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Paleomagnetic and rock-magnetic study on volcanic units of the Valsequillo Basin: implications for early human occupation in central Mexico

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Alleged human and animal footprints were found within the upper bedding surfaces of the Xalnene volcanic ash layer that outcrops in the Valsequillo Basin, south of Puebla, Mexico (Gonzalez *et al.*, 2005). The ash has been dated at 40 ka by optically stimulated luminescence analysis, thereby providing new evidence that America was colonized earlier than the Clovis culture (about 13.5 Ma). We carried out paleomagnetic and rock magnetic analysis on 18 Xalnene ash block and core samples collected at two distinct localities and 19 standard paleomagnetic cores belonging to nearby monogenetic volcanoes. Our data provide evidence that both the volcanic lava flow and Xalnene ash were emplaced during the Laschamp geomagnetic event spanning from about 45 to 39 ka.

Key words: Paleomagnetism, volcanic ash, central Mexico, Lashamp event, human evolution.

1. Introduction

Paleomagnetic methods have long been used for dating and stratigraphic correlation in paleoantropological sites. Zhu *et al.* (2005) recently dated some hominid-bearing sediments (presumably oldest hominoids found in Eurasia) in southwestern China using just such a method. Based on the magnetostratigraphy of more than 200 remanent directions, the Zhupeng sedimentary layer (Yuanmou Basin) has been dated within polarity chrons 3Br 2r or 3Br 1r, i.e., within the interval 7.43–7.38 Ma or 7.34–7.14 Ma. A paleomagnetic and rock magnetic study carried out on the Dmanissi (Caucasus) paleoanthropological site (Calvo-Rathert *et al.*, 2007) provided data that enable the hominid-bearing volcanogenic sediments to be correlated with the Olduvai subchron (1.95–1.77 Ma). The paleomagnetic age of hominid fossils at the Atapuerca archaeological site (northern Spain) coincides with the last Matuyama-Brunhes geomagnetic reversal dated at about 0.78 Ma (Pares and Pérez-González, 1995). To date, however, reliable data from serious paleomagnetic studies on paleoanthropological sites in America are not available.

One of the most important and long-standing issues in anthropological research is the study of early human migration and the peopling of the Americas (e.g., Dixon, 2001; Marshall, 2001; Bradley and Stanford, 2004; Mioti, 2006; Gonzalez *et al.*, 2006; Fujita *et al.*, 2006). Years ago, it was a widely held belief that ancestral Native Americans came from central Siberia (then across Beringia) around 13,000 ka BP, after a trek between the recently separated Canadian ice sheets. Recent findings from various studies, including those on the genetics of human populations and occupation sites, have challenged conventional models and the temporal framework for early human migration onto the continent. Given the implications of these findings, reports on early human occupation sites with dates considerably older than those of the Clovis sites have met with skepticism and prompted intense scrutiny. This has also been the case for the reports on the Valsequillo site in central Mexico (Steen-McIntyre *et al.*, 1981; Pichardo, 1997; Fiedel, 2000; Ochoa-Castillo *et al.*, 2003; Renne *et al.*, 2005; Gonzalez *et al.*, 2005). Alleged human and animal footprints were found within the upper bedding surface of the Xalnene volcanic ash layer that outcrops in the Valsequillo Basin, south of Puebla, Mexico (Gonzalez *et al.*, 2005). The ash has been dated at about 40 ka by optically stimulated luminescence analysis (OSL), which has been taken as new evidence that America was colonized earlier. In contrast, the same ash was dated at 1.30±0.03 Ma by Ar-Ar (Renne *et al.*, 2005). Furthermore, based on a paleomagnetic analysis of nine non-oriented samples, the authors stated that ash samples are reversely magnetized—consistent with chron C1r.2r (1.77 to about 1.07 Ma). Preliminary results on oriented samples gave evidence of intermediate directions (Goguitchaichvili *et al.*, 2007), emphasizing the need for

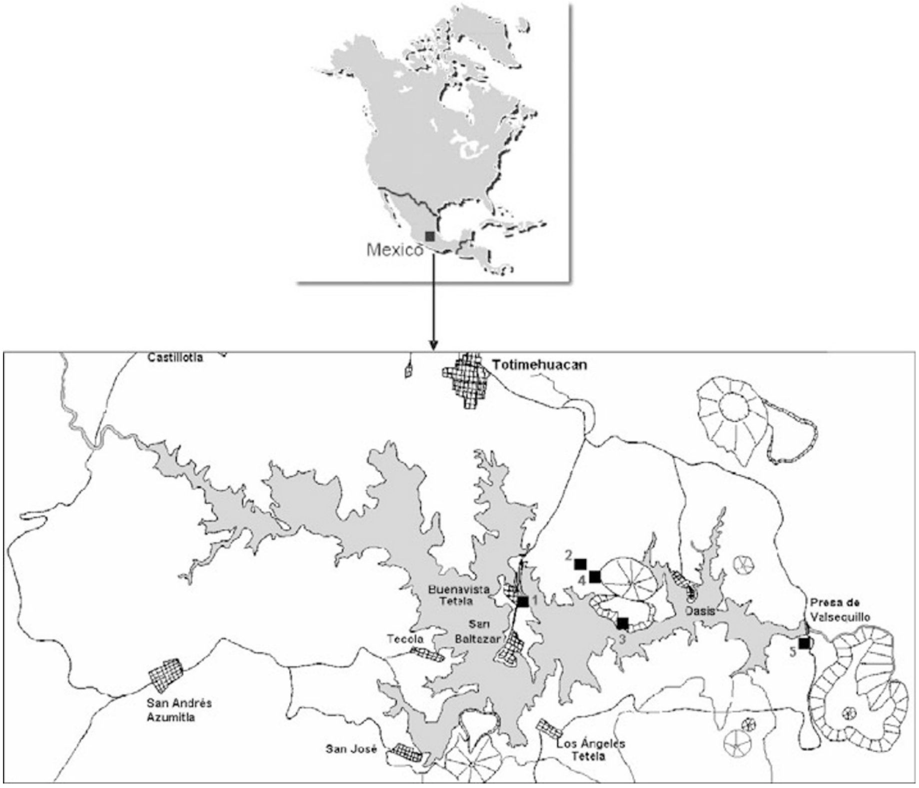

Fig. 1. Geological map of Valsequillo area showing sampled site locations. The larger numbers are the palaeomag sampling sites.

Table 1. Site mean characteristic paleodirections from Valsequillo area. N: Number of treated samples, n: number of samples used for calculation, Dec: declination, Inc: inclination, k and α_{95}: precision parameter and radius of confidence cone. Pol: magnetic polarity.

Site mean paleodirections from Valsequillo area

Site	Location	n/N	Inc (°)	Dec (°)	α_{95} (°)	k	Pol
White ashfall (1)	98°10′20.1″/18°55′05″	6/6	32.8	1.4	2.6	654	N
Blackish ash (2)	98°09′22.3″/18°55′24″	6/6	13.1	264.6	6.7	99	I
Xalnene ash (4)	98°09′21.5″/18°55′21″	10/10	17.8	280.8	6.8	52	I
Toluquilla volcano basalt (3)	98°09′06″/18°54′48.4″	8/8	−29.7	169.8	5.8	93	R
Avila Camacho basalt (5)	98°06′29.5″/18°54′37″	8/8	−36.4	189.5	2.2	891	R

further detailed studies.

Here, we present and discuss the results of a detailed paleomagnetic and rock magnetic analysis of 18 Xalnene ash block and core samples collected at two distinct localities and 19 standard paleomagnetic cores belonging to nearby monogenetic volcanoes. Our data provide evidence that both the volcanic lava flow and Xalnene ash were emplaced at the time of the Laschamp geomagnetic event (dated 45 to about 39 ka).

2. Sampling Details and Absolute Ages

The Valsequillo basin (Fig. 1) is located in Puebla State, central Mexico. It was occupied during part of the Late Pleistocene by a shallow lake dammed by a thick lava flow to the south and east of the basin (Ochoa-Castillo *et al.*, 2003; Gonzalez *et al.*, 2005). A sequence of lake sediments and volcanic deposits was formed on the basement rocks (Balsas Group). Within a section of these sediments a volcanic ash of basaltic composition (Xalnene ash) was deposited during the eruption of the nearby monogenetic volcano Cerro Toluquilla (Fig. 1). The ash consists predominantly of multiple beds of coarse lapilli interbedded with fine ash and lake sediments.

Several studies have tried to establish the relative and absolute stratigraphy of the Valsequillo Basin (e.g., Armenta-Camacho, 1959, 1978; Szabo *et al.*, 1969; Steen-McIntyre *et al.*, 1981; Pichardo, 1997; Ochoa-Castillo *et al.*, 2003). More recent studies have used Ar-Ar systematics (Gonzalez *et al.*, 2005; Renne *et al.*, 2005). While Gonzalez *et al.* (2005) failed to obtain reliable ages (a total fusion age did not release sufficient radiogenic argon to determine an age), Renne *et al.* (2005) reported technically high-quality determinations yielding an age of 1.30±0.03 Ma. Optically stimulated luminescence provides an estimate of the time elapsed since the luminescent minerals were exposed to light or underwent heating. A well-constrained cluster of eight grains provided a weighted mean paleodose of 45.9±9.8 ka. This population of grains is believed to be related to thermal resetting of the OSL signal as a result of exposure to heat during the volcanic eruption. This explanation allowed Gonzalez *et al.* (2005) to estimate an OSL luminescence age of 38.1±8.6 ka.

The alleged human and animal footprints are exposed on bedding plane surfaces near Toluquilla volcano. The 4°–8° dip to the east is attributed to the primary depositional slope; consequently, no tectonic correction was applied in this study. We sampled the Xalnene ash at two localities—near the source and more than 1 km away. Ten hand samples oriented by both magnetic and sun compasses were obtained at the ash layer with alleged footprints, while eight oriented samples were collected at the second ash locality ('blackish ash'; Fig. 1, Table 1) with no footprint evidence. Finally, a topmost, younger white ashfall was sampled (eight oriented samples). For the volcanic lava flows, we collected ten standard paleomagnetic cores from the Toluquilla volcano. In addition, nine samples were obtained from the nearby Avila Camacho lava flow (Fig. 1, Table 1). Cores were obtained with a gasoline-powered portable drill and then oriented with both magnetic and sun compasses.

3. Laboratory Techniques

Low-field susceptibility measurements (k-T curves) under air were carried out using a Highmoore susceptibility bridge equipped with a furnace. The samples were heated up to about 600°C at a heating rate of 20°C/min and then cooled at the same rate. The Curie temperature was determined by the method of Prévot *et al.* (1983).

Hysteresis measurements at room temperature were performed on all studied samples using the AGFM 'Micromag' apparatus of the paleomagnetic laboratory at Mexico City in fields up to 1.4 Tesla. The saturation remanent magnetization (J_{rs}), the saturation magnetization (J_s), and the coercitive force (H_c) were calculated after correction for the paramagnetic contribution. The coercivity of remanence (H_{cr}) was determined by applying a progressively increasing backfield after saturation.

The remanent magnetization was measured with a JR-5A and JR6 spinner magnetometers (nominal sensitivity $\sim 10^{-9}$ A m^2). The measurements were recorded after stabilization of the remanence in this magnetometer. Alternating field demagnetization was carried out in seven to ten steps up to maximum fields of 100 mT using a Molspin AF demagnetizer. A characteristic magnetization direction was determined by the least squares method (Kirschvink, 1980), with 6–11 points taken in the principal component analysis for this determination. Directions were averaged by unit, and the statistical parameters were calculated assuming a Fisherian distribution.

The paleointensity experiments were carried out in air using a MDT80 paleointensity oven. The remanence measurements were made in a field-free environment in the paleomagnetic laboratory of the UNAM. Temperature reproducibility between two heatings to the same temperature was generally within 3°C up to 450°C, and 2°C above 450°C. The intensity of the laboratory field was 30 μT and was held at a precision better than 0.15 μT. We used the Coe version of the Thellier method (Thellier and Thellier, 1959; Coe, 1967) with sliding natural remanent magnetization-thermal remanent magnetization (NRM-TRM) checks (Prévot *et al.*, 1985). At each temperature step, the samples were heated twice: in the zero field for the first heating and in the presence of a field for the second heating. The pTRM checks were performed after every second step throughout the whole experiment.

4. Main Results and Discussion

The youngest volcanic ash (white) studied (Fig. 2(A); Table 1) yields normal polarity magnetization. A secondary component, probably of viscous origin, is also present and easily removed after applying a 10-mT alternating peak field. In contrast, Xalnene volcanic ash yields mainly single component magnetizations (Fig. 2(B, C)). A minor viscous overprint is removed at the very first steps of magnetic treatment. The ash layer with alleged footprints (18°55′21.8″N, 98°09′21.5″W) yielded reasonably well grouped mean paleomagnetic directions giving Inc = 17.8°, Dec = 280.2°, α_{95} = 6.8°, k = 52, N = 10. Because the mechanism and nature of the remanent magnetization remains a matter of debate (Feinberg *et al.*, 2007; Goguitchaichvili *et al.*, 2007), it is difficult to draw firm conclusions about the geomagnetic significance of the intermediate paleodirections. However, another ash locality (18°55′23.8″N and 98°09′22.3″W) with no footprint evidence and showing slightly distinct lithology yielded rather similar paleodirections (Inc = 13.0°, Dec = 264.6°, α_{95} = 6.4°, k = 99, N = 6). In any case, the obtained paleodirections at both localities are significantly deviated from the dipole (or expected) direction, which may be interpreted as an occurrence of an intermediate paleofield. If true, it is quite possible that the nature of magnetization in the Xalnene ash is similar to the slightly palagonitized hyaloclastites (Goguitchaichvili *et al.*, 1999). The NRM was generally found to consist of two components: a thermodetrital remanent magnetization (thermo-DRM) and a crystallodetrital remanent magnetization (crystalo-DRM). Thermo-DRM and cristallo-DRM are defined (Goguitchaichvili *et al.*, 1999) as the remanences acquired due to the deposition of magnetic particles of detrital origin individually carrying either TRM or a CRM (chemical remanent magnetization), respectively, which is consistent with the surge and fall origin of the deposit. This kind of remanence usually records the directions of the geomagnetic field at the moment of rock formation. However, some inclination error (commonly less than 10°) may be observed (Goguitchaichvili *et al.*, 1999).

The Toluquilla volcano lava flow yields well-defined reverse polarity magnetization (Table 1, Fig. 3(A)). The characteristic remanence is successfully isolated after applying a 40-mT alternating peak field. This strong secondary magnetization may be due to the lightning effect. The Avila Camacho lava flow is also reversely magnetized (Fig. 3(B)). No evidence of parasitic magnetizations was found. The median destructive fields range from 80 to almost 100 mT, which indicates that the dominant magnetization carrier is single-domain (SD) Ti-poor titanomagnetite. These SD grains should be ideal material for Thellier paleointensity measurements (Dunlop and Özdemir, 1997). Four samples out of eight analyzed yielded acceptable paleointensity estimates. We accepted only determinations that fulfill the following criteria: (1) the determination was obtained from at least six NRM-TRM points (Table 2, Fig. 3(B)), corresponding to a NRM fraction larger than 1/3 (Table 2); (2) the quality factor (Coe *et al.*, 1978) was 5 or more; (3)

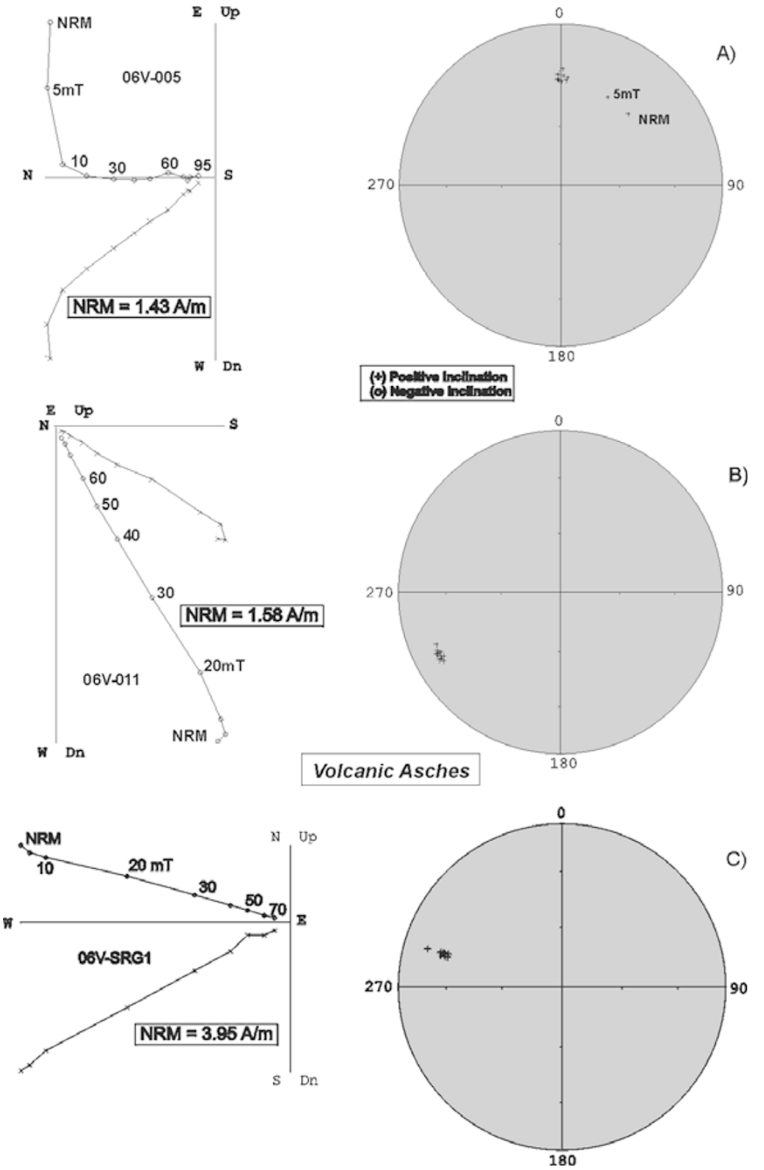

Fig. 2. Orthogonal vector plots of stepwise alternating field demagnetization (stratigraphic co-ordinates) of representative ash samples. The numbers refer to peak alternating fields in mT. o, Projections into the horizontal plane; x, projections into the vertical plane.

the positive 'pTRM' checks—i.e., the deviation of pTRM checks—were less than 15%. The directions of the NRM remaining at each step obtained from the paleointensity experiments are reasonably linear and point to the origin. No deviation in the remaining NRM directions towards the direction of the applied laboratory field was observed. For these samples, the NRM fraction f that was used for the determination ranges from 0.51 to 0.68, and the quality factor q ranges from 6.2 to 15.2.

Both the volcanic ash and lava flow yield quite similar rock-magnetic behaviors (Fig. 4). High-T susceptibility experiments indicate, in both cases, the presence of Ti-poor titanomagnetites. The cooling and heating curves are not perfectly reversible, probably due to the low sensitivity of the Highmoore susceptibility system and heating in air. The hysteresis curves are symmetrical in both cases, yielding quite similar parameters (Fig. 4). Near the origin, no potbellied and wasp-waisted behaviors (Tauxe *et al.*, 1996) were detected, which probably reflects the very restricted ranges of the opaque mineral coercivities. Judging from the ratios of hysteresis parameters, it seems that all samples fall in the pseudo-single domain (PSD) grain size region (Day *et al.*, 1977; Dunlop, 2002), probably indicating a mixture of multi-domain (MD) and a significant amount of SD grains. Corresponding isothermal remanence (IRM) acquisition curves were found to be very similar for both types of rocks. Saturation is reached in moderate fields of the order of 150–200 mT, which points to Ti-poor titanomagnetites as remanence carriers. Thus, it may be argued that the magnetic carriers in the ash and lava flow are almost identical.

5. Conclusions

Our paleomagnetic investigation yields an intermediate magnetic polarity for the Xalnene ash deposits (Fig. 5(A)), while the nearby Toluquilla volcano is reversely magnetized, similar to the Avila Camacho lava flow. Moreover, the absolute geomagnetic paleointensity is significantly re-

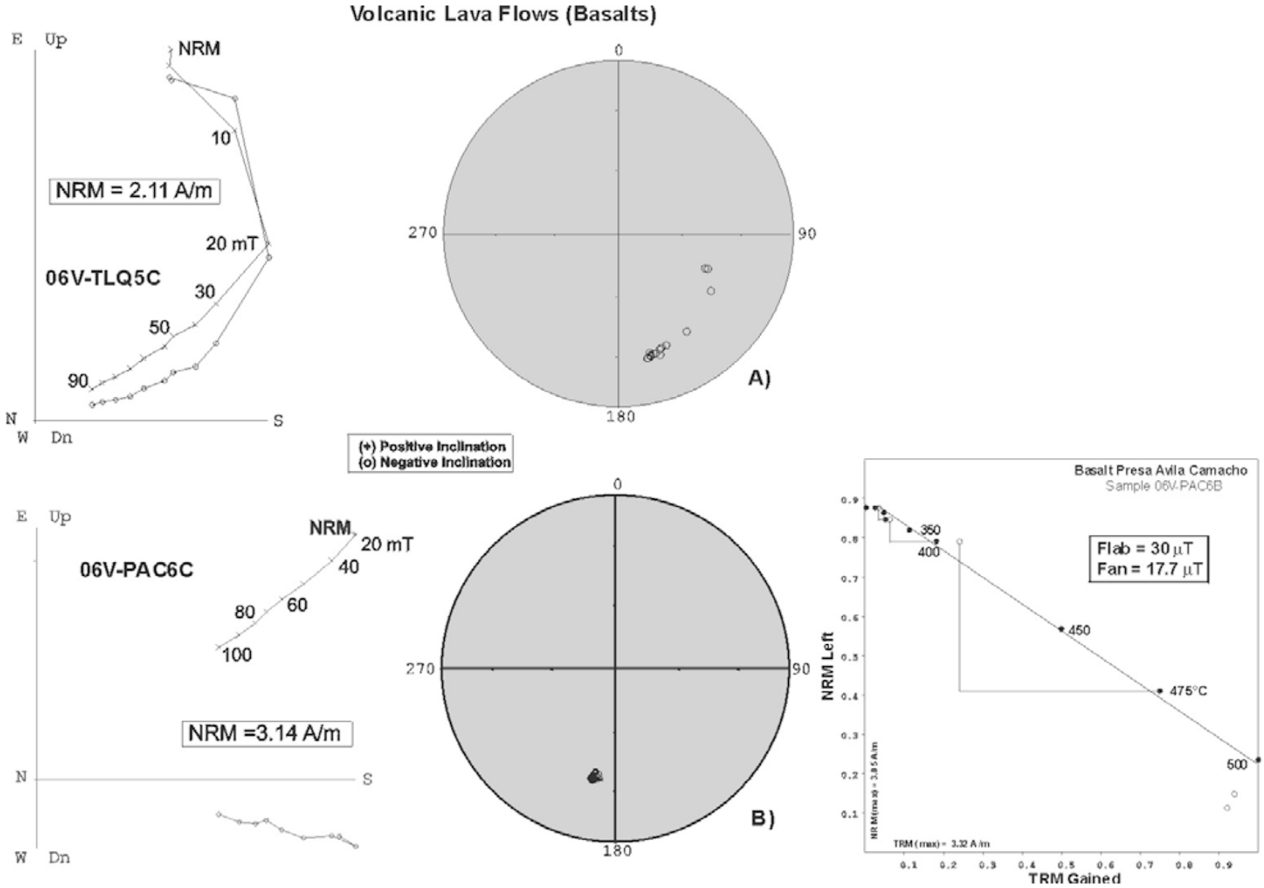

Fig. 3. Orthogonal vector plots of stepwise alternating field demagnetization (stratigraphic co-ordinates) of representative basalt samples. The numbers refer to peak alternating fields in mT. o, Projections into the horizontal plane; x, projections into the vertical plane. Also shown is the representative NRM-TRM plots (so-called Arai plots) for the Avila Camacho lava flow (see also text).

Table 2. Absolute paleointensity results from the Avila Camacho basalt. Inc and Dec are the magnetic inclination and declination of cleaned remanence of individual samples, n is the number of NRM-TRM points used for palaeointensity determination, $T_{\min} - T_{\max}$ is the temperature interval used, f, g and q are the fraction of extrapolated NRM used, the gap factor, and quality factor (Coe *et al.*, 1978), respectively. F_E is the paleointensity estimate for the individual specimen, $\sigma(F_E)$ is its standard error, F_E is the average paleointensity of individual lava flow with standard deviation, VDM and VDMe are individual and average virtual dipole moments, respectively.

Paleointensity results from near Avila Camacho basalt

Sample	Inc	Dec	n	$T_{\min} - T_{\max}$	f	g	q	$F_E \pm \sigma(F_E)$	VDM	$F_E \pm$ s.d.	VDMe
06VPAC6B	−33.9	184.9	7	200–500	0.68	0.80	15.2	17.7 ± 0.6	4.01	17.7 ± 0.7	3.9 ± 0.2
06VPAC8B	−37.2	190.2	7	200–500	0.71	0.78	21.9	18.6 ± 0.5	4.10		
06VPAC4C	−35.8	190.4	6	200–475	0.52	0.74	9.4	17.8 ± 0.6	3.97		
06VPAC3A	−37.4	192.8	6	200–475	0.51	0.71	6.2	16.8 ± 0.9	3.69		

duced relative to present-day field values. Many high-resolution studies have been carried out on monogenetic volcanoes in central Mexico. The principal outcome of these studies is the brief (less than 100 years or so) duration of volcanic activities (Hasenaka and Carmichael, 1987; Luhr and Carmichael, 1985; Luhr and Siminik, 1993; Hasenaka, 1994). While it cannot be ascertained whether the Toluquilla volcano first emitted lava or ashes, the duration between these two events may vary from several years to 100 years. The duration of geomagnetic excursion or reversal is definitively larger (10^3–8×10^3 years after Merrill and McFadden (1994) and $\geq 3 \times 10^3$ years after Gubbins (1999)). Thus, we assign the same gemaognetic event to the ash and lava flow.

The interpretation based on the Xalnene reverse polarity and 1.3 Ma date has challenged the assumed human origin of the footprints (Renne *et al.*, 2005). However, this age hardly can be accommodated within the geological framework of Valsequillo Basin. As reported by Gonzalez *et al.* (2005), the Xalnene ash layer is deposited between two lake sedimentary (and alluvial gravel) layers. The available ages for these formations vary between 36.9±0.6 ka BP and 25.1±0.1 ka BP. Thus, the Ar-Ar age reported falls definitively outside of the local stratigraphic context. This age is also completely out of line with any anthropological considerations since there is only a very remote possibility that humans arrived in America at almost same time as they did so in Europe. Because no evidence of an intermediate field is found within chron C1r.2r, we prefer the alternative interpretation that the intermediate polarity Xalnene

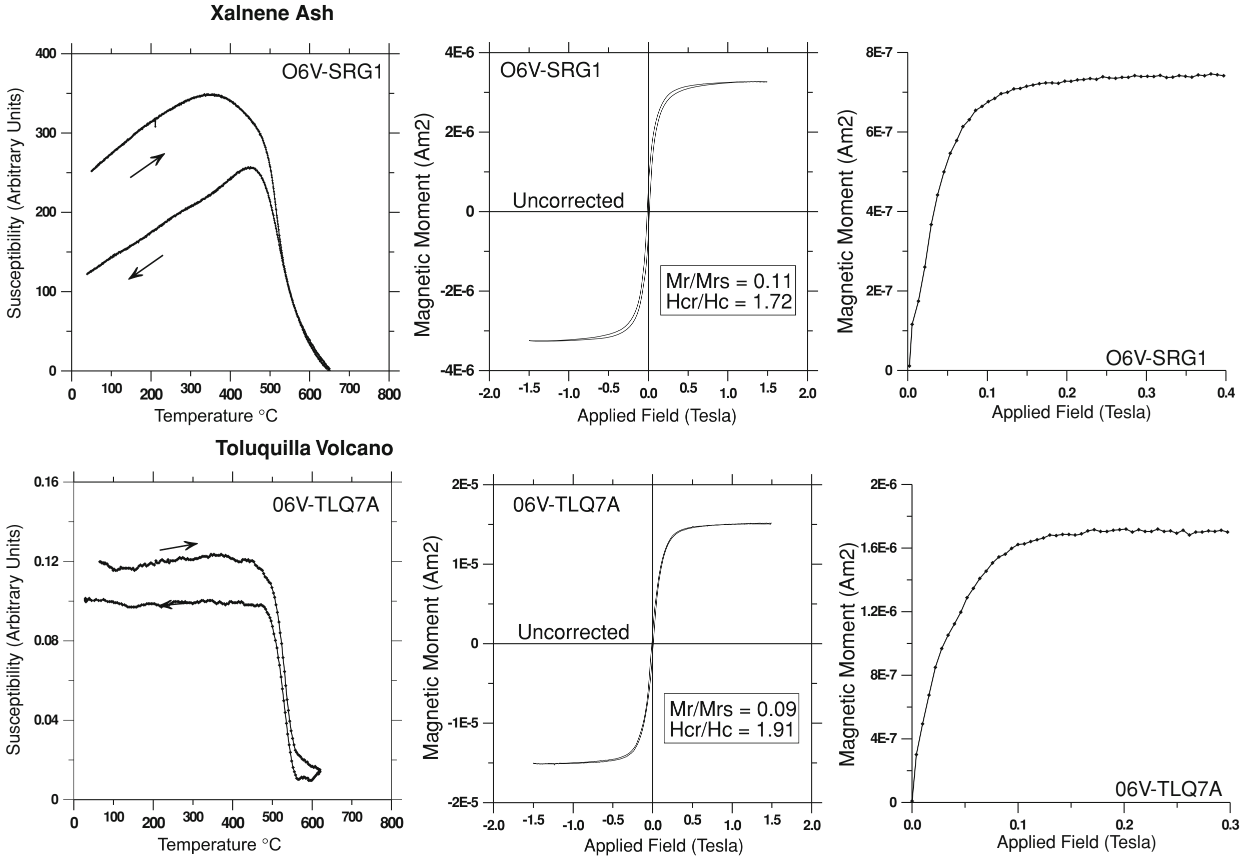

Fig. 4. Summary of rock-magnetic properties: representative susceptibility versus temperature curves (the arrows indicate the heating and cooling curves) and examples of hysteresis loops (uncorrected) of small chip samples with corresponding isothermal remanence (IRM) acquisition curves.

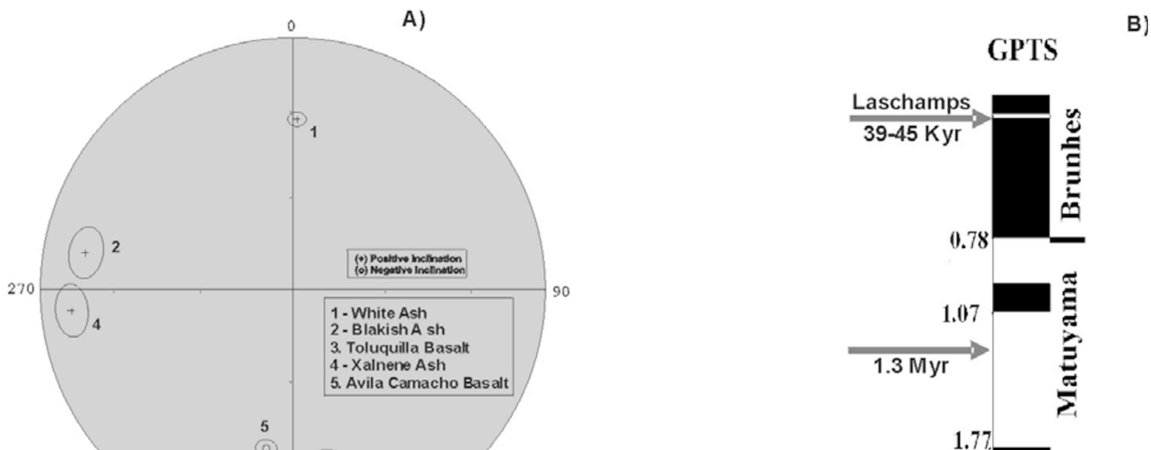

Fig. 5. Equal area projections (a) of the flow mean characteristic paleodirections, the Valsequillo area, and correspondence with the possible ages of the studied material. Circles/crosses denote the negative/positive inclination and (b) geomagnetic polarity time scale for the last 2 Myr (Cande and Kent, 1995).

ash and reverse volcanic lava formed during the Laschamp (Fig. 5(A, B)) geomagnetic event (dated 45 to about 39 ka). We note that there are several 'excursions' within Brunhes chron that yield fully reversed paleodirections (e.g., Knudsen *et al.*, 2003; Petronille *et al.*, 2005).

The Laschamp excursion (Bonnhomet, 1969) first discovered in the 1960s in the French Massive Central remains one of the best documented cases of a recent geomagnetic excursion, with worldwide expression (Guillou *et al.*, 2004). This interpretation indicates that Valsequillo probably remains one of the sites of early human occupation in the Americas, producing evidence of an early arrival.

Additional evidence for early human occupation in Mexico (about 40 ka ago) has recently been reported from the Espiritu Santo site in the Baja California peninsula (Fujita *et al.*, 2006). The timing, route, and origin of the first colonization in the Americas remain one of the important topics in human evolution (Dixon, 2001; Marshall, 2001).

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