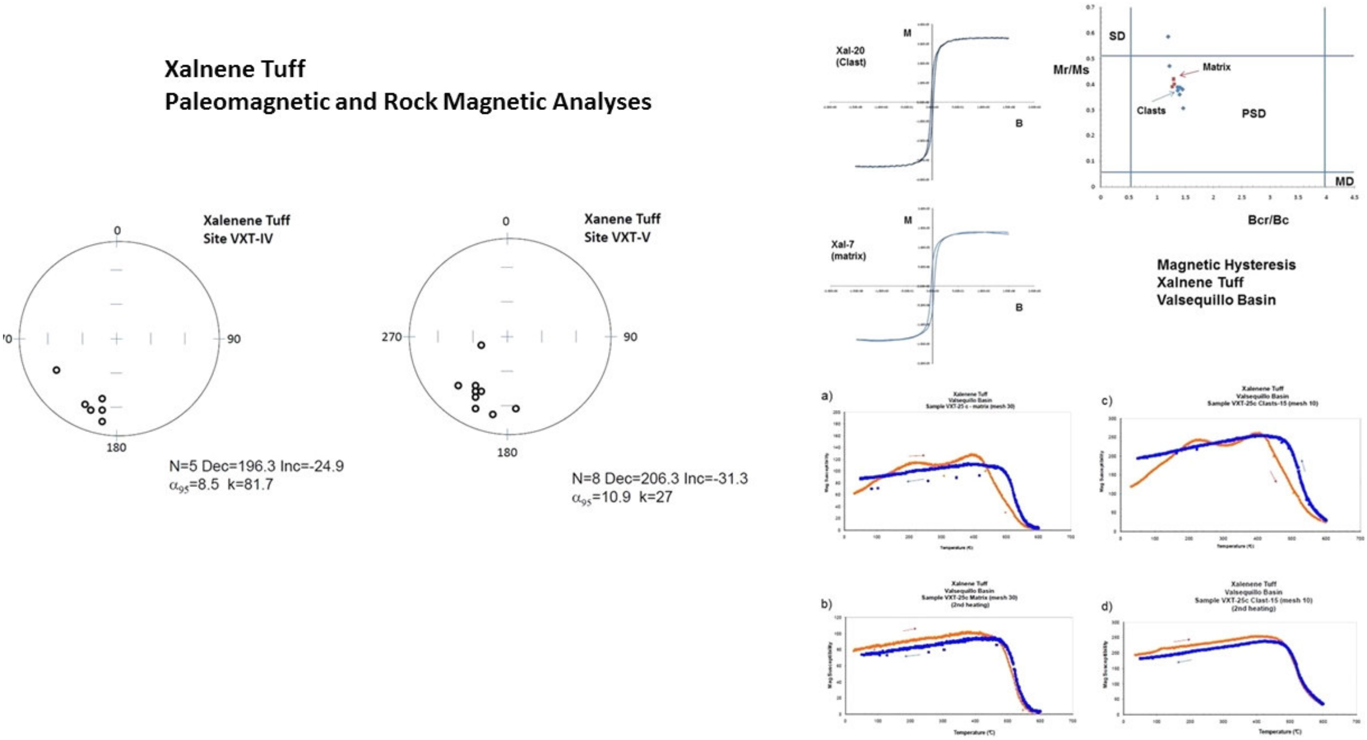

Figure 2. Example of paleomagnetic directional and rock magnetic data for the Xalnene tuff (Urrutia-Fucugauchi *et al.* 2012).

Different models were tested, including forward models of prismatic bodies with varying geometries and magnetization directions. The anomaly can be modeled assuming a simple geometry with a vertical 60 m square-section prism located at 50 m depth. The magnetization direction has a declination of 175° and inclination of –44°, which correlates with paleomagnetic directions for the lava flows with declination of 176.3° and inclination of –33.1° (Urrutia-Fucugauchi *et al.* 2012). Results show that the Xalnene tuff, lava flows and volcanic plug acquired reverse polarity remanent magnetizations.

For best fit geometry, different remanent magnetization directions were tried, evaluating inclinations in the range of the observed remanent inclinations in the lavas, tuff and lapilli (Feinberg *et al.* 2009; Goguitchaichvili *et al.* 2009). Modifying the source inclination resulted in changes in relative amplitude of high-to-low ratio and affecting the anomaly shape, confirming that best fit corresponded to a magnetization with inclination of –42°.

DISCUSSION

Paleomagnetic dating relies on reference datasets, which take advantage of the spatial/temporal variations of the geomagnetic field (Merrill & McElhinny 1983; Tarling 1983). Magnetostratigraphic studies consider the paleosecular variation (PSV) and polarity transitions, spanning a wide range of temporal scales, ranging from years to millions of years. Large directional and intensity changes characterize the excursions and short polarity events (Singer 2014). Paleomagnetic dating of volcanic eruptive history has increased accuracy and resolution (Risica *et al.* 2020, 2022).

The Quaternary spans two polarity chrons, the Matuyama and Brunhes chrons (Figure 4). There are ten polarity reversals and twenty-seven excursions documented over the period of 2.6 Ma (Singer 2014).

The Brunhes-Matuyama boundary occurs at 773 ka, representing a global marker horizon. They provide useful constrains for chronology and lateral correlation of events (Figure 4). The radiometric dates of 38 ka and 1.3 Ma for the Xalnene eruption referred to the Geomagnetic Instability Time Scale correspond to the Laschamp event in the Brunhes chron and to the Mesa del Lago event in the Matuyama chron, respectively. The correlation needs to consider the analytical uncertainties and the dispersion of radiometric dates.

Magnetic properties have been used for correlation of sedimentary and volcanic sequences. Magnetic susceptibility logs provide records that allow correlation with stratigraphic sequences in outcrops and boreholes

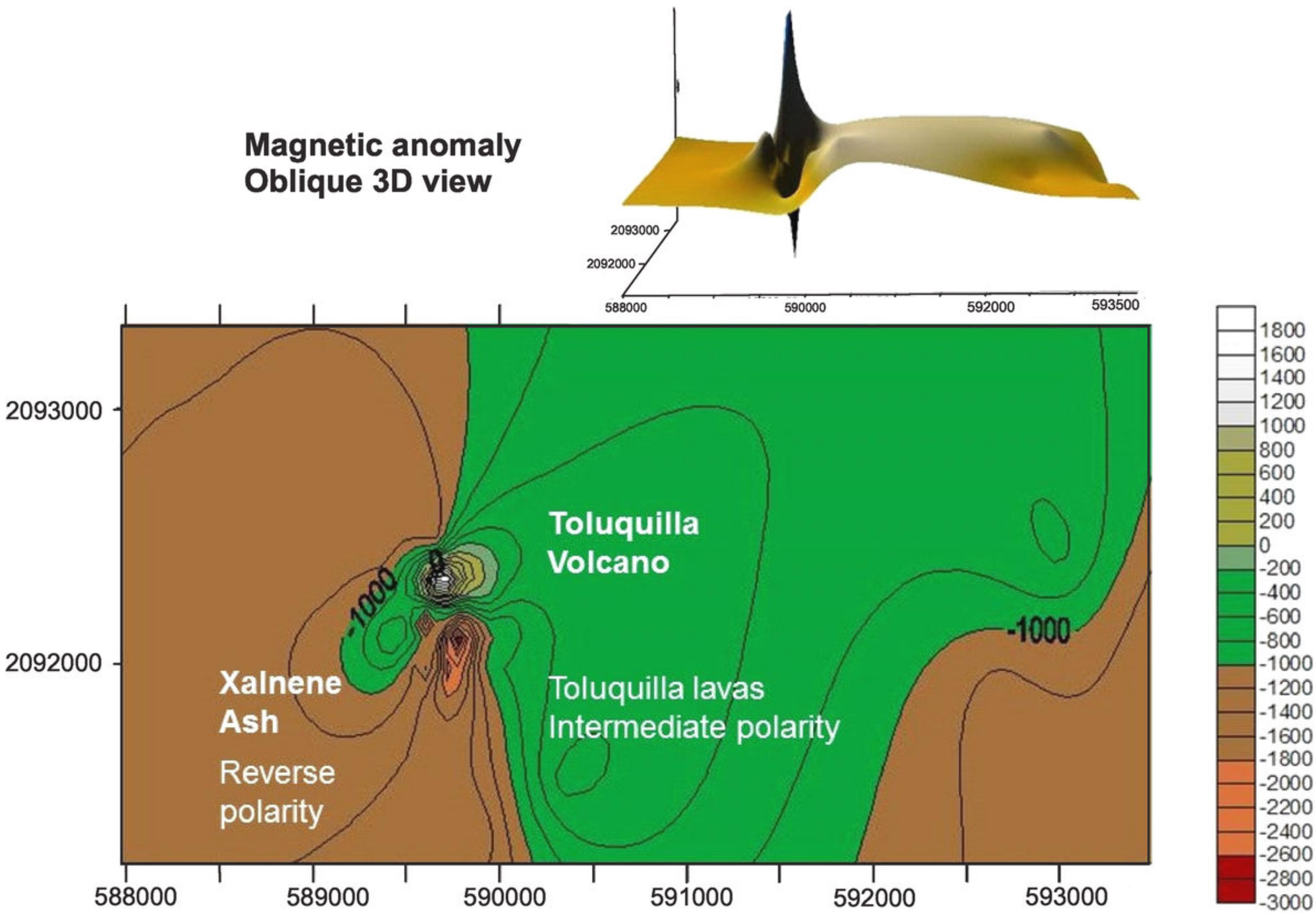

Figure 3. Total magnetic field of the northern sector of Valsequillo Basin showing the dipolar anomaly over the Cerro Toluquilla volcano (Urrutia-Fucugauchi *et al.* 2012). Dipolar magnetic anomaly corresponds to an inversely polarized source, with a small anomaly on western flank of dipolar anomaly.

(Tarling 1983). Analysis of loess-paleosol sections provide paleoclimate records of surface temperature and precipitation. Geochemical and mineralogic characterization of volcano-sedimentary sections have also wide applicability in tephra chronology, in which magnetic minerals add further constrains.

Paleomagnetically constrained eruptive chronologies, in addition to the excursions and polarity reversals, make use of short amplitude geomagnetic variations. Paleosecular variation reference curves have increased the resolution and temporal range in the past years (Risica *et al.* 2022). The development of global PSV models provides a chronological framework useful in different areas (Pavón-Carrasco *et al.* 2014).

In the study of the Valsequillo Basin volcano-sedimentary sequence, the magnetic survey over the volcano added another tool for the eruptive chronology. The magnetic survey over the Toluquilla volcano documented an inverse dipolar anomaly, indicating a reverse polarity magnetization (Urrutia-Fucugauchi *et al.* 2012). The finding provides constrains on the magnetization records of tuffs and lavas, as well as on the volcano structure.

The eruption dynamics involves different factors, which affect the thermal state evolution for volcanic eruptions (Valentine & Gregg 2008; Keating *et al.* 2008; Goto *et al.* 2008). Paleomagnetic studies can provide constraints on the cooling of volcanic products. In the case of Toluquilla volcano, Feinberg *et al.* (2009) considered that agreement in the reversed magnetization directions in Xalnene tuff and Toluquilla lavas was evidence for their emplacement in the reverse polarity C1r.2r chron. Providing temporal constraints for remanence acquisition in the conduit system is difficult. The conduit plug cooling covers a long time than that of tuff and lavas.

The inclination estimated in the magnetic modeling of –42° is steeper than the inclination for lavas and tuff of –33 and –32°. The 10° angular difference is larger than paleosecular variation scales and might be related

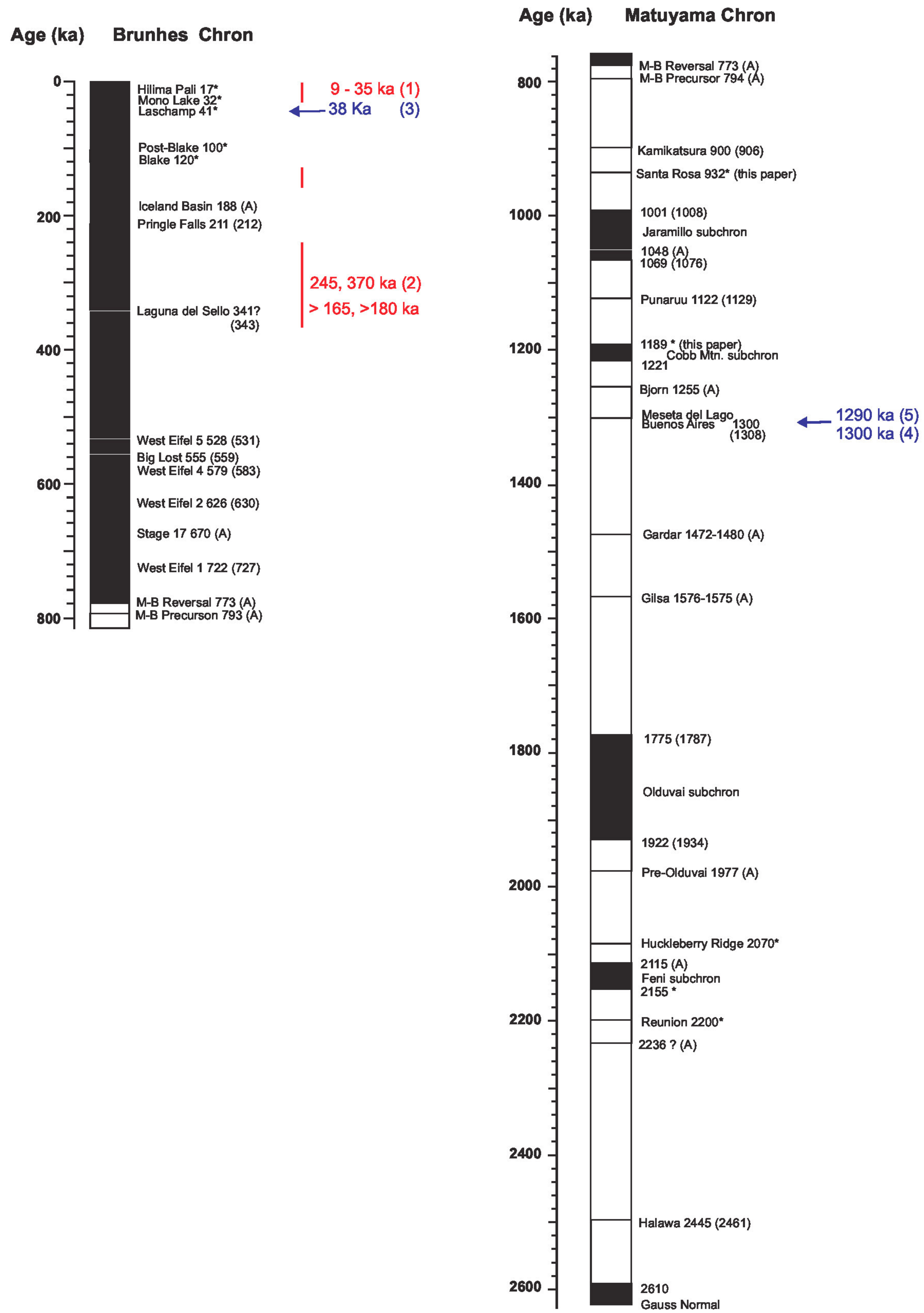

Figure 4. Quaternary geomagnetic instability time scale (taken from Singer 2014), with some of the radiometric dates reported for the Valsequillo Basin volcano-sedimentary sequence and the proposed dates for the Xalnene tuff eruption. References: 1) Szabo *et al.* (1969); 2) Steen-McIntyre *et al.* (1981); 3) González *et al.* (2006); 4) Renne *et al.* (2005); 5) Feinberg *et al.* (2009).

to the remanence acquisition process. Remanent magnetization acquisition in volcanic lavas and pyroclastics represents spot records of the paleomagnetic field (Merrill & McElhinny 1983; Tarling 1983). The remanence in the underground plug represents a long-term average, the time scale is difficult to quantify and there are several factors involved.

The uncertainties in the modeling and cooling process do not allow firm conclusions on the time scales for magnetization acquisition in the underground volcano system. Tephra cools faster than the lava flows, which is reflected in the magnetic mineralogy, domain state, and alteration effects. This is reflected in the acquisition mechanism and recording of short-term geomagnetic variations. Other possible factor is the influence of terrain magnetic effects, which is marked in the volcano magnetic anomaly (Figure 3). The magnetic anomaly over Toluquilla volcano is dominated by the inverse dipolar anomaly, with a smaller anomaly over the western flank, which appears related to a secondary dike vent. The northeast-southwest orientation suggests an intermediate normal polarity source, which could be related to an intermediate remanent magnetization.

CONCLUSIONS

Stratigraphic and radiometric dating permit the construction of high resolution records, with precision increasing alongside new advances in the field. Volcanic rocks provide reliable spot records, which are referred to the paleosecular variation and magnetic polarity time scales. Joint directional and paleointensity data provide full vector data sets, with rock magnetic parameters and logs providing additional constraints for correlation and relative dating.

The Xalnene tuff eruption of the Toluquilla cinder cone in the Valsequillo Basin provides an interesting case study, with contrasting chronologies and differing implications for early human occupation in central Mexico. Paleomagnetic analyses on the tuff and lavas have been interpreted in terms of young and old ages. The study of the Cerro Toluquilla documents a dipolar magnetic anomaly with a source of reverse polarity, linking the volcano to the tuff and lavas, consistent with the paleomagnetic studies supporting a genetic link and a Matuyama chron age.

Paleomagnetic data on lavas and pyroclastics provide spot readings. The underground volcanic conduit system covers a slightly longer temporal scale. Correlation of the distinct cooling records provide further constrains on the remanent magnetization records and for dating.

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