Geofísica Internacional (2014) 53-1: 87-94

Short note

Volcano-sedimentary stratigraphy in the Valsequillo Basin, Central Mexico inferred from electrical resistivity soundings

Jaime Urrutia-Fucugauchi*, Alfonso Trigo-Huesca, Eloísa Téllez-García, Ligia Pérez-Cruz, Fabiola Méndez-Rivero and Valsequillo Project Team

Received: July 22, 2013; accepted: July 31, 2013; published on line: December 11, 2013

Resumen

La estratigrafía de la secuencia volcano-sedimentaria en la cuenca de Valsequillo, Puebla es investigada por medio de sondeos eléctricos de resistividad. Los depósitos en la cuenca preservan registros paleontológicos, paleoclimáticos y paleoambientales, que incluyen evidencias sobre restos fósiles de megafauna asociados con artefactos humanos. El reporte de posibles huellas de humanos preservadas en la tefra Xalnene, con una edad de alrededor de 38 mil años, ha atraído nuevamente interés en analizar la estratigrafía en Valsequillo. Este estudio se realizó en la zona cubierta por la tefra Xalnene, en la planicie situada al noroeste del volcán Toluquilla, empleando sondeos eléctricos verticales (SEVs). Los modelos de inversión de las curvas SEVs muestran una secuencia caracterizada por unidades de alta y baja resistividad aparente, que son asociadas a las tefras, sedimentos lacustres y fluviales y rocas volcánicas. Las secciones compuestas de resistividad documentan tres unidades, con las tefras y sedimentos formando una sección de unos 30 m sobre las rocas volcánicas. Los datos relacionan las tefras con el volcán monogenético, las cuales se emplazan en un ambiente lacustre somero. Las secciones de resistividad documentan las variaciones de espesores de los depósitos. Observaciones durante los estudios de campo y adquisición de datos proporcionan evidencias adicionales sobre el posible origen de las huellas aparentes, que estarían asociadas a las excavaciones de las tefras como materiales de construcción y los procesos de erosión. Estudios de detalle y experimentos en laboratorio proporcionarían mayor evidencia para entender la morfología y rasgos en las tefras. El retiro y actividades de corte están afectando significativamente al depósito por lo que se requieren de medidas de protección para proteger la zona dado su valor científico.

Palabras clave: Cuenca de Valsequillo, Tefra Xalnene, estratigrafía, estudio eléctrico de resistividad, sondeos eléctricos verticales, centro de México.

Abstract

Initial results of an electrical resistivity survey of the volcano-sedimentary sequence of the Valsequillo basin in central Mexico are presented. The volcano-sedimentary deposits preserve rich paleontological, paleoclimatic and paleoenvironmental records, which include extinct megafauna remains associated with human artifacts. The report of possible 38 ka old human footprint tracks in the Xalnene tuff attracted renewed interest in the basin stratigraphy. We examine the shallow stratigraphic sequence in the Xalnene tuff outcrop plain northwest of Cerro Toluquilla volcano using vertical resistivity soundings (VES). Inversion models of VES soundings show a layered structure of high and low resistivity units, which characterize the Xalnene tuff, lacustrine and fluvial sediments and volcanic rocks. 2-D resistivity cross sections document three major units corresponding to the Xalnene tuff and sediments filling a <30 m deep basin lying on volcanic rocks. Resistivity models provide further support for the association of Xalnene tuff with the Toluquilla volcano and emplacement of the pyroclastic deposits on a shallow lacustrine environment. The resistivity cross sections constrain the thickness of the tuff layers and underlying lacustrine sediments. Observations during the data acquisition field work provide insight on the possible origin of the apparent tracks, which seem to develop from erosion processes acting on quarrying marks. Further analysis and experimental evidence is required to understand the morphology and weathered patterns. The tuff layers are being removed by quarrying operations and the outcrops significantly altered. Adequate conservation measurements should be implemented to preserve the deposits for scientific research.

Key words: Valsequillo basin, Xalnene tuff, stratigraphy, electrical resistivity survey, vertical resistivity soundings, central Mexico.

J. Urrutia-Fucugauchi*
A. Trigo-Huesca
E. Téllez-García
L.Pérez-Cruz
F. Méndez-Rivero
and Valsequillo Project Team
Laboratorio de Paleomagnetismo y Paleoambientes, Instituto de Geofísica
Universidad Nacional Autónoma de México
Ciudad Universitaria
Delegación Coyoacán, 04510
México D.F., México
*Corresponding author: juf@geofisica.unam.mx

Introduction

Finding of apparent human footprint tracks in the Xalnene tuff in the Valsequillo basin, central Mexico sparked renewed interest on the basin volcano-sedimentary sequences (González *et al*., 2006a,b). The possible footprint tracks are preserved in an indurate ash layer associated with Cerro Toluquilla monogenetic volcano (Figure 1). The tuff was dated at 38 ka using optical stimulated luminescence (OSL). The implications for an early presence of humans in the Americas (Goebel *et al*., 2008; Urrutia-Odabachian and Urrutia-Fucugauchi, 2011) promptly attracted further studies on the nature of the tracks, age of eruption and stratigraphy of the volcano-sedimentary deposits. Renne *et al*. (2005) reported Ar/Ar dates of 1.3 Ma, challenging the interpretation as possible human footprint tracks. Further radiometric and magnetostratigraphic studies were conducted, which have supported an old age for the Xalnene tuff (Feinberg *et al*., 2009). Re-analyses of the tracks have questioned an origin as human tracks (Morse *et al*., 2010). The studies have highlighted the interest in the volcano-sedimentary sequences in the Valsequillo basin. Here we present the initial results of a geophysical study of the basin, with the inversion models from electrical resistivity soundings of the lacustrine, fluvial and volcanoclastic deposits in the Xalnene tuff outcrop plain (Figure 1).

Electrical resistivity soundings appear well suited for shallow stratigraphic investigations of the volcano-sedimentary deposits, with vertical resistivity contrasts associated with the different lithologies and fluids in stratified deposits. Electrical resistivity surveys have been applied to geohydrology, geological mapping, geotechnical and archaeological prospecting and mineral deposits exploration (e.g., Keller and Frischknecht, 1966; Roy and Apparao, 1971; Zhdanov and Keller, 1994; Urrutia-Fucugauchi, 1992; Loke and Barker, 1996a,b; Marin *et al*., 1998). Vertical electrical resistivity soundings (VES) have been used to investigate the underground structure and stratigraphy of sedimentary sequences in different geologic settings.

The Valsequillo volcano-sedimentary sequences have long been investigated because of the rich paleontological and archaeological remains (e.g., Malde, 1968; Szabo *et al*., 1969; Steen-McIntyre *et al*., 1981; González *et al*., 2006a). Studies conducted in the 1960's as part of a joint project between Harvard University and University of Puebla documented evidence for extinct megafauna remains associated with human artifacts. Reconnaissance field surveys and excavations reported occurrence of fossil remains of mammoth, mastodon, camel, horse, four-horned antelope, saber-toothed tiger, and dire wolf in five different localities, mainly in the Tetela peninsula of the Valsequillo dam

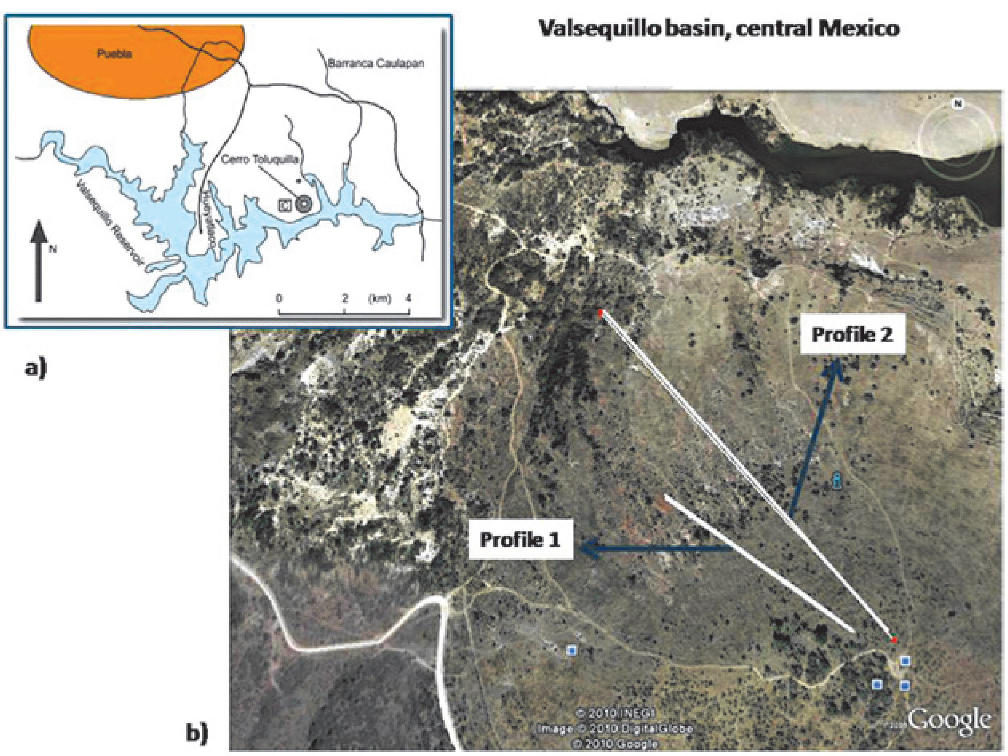

Figure 1. Valsequillo basin study area, central Mexico. (a) Schematic map of the Valsequillo dam reservoir. Study area is in the northern sector (González *et al*., 2006a). (b) Location of resistivity profiles in the Xalnene outcrop plain (base map is a Google Landsat satellite image).

reservoir. Along the shores of the Valsequillo dam, built in 1944, fluvial, lacustrine, tephras and volcanoclastic deposits are exposed, with fossil remains recovered from the Valsequillo gravels.

Xalnene Tuff and Toluquillla volcano

González *et al*. (2006a) reported an emplacement age for the Xalnene tuff of 38.04 + 8.57 ka based on OSL dating, which lead to the proposal that humans were present in central Mexico by around 40 ka ago. This interpretation was challenged by Renne *et al*. (2005) based on Ar/Ar dates on the basaltic lapilli retrieved from the tuff, with a mean age of 1.30 + 0.03 Ma. Renne *et al*. (2005) also presented paleomagnetic evidence, with reverse paleomagnetic directions for the Xalnene tuff, which were correlated to the Matuyama C1r.2r chron. González *et al*. (2006a, b) argued that the lapilli in the tuff could be reworked or inherited, resulting in heterogeneous material not suitable for dating. They also suggested that the paleomagnetic record could result from self-reversal phenomena or related to the Laschamp subchron in agreement with the 40 ka age. Gogichaishvili *et al*. (2007) reported intermediate directions for the Xalnene tuff and low paleointensities for Cerro Toluquilla volcano lavas, interpreted in terms of the Laschamp subchron.

Feinberg *et al*. (2009) reported additional paleomagnetic data from lava samples of Cerro Toluquilla volcano and from individual lapilli grains in the Xalnene tuff, which yield reverse directions. They conclude that the Xalnene tuff has not been disturbed since emplacement by re-working associated with wave action in the lake shore. Feinberg *et al*. (2009) also report additional Ar/Ar dates for Toluquilla lavas, with a mean age of 1.29 + 0.02 Ma, supporting the date for the Xalnene tuff. The nature of the fossil evidence, age dating and stratigraphy are being examined using different methods and approaches (e.g., Renne *et al*., 2005, González *et al*.,2006a,b; Duller, 2006; Gogichaishvili *et al*., 2007; Feinberg *et al*., 2009; Urrutia Fucugauchi *et al*., 2012).

Electrical Resistivity Survey

The shallow stratigraphy underlying the Xalnene ash deposits was investigated using vertical electrical resistivity soundings along two profiles in the tuff outcrop in the area with the apparent human and animal footprint tracks (Figure 1). Survey area is located northwest of Toluquilla volcano and north of the Valsequillo reservoir.

The local basement for the volcano-sedimentary sequences is the Balsas Group (Figure 2b), which is a continental red bed sequence that is widespread in central and southern Mexico. Age of the Balsas Group ranges from Late Cretaceous to Eocene. González *et al*. (2006a) summarized the stratigraphy, with older deposits in the eastern sector, east of the Barranca Calpulapan are the Zacachimalpa or Calpulapan tuffs and lake sediments and the Ixcalo lavas. The lower

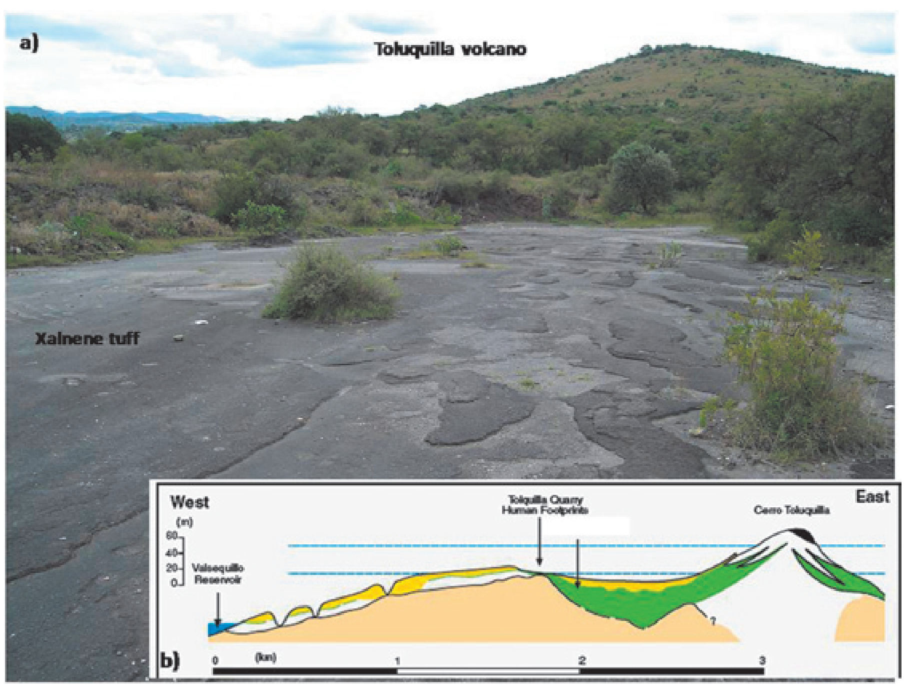

Figure 2. Cerro Toluquilla volcano and Xalnene tuff. View of Cerro Toluquilla volcano from the Xalenene quarry. (b) Cross section showing subsurface stratigraphy (González *et al*., 2006a).

local lacustrine sequence then lies above the Ixcalo lavas or in the study area appears directly on top of the Balsas red beds. The Xalnene tuff serves as a local marker to separate the lacustrine sequence into a lower and upper sequence. Lahar deposits are interbedded within the lacustrine sediments. The fossil-bearing Valsequillo gravels and colluviums deposits correlate with the upper lacustrine sequence and are then above the Xalnene tuff.

The Xalnene quarry is characterized by an extended outcrop of the tuff that covers the surface (Figure 1). In the outcrop the tuff is flat-lying and formed by a succession several meters thick of multiple gradded tuff layers of coarse lapilli interbedded with fine ash. The Xalnene tuff has been described in González *et al*. (2006 a, b) and Feinberg *et al*. (2009) and studies cited therein. The Xalnene tuff is a moderately indurate olivine basalt lapilli tuff deposited from eruption of Cerro Toluquilla.

The electrical resistivity survey was carried out using vertical resistivity soundings with the Schlumberger electrode configuration. The instrument used is a Siscal resistivity meter equipped with a portable electronic acquisition unit. VES profiles are oriented along the long dimension in the Xalnene tuff outcrop, to permit the larger electrode apertures. The profiles were oriented towards the slope of Toluquilla volcano (Figures 1b and 2a), with current electrode apertures up to 30 and 40 m.

Resistivity VES profile curves show a marked change in shape approaching the volcano slopes, indicating low to high resistivities, suggesting a change in subsurface structure. The VES soundings are quantitatively modeled using inversion procedures described in Edwards (1977) and Locke and Barker (1996a, b). VES data inversions are carried out using the RES2DINV GISCO software version 3.2 and IPI2WIN software version 3.01 (Edwards, 1977; Shevnin and Modin, 2003). The inversion assumes horizontal stratified layers with vertical resistivity contrasts. Inversion models permit to estimate the thickness of the layers and resistivity values. Three to five layer models are used in the inversion procedure. Examples of VES curves showing the different curve types and inversion models are shown in Figure 3.

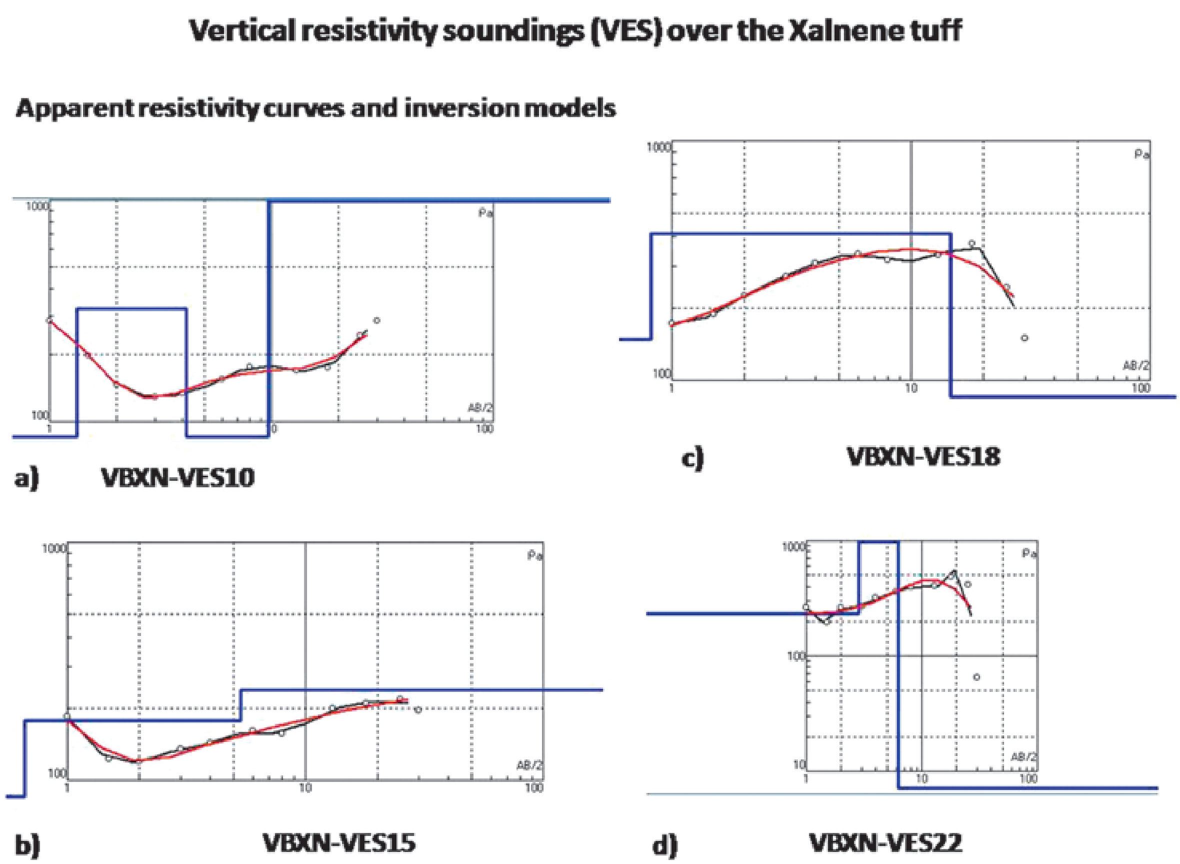

Figure 3. Representative examples of vertical electrical soundings (VES) in Xalnene tuff plain. The inversion models are included in the blue lines.

Resistivity cross sections are constructed from the SEVs (Figure 4). Cross sections show occurrence of a high resistivity zone which is associated with volcanic rocks from the Toluquilla volcano. The volcanic rocks form the basement to the lacustrine and fluvial deposits, represented by lower resistivity contrasts. The zone of low resistivities is associated with the Lower lacustrine sequence, with a thickness up to ~25-30 m. The lacustrine sequence gets thinner towards the Toluquilla volcano (Figure 4). The Xalnene tuff is characterized by intermediate resistivities. Intermediate resistivities may indicate ash and pyroclastic layers, although this is not well constrained in the models.

Discussion

The vertical electrical resistivity soundings assist in reconstructing the lake basin topography and the construction of Cerro Toluquilla volcano. The electrical resistivity cross sections provide indications on the lacustrine sequences and the pyroclastic flows and Xalnene tuff.

Eruption of Toluquilla volcano probably started underwater in the former lake, with eventual rising of a subaerial cone above the water level and emplacement of lava flows. The Xalnene tuff was probably emplaced as subaqueous density flows and subaerial base surges. In the quarrying trenches and pits, individual tuff layers visible by alternations of thin ash layers are between 1 and 10 cm thick. Ash layers contain baked, orange, sandy-silty, angular fragments derived from the lower lake sediments (González *et al*., 2006a, b). The lake sediments above the Xalnene tuff display evidence of shallow water re-working possibly due to lake level changes. Presence of palagonite surfaces suggests hot ash emplacement in water.

The resistivity cross sections constrain the thickness of the tuff layers and underlying lacustrine sediments. Inversion models of VES soundings show a layered structure of high and low resistivity units, which characterize the Xalnene tuff, lacustrine and fluvial sediments and volcanic rocks. 2-D resistivity cross sections document three major units corresponding to the Xalnene

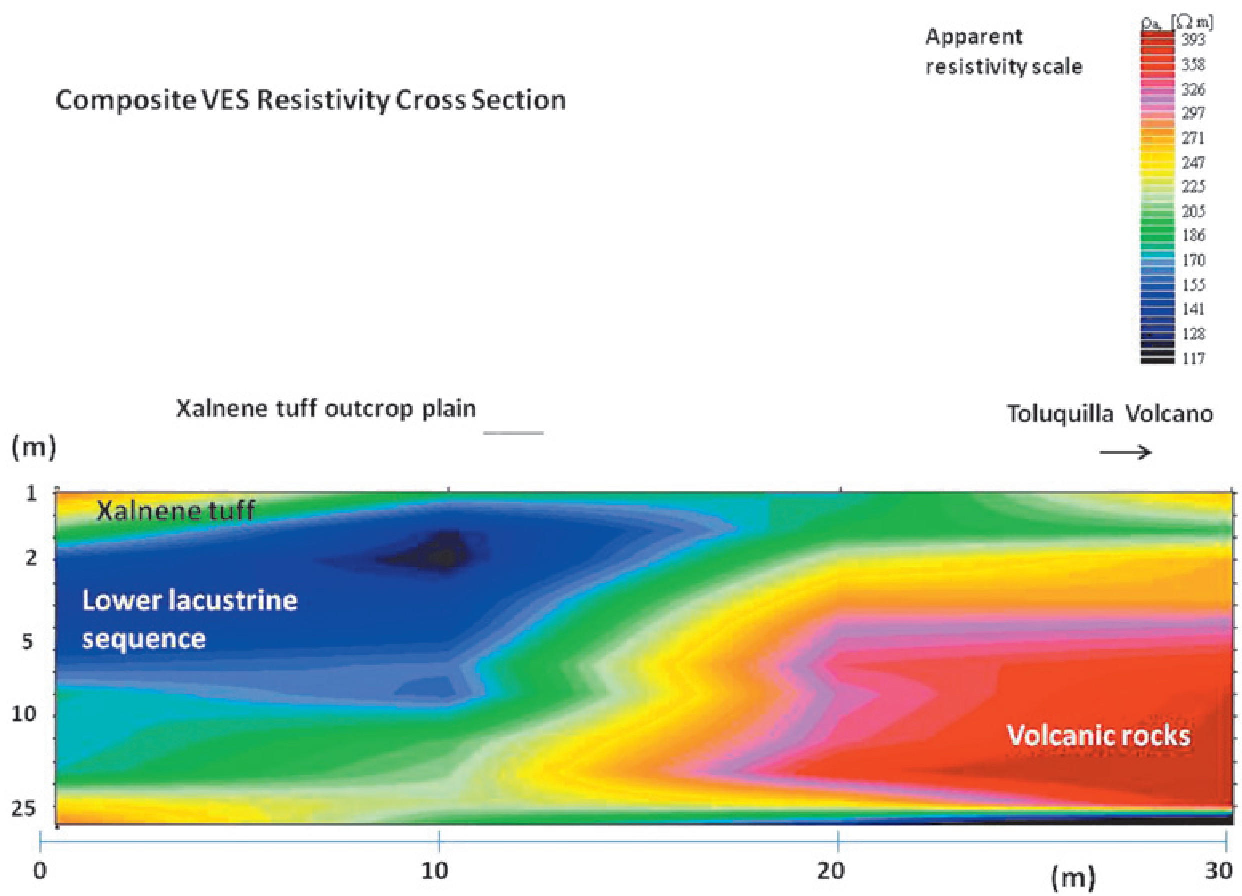

Figure 4. Resistivity cross section in the Xalnene tuff plain. Note that the vertical depth scales in the resistivity cross sections are not linear.

tuff and sediments filling a <30 m deep basin lying on the volcanic flows from the Toluquilla volcano (Figure 4). Resistivity models link the Xalnene tuff and underlying volcanic rocks with the Toluquilla volcano. González *et al*. (2006a) estimated a thickness for the Xalnene tuff of about 5.4 m close to Cerro Toluquilla and thinning down to 10 cm some 4 km to the northwest. The resistivity cross sections image the lower lacustrine unit and the pyroclastic deposits, deposited in a shallow lacustrine environment. González *et al*. (2006a, b) suggested that if ash layers are interbedded with the lacustrine sediments, then lacustrine sedimentation alternated with volcanic activity episodes. The resistivity cross sections do not permit to resolve alternations of ash and lacustrine sediments (Figure 4).

The Xalnene tuff is being quarried for construction and ornamental material (Figure 5). The tuff layers are being removed by quarrying operations and the outcrops significantly altered (Figure 5b, c). Taking into consideration the rich paleontological and paleoenvironmental record preserved in the volcano-sedimentary deposits, it is proposed that adequate conservation measurements should be implemented. It is proposed that the Valsequillo basin should be granted status of a national geological heritage park.

Morse *et al*. (2010) reported a re-examination of the apparent footprint tracks, and compared the observations with other footprint-bearing sites. They concluded that the footprint tracks in the Xalnene tuff are not consistent with the morphology and characteristics of known tracks and are of questionable origin, suggesting that the marks in the tuff originated from the quarrying activities. Quarrying been carried out using manual and machine methods, using hand picks and a mechanical excavator. From our observations during the data acquisition field work, we consider the proposal by Morse *et al*.

Figure 5. Views of the Xalnene tuff. (a) View of the quarry zone investigated by the resistivity soundings. (b, c) Views of the quarry operations, showing the trenches and the slabs cut from the ash layers. (d) View of marks left from quarry operations, modified by erosion. (a) View of marks produced by the mechanical excavator, partly eroded. The incision pattern with parallel groves can be observed.

(2010) a likely explanation. The apparent tracks seem to develop from erosion processes acting on quarrying marks. The mechanical excavator produces deep incisions (Figure 5d), which are eroded and modified. The extraction involves excavating trenches and is directed to cutting slabs (Figure 5b, c), which results in an apparent regular pattern, plus the waste material and gaps in between trenches. The surface layer is altered and eroded and linear features and other marks left by the quarrying activities might be modified into intermittent marks. However, isolated marks and linear incisions can be observed at various parts of the surface. A clear pattern for the modification process is not apparent and further analyses and experimental evidence are needed. Experiments may help understanding the morphology and weathered patterns.

Acknowledgments

This study forms part of the Valsequillo Basin geophysics project. We thank team members participating in the study A. Ortega, E. Torres, D. Lopez, J. Mayo and R. Zamora.

Bibliography

Duller G.A.T., 2006, Comment on "Human footprints in central Mexico older than 40,000 years". *Quaternary Science Reviews*, 25, 3074-3076.

Edwards L.S., 1977. A modified pseudosection for resistivity and induced-polarization. *Geophysics*, 42, 1020-1036.

Feinberg J.M., Renne P.R., Arroyo-Cabrales J., Waters M.R., Ochoa-Castillo P., Perez-Campa M., 2009, Age constraints on alleged "footprints" preserved in the Xalnene tuff near Puebla, Mexico. *Geology*, 37, 267-270.

Goebel F.E., Waters M.R., O'Rourke D.H., 2008, The Late Pleistocene dispersal of modern humans in the Americas. *Science*, 319, 1497-1502.

Gogichaishvili A., Martin del Pozzo A.L., Urrutia Fucugauchi J., Soler A.M., 2007, Human footprints found in central Mexico could be at least 40,000 years old. *Geofisica Internacional*, 46, 85-87.

González S., Huddart D., Bennett M.R., González-Huesca A., 2006 a, Human footprints in central Mexico older than 40,000 years. *Quaternary Science Reviews*, 25, 201-222.

González S., Huddart D., Bennett M.R., 2006b, Valsequillo Pleistocene archaeology and dating: Ongoing controversy in Central Mexico. *World Archaeology*, 38, 611-627.

Keller G.V., Frischknecht F.C., 1966, Electrical Methods in Geophysical Prospecting. Pergamon Press, Oxford, 519 pp.

Loke M.H., Barker R.D., 1996a, Rapid least-squares inversion of apparent resistivity pseudosections using a quasi-Newton method. *Geophys*. *Prosp*., 44, 131-152.

Loke M.H., Barker R.D., 1996b, Practical techniques for 3D resistivity surveys and data inversion. *Geophys. Prosp*., 44, 499-523.

Marin L., Steinich B., Jaglowski D., Barcelona M.J., 1998, Hydrologic site characterization using azimuthal resistivity surveys. *J. Envrion. Eng. Geophys*., 3, 179-184.

Morse S.A., Bennett M., González S., Hudart D., 2010, Techniques for verifying human footprints: reappraisal of pre-Clovis footprints in Central Mexico. *Quaternary Science Reviews*, 29, 2571-2578.

Renne P.R., Feinberg J.M., Waters M.R., Arroyo-Cabrales J., Ochoa-Castillo P., Perez-Campa M., Knight K.B., 2005, Age of the Xalnene ash, Central Mexico, and archaeological implications. *Nature*, 438, E7-E8.

Roy A., Apparao A., 1971, Depth of investigation in direct current methods. *Geophysics*, 36, 943-959.

Shevnin V.A., Modin I.N., 2003, IPI2WIN (3.0.1) Free Version, [1D interpretation of VES profile], Moscow State University, Geological Faculty, Department of Geophysics: GEOSCAN-M Ltd.

Steen-McIntyre V., Fryxell R., Malde H.E., 1981, Geologic evidence for age of deposits at Huayatlaco archaeological site, Valsequillo, Mexico. *Quaternary Research*, 16, 1-17.

Szabo B.J., Malde H.E., Irwin-Williams C., 1969, Dilemma posed by uranium-series dates on archaeologically significant bones from Valsequillo, Puebla, Mexico. *Earth Planetary Science Letters*, 6, 237-244.

Urrutia-Fucugauchi J., 1992, Reconnaissance electrical resistivity and self-potential studies of the Atotonilco-Jonacatepec region, Morelos State, Mexico. *Geofisica Internacional*, 31, 341-358.

Urrutia-Fucugauchi J., Trigo-Huesca A., Pérez-Cruz L., 2012, Magnetic links among lava flows, tuffs and the underground plumbing system in a monogenetic volcano, derived from magnetics and paleomagnetic studies. *Phys. Earth Planet. Int.*, 212-213, 10-18.

Urrutia-Odabachian A., Urrutia-Fucugauchi J., 2011, El poblamiento temprano de América: ¿cómo, cuándo, dónde, quiénes?. In: Escenarios de cambio climático: Registros del Cuaternario en América Latina, Universidad Nacional Autónoma de México, México, v. I, p. 9-28.

Van Landingham S.L., 2006, Diatom evidence for autochthonous artifact deposition in the Valsequillo region, Puebla, Mexico during the Sangamonian (sensu lato = 80,000 to ca. 220,000 yr BP and Illinoian (220,000 to 430,000 yr BP)). *Journal Paleolimnology*, 36, 101-116.

Zhdanov M.S., Keller G.V., 1994, The Geoelectrical Methods in Geophysical Exploration, *Elsevier Sci. Publ.*, 873 pp.