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Age constraints on alleged "footprints" preserved in the Xalnene Tuff near Puebla, Mexico

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ABSTRACT

Impressions in a basaltic tuff located around Valsequillo Reservoir near Puebla, Mexico, have been interpreted as human and animal footprints along an ancient lakeshore, and are cited as evidence of the presence of humans in North America at 40 ka B.P. In this paper, we present new data that challenge this interpretation. Paleomagnetic analyses of the Xalnene Tuff, and lavas from the volcano from which it erupted, yield fully reversed magnetic polarities, indicating that the tuff was deposited prior to the last geomagnetic reversal (the Brunhes-Matuyama ca. 790 ka). ^{40}Ar/^{39}Ar dating of Xalnene lapilli and lava from the source volcano yields indistinguishable ages of ~1.3 Ma, consistent with a period of reversed magnetic polarity (C1r.2r). Additional paleomagnetic measurements of individual millimeter-size lapilli indicate that the pyroclastic grains within the Xalnene Tuff have not been disturbed or rotated since their initial deposition, thereby ruling out the possibility that the tuff was reworked by wave action along the shores of an ancient lacustrine environment. This and other evidence indicate that the marks observed in the stone quarry site are not human ichnofossils.

INTRODUCTION

When and how the first humans entered the Americas is unresolved. The oldest widely recognized and distinctive early assemblage is that of the Clovis Complex (Tankersley, 2004). Clovis artifacts are found throughout North America, but are rare beyond southern Mexico. The earliest radiocarbon dates for the Clovis complex are 13.1 cal ka B.P. (Waters and Stafford, 2007). For many decades, archaeologists have searched for evidence of an even earlier occupation. Yet most of these sites failed to provide convincing geochronologic evidence of human occupation before Clovis. This has changed recently, with a few sites dating as early as ca. 15–16 cal ka B.P., which offer compelling evidence of pre-Clovis human populations in the Americas (Goebel et al., 2008).

Recently, a site in the Valsequillo Basin of Mexico (Fig. 1) was reported to have human footprints preserved within a basaltic tuff. Impressions found on the exposed surface of a tuff layer were inferred to represent human and animal footprints (González et al., 2006a). The researchers who interpreted these impressions attempted to date the tuff using a variety of geochronologic techniques, and arrived at a depositional age of 38.04 ± 8.57 ka using optically stimulated luminescence (OSL) (González et al., 2006a). González et al. (2006a) interpreted the putative footprints as having formed immediately after deposition of the tuff in a lake margin setting, and concluded that humans had migrated into the Americas by ~40 ka ago. This interpretation added a new layer of controversy to the ongoing debate about the antiquity of archaeological remains found in the Lake Valsequillo Basin (see reviews by Ochoa-Castillo et al., 2004; González et al., 2006b)

The Xalnene Tuff had previously been dated to 1.30 ± 0.03 Ma using the ^{40}Ar/^{39}Ar technique applied to nine individual basalt lapilli in the tuff (Renne et al., 2005). Renne et al. (2005) also reported a reverse paleomagnetic polarity for the tuff, consistent with deposition during chron C1r.2r (Cande and Kent, 1995), and concluded that such antiquity argued against the interpretation of the impressions as *Homo sapiens* footprints.

González et al. (2006a, 2006b) questioned the validity of the ^{40}Ar/^{39}Ar dating by Renne et al. (2005), asserting that the Xalnene Tuff is heterogeneous, and implying that the lapilli dated by Renne et al. were reworked or inherited. González et al. (2006a, 2006b) also challenged the significance of the reversed paleomagnetic polarity by suggesting self-reversal or emplacement during the Laschamp geomagnetic excursion. Thus, the sole basis for the inference of a ca. 40 ka age for the Xalnene Tuff is an OSL date obtained from a single quartzofeldspathic xenolith in the tuff (González et al., 2006a, 2006b). The validity of this OSL age has since been questioned (Duller, 2006; Schwenninger et al., 2006).

The latest contribution to the ongoing debate about the age of the Xalnene Tuff is a report by Gogichaishvili et al. (2007) of transitional paleomagnetic directions from the Xalnene Tuff, and of anomalously weak geomagnetic paleointensity recorded by lavas from the eruptive center for the tuff (Cerro Toluquilla), collectively interpreted to support the Laschamp age suggested by González et al. (2006a, 2006b).

In an attempt to reconcile this debate, we report new paleomagnetic and radioisotopic data for both the Xalnene Tuff and the volcano from which it erupted.

THE XALNENE TUFF

The Xalnene Tuff is a layered sequence of pyroclastic deposits produced by eruptions from Cerro Toluquilla, a small monogenetic volcano located ~1 km from the site of the footprint-like impressions (Fig. 1). At the "footprint" locality (18° 55.402′ N, 098° 09.375′ W), the pyroclastic

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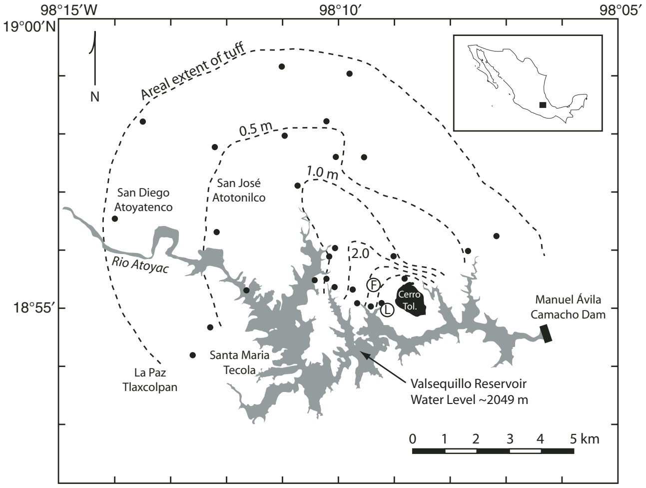

Figure 1. Schematic map showing areal extent and thickness of Xalnene Tuff. Thickness contours are approximate and are based on field observations by H.E. Malde (2006, personal commun.), which are denoted by black circles. The two circles show locations of the "footprint" locality (F) and the lava sampling locality (L).

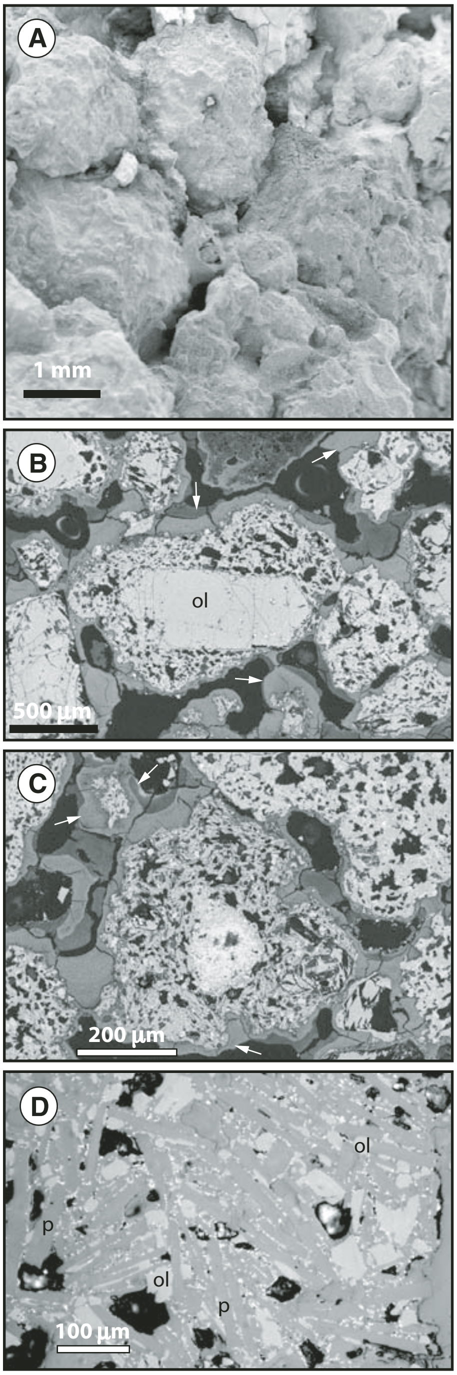

Figure 2. A: Scanning electron microscope micrograph of Xalnene lapilli encased within secondary goethite-rich clay. B: Backscattered electron (BSE) image of an armored lapillus with an olivine core. C: BSE image of an armored lapillus with a polycrystalline core. Arrows point to goethite-rich clay rinds. ol—olivine. D: Reflected light image of small (<1 µm) titanomagnetite crystals (white) decorating the edges of plagioclase laths within the crystalline lapilli matrix. p—plagioclase.

deposits overlie lake sediments and comprise a stratigraphic succession of several meters of bedded 1–10 cm thick tuff layers. The sample we analyzed was collected from the top of the sequence at the exact stratigraphic level containing the reported footprints, and is an azimuthally unoriented, tabular block. Lake sediments overlie the Xalnene Tuff, indicating that the pyroclastic material has experienced water exposure and possible hydrous alteration.

In order to properly interpret the paleomagnetic record preserved in the Xalnene Tuff, it is important to describe its composition and subsequent alteration. The tuff layer containing the alleged footprints is a moderately indurated, basaltic, coarse ash and lapilli tuff in which the lapilli are locally cemented by a matrix of fine-grained clay-like minerals that appear to be formed by marginal alteration of the lapilli (Fig. 2). Lapillus diameters range from 0.5 to 4 mm. The cores of the lapilli comprise porphyritic basalt with euhedral olivine phenocrysts (0.3–1.5 mm) and/or dense polycrystalline aggregates of plagioclase laths, olivine, occasional clinopyroxene, and rare oxides. Typically, the cores are surrounded by a matrix of olivine (~40 µm) and plagioclase (~15 × ~80 µm) whose edges are decorated with <1 µm oxide crystals (Fig. 2D). In reflected light, these oxides show isotropic reflectivity, establishing their cubic structure. Rock magnetic analyses (see the GSA Data Repository[1]) show these cubic oxides to be titanomagnetite ($Fe_{3-x}Ti_xO_4$) or titanomaghemite, its oxidized equivalent. Little glass is observed in the lapilli.

In thin section, the brown, fine-grained, clay-rich cement forms concentric layers within embayments along the edges of the lapilli. Scanning electron microscope images (Figs. 2A–2C) show clay rinds surrounding the lapilli, suggesting pervasive hydrous alteration, or palagonization, of the pyroclastic deposit.

Paleomagnetic results for bulk samples of Xalnene Tuff reported in Renne et al. (2005) are briefly summarized in Table 1. Because the Xalnene Tuff experienced mineralogical alteration (Fig. 2), oriented individual lapilli were extracted from the surface of the bulk sample in order to isolate the carrier phase of the original thermal remanent magnetization and clarify the sources of the dual-polarity remanence found by Renne et al. (2005). The clay-rich cement was minimized using a plastic needle, sandpaper, and ultrasonic cleaning in distilled water. Fiducial marks on each lapillus allowed for their reorientation with an estimated accuracy of ±5°. Each lapillus was glued to a quartz slide for manipulation during measurements.

The magnetic mineralogy of individual lapilli was characterized using several rock magnetic techniques (Data Repository). Isothermal remanent magnetization (IRM) acquisition experiments revealed plateaus in saturation remanence magnetization values shortly after 300 mT, indicating that the lapilli's remanence is held primarily by a cubic spinel. Strong-field thermomagnetic curves showed that magnetization is most rapidly unblocked at 450 °C, consistent with a titanomagnetite composition of $Fe_{2.76}Ti_{0.24}O_4$ (Lattard et al., 2006). When the lapilli are cleaned of their hydrous alteration products, their magnetic mineralogy comprises an assemblage dominated by titanomagnetite grains.

Two components of magnetization were revealed during alternating field (AF) demagnetization of oriented lapilli: a low-coercivity reversed component that is typically removed after 15 mT, and a randomly oriented, but well-defined, high-coercivity component (Fig. 3, Table 1). As a general trend, lapilli with smaller diameters have smaller to nonexistent low-coercivity components, while larger lapilli have greater low-coercivity components. The low-coercivity component in all samples never exceeded 10% of the natural remanent magnetization intensity. Because the lapilli were

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[1] GSA Data Repository item 2009068, rock magnetic measurements and $^{40}Ar/^{39}Ar$ results, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. SUMMARY OF PALEOMAGNETIC RESULTS

Site	Dec. (°)	Inc. (°)	N	K	α_{95} (°)	Polarity
Xalnene Ash						
Bulk Samples*	194†	–32.10	5	146.6	6.4	Reversed
Individual Lapilli	205.1	–48.00	20	5.8	14.9	Reversed
Cerro Toluquilla						
High-coercivity	176.3	–33.10	12	100.9	4.3	Reversed
Low-coercivity	354.0	–11.10	10	112.5	4.6	Reversed

*From Renne et al., 2005.

†These samples come from an azimuthally unoriented block. For the sake of comparison with the lapilli and Cerro Toluquilla samples, they have been rotated parallel to 194°, the orientation of a reversed polarity field relative to the modern declination at the field site.

collected from the same azimuthally unoriented block reported by Renne et al. (2005), their declination is meaningless, but their inclination is significant. Such azimuthally unoriented samples are routinely used in paleomagnetic studies, and are the foundation for polarity determinations in cores recovered in continental and ocean drilling projects. Direct comparison of the declinations of the bulk samples and the individual lapilli is also valid because they share the same reference frame. The lapilli's low-coercivity component agrees within error with the Xalnene Tuff bulk sample site average reported in Renne et al. (2005) (Table 1).

The lapilli's two magnetic components are best understood by considering the physical processes inherent in a volcanic eruption. Each lapillus initially forms as partially molten volcanic ejecta erupted at a temperature of ~1200 °C. During transport and deposition, each lapillus experiences conductive and radiative cooling, the extent of which will depend on factors such as the velocity, distance, and path of ejection, lapillus volume, and final depositional environment (subaerial or subaqueous). As a lapillus cools, its constituent titanomagnetite grains pass through their magnetic blocking temperatures and acquire a thermal remanent magnetization. If cooled rapidly, a lapillus may acquire its full magnetization during eruptive transport, in which case its magnetization would represent an arbitrary orientation related to the lapilli's eruption trajectory and aerodynamic properties. At the time of deposition, the magnetization of such lapilli will be randomized. The directions of the Xalnene lapilli's high-coercivity component shown in Figure 3B fail the Watson test for randomness, and cannot be distinguished from a random set of directional data. Thus, we interpret the lapilli's high-coercivity component of magnetization to be a thermoremanence acquired during the ejecta's eruption and deposition.

Some of the tuff layers within the Xalnene Tuff are more indurated than others, suggesting that they were deposited with residual heat. In such cases, it is likely that some of the lapilli within the tuff will also record a component of magnetization parallel to Earth's magnetic field. We interpret the low-coercivity component in Figure 3C to represent thermoremanent magnetization acquired after the lapilli were deposited but still hot. It is this reversed component that represents the polarity of the geomagnetic field during the time of eruption.

Hydrous alteration observed at lapilli margins must have occurred after the tuff's deposition. Magnetic oxides and oxyhydroxides often form during this weathering process, and can record the direction of Earth's magnetic field during their growth. The normal magnetic component reported in bulk samples of the Xalnene Tuff (Renne et al., 2005) is held by goethite formed in this manner. Because the lapilli were able to maintain their original reversed thermoremanent magnetization during this secondary mineral growth, the tuff must have been relatively well indurated before palagonization occurred. Thus, prolonged exposure to groundwater during high stands in Lake Valsequillo, in combination with dissolved CO_2 originating from local volcanism, may have partially altered the basaltic tuff to form secondary magnetic minerals.

CERRO TOLUQUILLA

Cerro Toluquilla is a small cinder cone that is the source of the Xalnene Tuff. The tuff thins rapidly outward from the cinder cone to a thickness commonly less than 1 m (Fig. 1). In order to test whether the paleomagnetic and $^{40}Ar/^{39}Ar$ results from the Xalnene Tuff are reliable, fully oriented basaltic lava samples were collected from the southern flank of Cerro Toluquilla (18° 54.851′ N, 098° 09.129′ W).

Results from thermal and AF demagnetization yield a site average direction for the Cerro Toluquilla samples that is reversed, with an inclination almost identical to that measured for the Xalnene Tuff (Table 1). The magnetizations of the bulk Xalnene Tuff, the individual lapilli, and the Cerro Toluquilla lavas all agree within error (Table 1). A secondary, lower-coercivity, reversed component of magnetization is also present in the Cerro Toluquilla lava, but its origin is unclear. It is important to note that the magnetic mineralogy in the lava is different from that in Xalnene Tuff (Data Repository). Thin sections are characterized by fine intergrowths of ilmenite and titanomagnetite, which form in lavas during high-temperature oxidation (Grommé et al., 1969; González et al., 1997).

The Cerro Toloquilla lava was analyzed by the incremental heating $^{40}Ar/^{39}Ar$ method in two experiments. Details of the methodology, and the Ar isotopic data, are provided in the Data Repository. Age spectra for the two analyses, based on the 1.193 Ma Alder Creek sanidine standard (Nomade et al., 2005), are given in the Data Repository. Both samples yielded 100% concordant age spectra, with plateau ages of 1.28 ± 0.03 Ma and 1.30 ± 0.03 Ma. The weighted

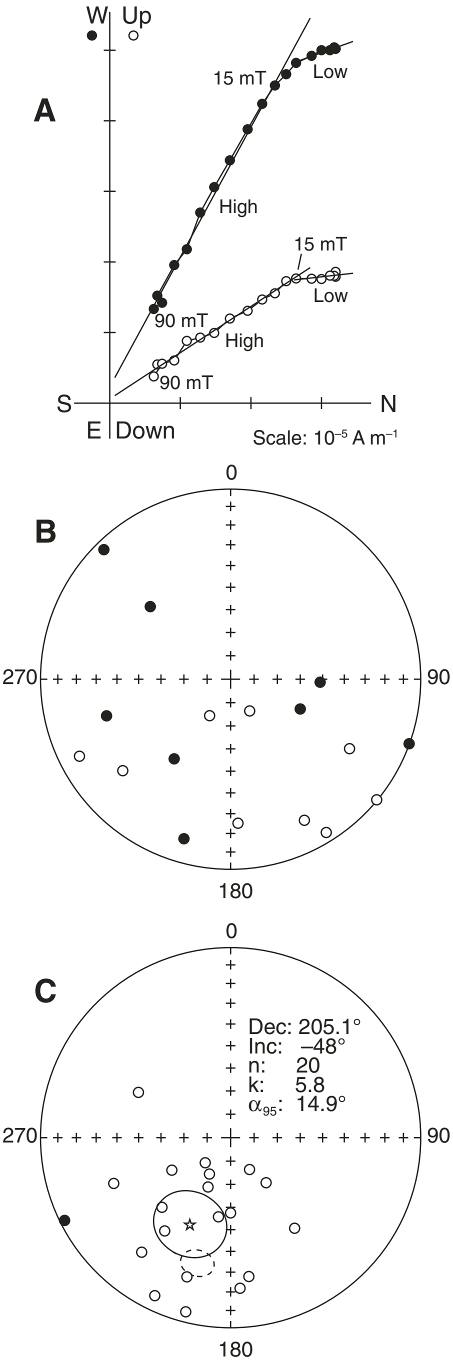

Figure 3. A: Orthogonal vector end-point diagram for a typical lapillus showing two components of magnetization. B: Equal area plot of the lapilli's high-coercivity component. C: Equal area plot of the lapilli's low-coercivity component. Solid (hollow) symbols in (B) and (C) refer to lower (upper) hemisphere projection.

mean age (1.29 ± 0.02 Ma) is interpreted as the lava's eruption age, and we note that it is identical to that (1.30 ± 0.03 Ma) reported by Renne et al. (2005) for a Xalnene Tuff sample.

DISCUSSION

Three lines of evidence point to Cerro Toluquilla as the source of the Xalnene Tuff: the decreasing thickness of the tuff with distance from the cinder cone (Fig. 1), the indistinguishable ^{40}Ar/^{39}Ar ages for both features, and the similar paleomagnetic remanence directions. That the Xalnene Tuff and the Cerro Toluquilla lava both record the same reversed magnetization is strong evidence that (1) the Xalnene Tuff was deposited during a time of reversed polarity, and that (2) the lapilli in the Xalnene have not experienced reworking since their original deposition. ^{40}Ar/^{39}Ar ages for individual lapilli are consistent and tightly clustered, indicating a monogenetic source of basaltic lapilli uncontaminated by xenolithic volcanic materials.

In rare instances, a rock may be "self-reversed" and record a magnetic remanence antiparallel to the Earth's field. González et al. (2006a, 2006b) invoked self-reversal as a possible explanation for the reversed polarity of the Xalnene Tuff reported in Renne et al. (2005). Processes leading to self-reversal fall into two broad categories: extreme low-temperature oxidation and ionic reordering (see review by Doubrovine and Tarduno, 2006), and classic exchange coupling (Nagata et al., 1952). Ionic reordering appears to be limited to very high oxidation states and is excluded in the case of this study by Curie temperature plots in the Data Repository. Moreover, laboratory partial thermoremanent magnetization experiments on cleaned Xalnene lapilli and samples of Cerro Toluquilla lava show no evidence of self-reversal. Furthermore, the similarity of paleomagnetic directions between the tuff and the lava, despite their different magnetic mineralogy, argues against the suggestion that the tuff's reversed magnetization is due to self-reversal (González et al., 2006b).

The 1.3 Ma age for the volcano and its pyroclastic deposit confirm that the eruption occurred during reversed polarity chron C1r.2r as originally concluded by Renne et al. (2005). Suggestions that the lava and tuff record a fully reversed instant during the ca. 40 ka Laschamp geomagnetic excursion (González et al., 2006b, Gogichaishvili et al., 2007) are not supported by the recent ^{40}Ar/^{39}Ar results. Intermediate paleomagnetic directions for bulk samples of the Xalnene Tuff were reported in Gogichaishvili et al. (2007) and interpreted as transitional directions recorded during the Laschamp excursion. We offer an alternative explanation for such "transitional" results, whereby the lapilli that make up the tuff were cooled below their blocking temperatures prior to deposition, such that the majority of thermoremanence recorded by the samples of Gogichaishvili et al., (2007) was pre-depositional. The resulting magnetizations of bulk samples (as analyzed by Gogichaishvili et al., 2007) would be the vector sum of the randomized lapilli contributions and would appear to have scattered directions and anomalously weak intensities. The variability of induration and palagonitization throughout the layered zone of the Xalnene Tuff suggests that not all of the tuff layers were deposited with enough residual heat to acquire a component of magnetization parallel to the geomagnetic field.

CONCLUSIONS

The evidence from paleomagnetic analysis and ^{40}Ar/^{39}Ar dating show that the Xalnene Tuff is not 40 ka old. Instead, our data show unambiguously that the Xalnene Tuff is 1.3 Ma. If the marks identified by González et al. (2006a) were of human origin, then they would probably belong to early *Homo erectus* (Antón and Swisher, 2004). This is unlikely, based on the known geographic distribution of these early hominids (Antón and Swisher, 2004) and the genetic and archaeological evidence for the peopling of the Americas (Goebel et al., 2008). The marks observed by González et al. (2006a) were found in a stone quarry and are more likely to represent marks left behind from this quarrying, which were later enhanced by weathering and erosion.

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