Holocene-aged human footprints from the Cuatrociénegas Basin, NE Mexico

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Abstract

Two sets of well-preserved human footprints have been found in tufa sediments in the Cuatrociénegas Basin, NE Mexico, and here we present their U-series dates of 10.55 ± 0.03 ka and 7.24 ± 0.13 ka. The former are the oldest known footprints in Mexico, although their exact location is unknown, the latter form part of a trackway with eleven *in situ* human footprints. Oxygen (and to a lesser extent) carbon isotope data from the sediments suggest that the tufa with *in situ* footprints formed during a transition to a wetter (less arid) period, while pollen evidence indicates the basin floor presence of Pecan (*Carya*) and Willow (*Salix sp*.) before the onset of regional Chihuahuan Desert aridity. These footprints confirm the presence of humans, possibly nomadic hunter-gatherer groups, which persisted until the 18th Century AD.

Keywords: human footprints, tufa, Cuatrociénegas, Palaeoindian, Mexico

1. Introduction

Archaeological evidence indicates that during the Late Pleistocene-Holocene, humans occupied Northern Mexico and the Southern USA in a cultural area known today as Aridamerica. This area was inhabited by the nomadic Coahuiltecas groups, which the Mexicas from Mesoamerica called 'The Land of Dogs people' (Braniff-Cornejo, 2004), because they were considered to be less civilised groups. The Coahuiltecas remained nomads until the period when the first Spaniards arrived in Coahuila, maintaining cultural traditions associated with the Archaic Period that were abandoned thousands of years earlier in other areas in the Americas.

The Coahuiltecas of the Cuatrociénegas Basin (CCB) are known to have been nomadic hunter-gatherers during the late Pleistocene, and into the Holocene. Caves and rock shelters in the mountains surrounding the CCB were used as habitation, ceremonial or mortuary sites, some with important rock art evidence (petroglyphs and cave paintings) (Badino *et al*. 2004), and well-stratified archaeological deposits (Palmer, 1882; Taylor, 1956, 1964, 1966, 1968, 2003). Frightful Cave (Fig. 1), discovered and excavated by Walter W. Taylor in the 1940s (Taylor, 2003; Turpin, 2003), is the most extensively studied cave in the region with roughly 50% of the cave floor excavated producing hundreds of sandals, stone points, vegetal fibre artefacts and human hair.

Figure 1

The chronology of the arrival of humans in the Americas remains controversial due to the paucity of directly dated human fossils (Gonzalez *et al*. 2003) and the reliance in some instances upon the dating of non-anthropogenic material thought to be coeval with human presence (e.g. Valladas *et al*. 2003). Human footprints, although uncommon in the archaeological record, provide direct evidence of human presence and when preserved in fast forming tufa sediments have the potential for being accurately dated using U-series techniques. Here we report new U-series dates from human footprints in tufas found in the Cuatrocienegas Basin (CCB), in the state of Coahuila in the southern part of the Chihuahuan Desert, Mexico, and discuss the archaeological significance of the presence of humans in this region of Mexico. This desert ecosystem is unique due to the constant presence of water from the hydrothermal pools and rivers that produced a wide range of flora and fauna in the basin that make it highly suitable for human occupation.

2. Archaeological context

2.1 Cultural stages

Three major cultural stages, or complexes, have been proposed for the Coahuiltecas - Cienegas, Coahuila and Jora/Mayran. Vegetal remains (sandals, baskets, nets and mats) provided 45 radiocarbon dates used to develop a Cuatrociénegas chronology (Taylor, 2003). However, of the 45 radiocarbon dates obtained from the Frightful cave material, only four were directly on human remains, the oldest being human faeces (coprolites) dated to ~9 cal ka BP (Taylor, 2003). All radiocarbon dates on archaeological material presented in the literature have previously been published as radiocarbon years before present (where present is 1950) and were used to establish an archaeological sequence for the CCB (Taylor, 1956, 1966, 2003). For comparison with U-series results these dates have been calibrated to calendar years BP using the CALIB 6.0.1 program and INTCAL09 calibration curve (Reimer *et al*. 2009). The chronology of these complexes is however somewhat problematic as several radiocarbon dates throughout the cave stratigraphy are out sequence (Browman, 2003). Although stratigraphically continuous, the lack of chronological integrity in the Frightful cave deposit suggests some degree of disturbance, the nature of which is unclear (e.g. re-use of old artefacts by subsequent occupants or disturbance by animals) (Browman, 2003). With this in mind the three cultural complexes have been broadly categorised and assigned dates of ~10.4 to ~8 cal ka BP for the Ciénegas Complex; ~8 to ~5 cal ka BP for the Coahuila Complex; and ~5 to ~1.5 cal ka BP for the Jora/Mayran Complex (Browman, 2003). It is suggested that the three complexes share one common cultural tradition that became modified throughout the course of the Holocene (Taylor, 1956, 1966, 2003; Browman, 2003), and though somewhat ambiguous, these age ranges are broadly representative of the different stages of cultural development in the CCB.

The major cultural stages have been defined as:

1. **Ciénegas Complex (~10.4 to ~8 cal ka BP) –** this complex encompasses the most ancient occupation phases of the Coahuiltecas. The presence of animal bones consisting of grizzly bear (*Ursus arctos horribilis*), elk (*Cervus canadensis*) and buffalo (*Bison bison*) were reported (Gilmore, 1947). The animal species present within this complex are interpreted as reflecting a cooler, wetter climate than today.

2. **Coahuila Complex (~10.6 ± 1.1 cal ka BP to ~1.8 ± 0.5 cal ka BP, adjusted to ~8 to ~5 cal ka BP) –** though stratigraphically disturbed, this is the most extensively studied complex. Within this complex, the use of seed and nut grindstones and the presence of chewed vegetal fibres ('quids') is suggested to reflect a shift to more harsh, arid conditions where collection and storage of foods including cacti was necessary (Taylor, 1966).

3. **Jora/Mayrán Complex (~5 to ~1.5 cal ka BP) –**the presence of smaller lithic tips, for use with bows, and lithic scrapers suggests closer relations with nomadic groups from other areas of Coahuila and possibly the Trans-Pecos region of the USA-Mexico border.

A common cultural tradition throughout the three cultural complexes described above, was based on the premise of a constant supply of water in the basin, and Taylor (1964) suggested the hypotheses of 'tethered nomadism' and 'water territoriality'. Here exploitation of different resources was undertaken radially from a water source, which resulted in reduced cycles of nomadism and the need to regularly return to the initial water source, effectively tethering the Coahuiltecas to the CCB. Taylor also suggested that a type of social control may have been in place on water sources, particularly, if as suggested, the environment became increasingly more arid.

2.2 The Cuatro Ciénegas human footprints

During the construction of the Mex-30 highway between the towns of Cuatro Ciénegas and Torreón (Coahuila State), two well preserved human footprints preserved in tufa deposits were discovered in the CCB, near the NW end of the Sierra San Marcos y Pinos (Fig. 1). The footprints were removed and placed in the Museo Regional de La Laguna in Torreón, Coahuila. Since 1999, they have been on permanent exhibition in the Museo del Desierto, in Saltillo (Gonzalez *et al*. 2009). The approximate location of these footprints was described by local people and this information led to a search of the region for additional prints, culminating in the discovery in 2006 of a new *in situ* human footprint trackway preserved in tufa, documented by Gonzalez *et al*. (2007, 2009).

The two Museum del Desierto footprint specimens (right and left foot) show clearly visible narrow ridges (mud rims) within the toe impressions and between the posterior margins of the impressions made by the toe and ball of the foot (Fig. 2) indicating that a soft surface sediment layer was present when the print was made.

Figure 2

The new *in situ* footprint trackway was discovered at the Tierra Blanca Quarry after exposure by quarrying. The footprint trackway is located approximately 500 m west of the piedmont of the Sierra San Marcos y Pinos and the Mex-30 highway (Grid reference: N. 26˚54.526, W. 102˚09.117) in the central marsh (*ciénega*) area (Fig. 1), and is associated with a fossil spring mound complex and a small pool.

Five well preserved footprints were observed in the tufa surface at the Tierra Blanca quarry, whilst six were less well preserved, having been either partially or completely eroded away. Due to the fragility of the tufa surface and the fact that they were undergoing active erosion it was decided to apply a non-destructive 3D laser scanning technique to the *in situ* trackway (Fig. 3) to record detailed anatomical information of these ephemeral and endangered human prints (Bennett *et al*. 2009). Gonzalez *et al*. (2007, 2009) described the footprints in detail and inferred that the Tierra Blanca quarry footprint site was likely the same as the site where the 1961 Highway finds originated, based on shared characteristics of footprint size and style, lithology, and mode of preservation.

Figure 3

2. Regional setting

The Cuatrociénegas, or “Four marshes”, basin is a 1426 km^2 National Park protected area of the Chihuahuan Desert, in Coahuila State, Mexico (Fig. 1). The basin is located on the western flank of the Sierra Madre Oriental, which is characterized by steeply folded Cretaceous limestone beds, located roughly 26˚N and 102˚W with an average basin floor elevation of 742 m a.s.l. (Badino *et al*. 2004).

2.1. Climate

The CCB today has a semi-arid desert climate with annual rainfall of <200 mm and potential evaporation of >2000 mm (Badino *et al*. 2004). The bulk of the mean annual precipitation (~60%) is provided by the North American Monsoon (NAM) and falls between July and September due to eastward flow of low- and mid-level moisture advected from the Gulf of Mexico (GoM) (Mitchell *et al*. 2002). Temperatures can range from 0˚C –25˚C in winter and +10˚C to +45˚C in summer with diurnal variations of up to 30˚C (Badino *et al*. 2004).

2.2. Flora and fauna

The vegetation type of the CCB is classified as Chihuahuan desert scrub, following Merriam's Lower Sonoran Life-zone (Baker, 1956; Minckley, 1969) for plants growing <1500 m. a.s.l. Vegetation in this zone tends to favour desert succulents and xeric annuals, including mesquite (*Prosopis* sp.), creosote bush (*Larrea* sp.), *Agave* sp. (*A. lechuguilla* and *A. maguey*), yucca varieties, prickly pear cactus (*Opuntia* sp.), tarbush (*Flourensiacernua*), ocotillo (*Fouquieria splendens*),candelilla (*Euphorbia antisyphilitica*) and many species of grasses (*Poaceae* sp.) and desert flowers (*Cheno-Ams*). However, dense riparian vegetation can be found in close proximity to pools, springs and seeps with variety of sedges (Cyperaceae), cattail (*Typha* sp.) ash (*Fraxinus* sp.), sotol (*Dasylirion*sp.) and seep-willow (*Baccharisglutinosa*) commonplace.

Transitional woodland vegetation is found between 1500 and 2000 m. a.s.l. with scrub oak (*Quercus*), barrel cactus (*Ferocactus*), piñon (*Pinus cembroides*) and Arizona cypress (*Cupressusarizonica*) most common, with some grasses, prickly-pear, agave and palm (*Braheabella*). Above 2000 m. a.s.l. *montane* vegetation forms a well-defined zone, with pine forests dominated by ponderosa pine (*Pinus ponderosa*), fir (*Abies* sp.) and Douglas fir (*Pseudotsuga menziesii*).

2.3. Hydrogeology

The hydrogeological conditions of the CCB create a unique desert ecosystem through a series of over 200 groundwater-fed pools (*pozas*), springs/seeps, lakes (*lagunas*) and rivers. These pools, springs and lakes result in the active deposition of calcium carbonate at several locations in the CCB (Badino *et al*. 2004; Wolaver *et al*. 2013).

Today, about 85% of the water originates in a deep regional aquifer known as the Cupido-Aurora aquifer (C-AA), with a catchment area of 91,000 km^2 (Wolaver *et al*, 2008, 2013), with the other ~15% recharging in the surrounding limestone karst system (Piccini *et al*. 2007; Wolaver *et al*.2008). Evaporative through-flow systems, fed predominantly from the C-AA to the west of the basin, link these differing types of water body through ciénega (marsh) systems and sub-surface channels.

$\delta^{13}C_{DIC}$ values of the surface waters are between –9.2‰ and –21.6‰ (VPDB) (Felstead, 2012), thought to be mainly due to a high contribution of C_4 and aquatic plant organic carbon (Andrews *et al*. 1993; 1997) and some dissolution of carbonate from the surrounding Cretaceous limestone ($\delta^{13}C$ +2 to +4.5‰, Bralower *et al*. 1999). $\delta^{18}O$ values of modern surface waters are between –7.99‰ and +4.97‰, with these end values representing waters issuing directly from meteoric sources and endorheic pools respectively (Felstead, 2012). However, the majority of pools display $\delta^{18}O$ values between –6.92‰ and –5.67‰ in the main through-flow system and ciénega. The most negative values represent waters issuing directly from the C-AA, before gradual evaporative enrichment as waters mix through the complex surface and sub-surface flow patterns of the CCB (Felstead, 2012).

3. Methods and results

For this study a 2 cm thick slice was taken along the left human footprint block on display at the Museo del Desierto (Fig. 4a) for U-series dating. Additional tufa samples for U-series dating, $\delta^{18}O$ and $\delta^{13}C$ isotope and pollen analysis were collected in 2006 from a small pit, located 5 m from the exposed *in situ* footprint trackway (Figs. 4b and 5). The pit was dug to approximately 40 cm depth and contained the same stratigraphy as the tufas lying directly beneath the trackway. The tufa sediments in which the *in situ* footprints are preserved are mineralogically very pure comprising filamentous clusters of $CaCO_3$ crystals around organic matter. XRD analysis indicates that the tufas comprise 52% CaO, 42% organic matter (LOI), 6% SO_3 with traces of other oxides (Felstead, 2012).

Figure 4

3.1. U-series dating

The Museo del Desierto footprint samples were dated at the School of Geographical Sciences at Bristol University, dating of the 2006 *in situ* specimens was done at the NERC Isotope Geosciences Laboratory (NIGL).

Nine subsamples were taken from the 2 cm thick slice of the Museo del Desierto specimen for U-Th analysis. Five sub-samples (d, e, f, g, h) are taken from the denser bottom part, three sub-samples (a, b, c) were taken from the more porous top part and one sample (i) integrates the whole profile of the tufa piece. Four of the five bottom samples (d, e, f, g), all three top samples and sample (i) were cut as solid pieces using a diamond band saw and cleaned in an ultrasound bath prior to further chemical treatment. Sub-sample (h) was drilled using a handheld drill and a tungsten carbide drill bit. Chemical separation and purification of U-Th isotopes and analytical methods followed Hoffmann *et al*. (2007) with samples analysed on a Neptune multicollector inductively coupled mass spectrometer (MC-ICP-MS).

U-series dating of the Tierra Blanca quarry *in situ* trackway sediment samples was performed at NIGL. Tufas were sampled with a Dremel tool using a diamond-encrusted dental bit. Aliquots of tufa were extracted from the upper surface of three samples, with further subsamples taken to depth profile one of the tufa samples (Fig. 4b). As the NIGL U-series analytical methods have not been described elsewhere they are briefly summarized here. Powdered tufa samples were dissolved in ultrapure HNO_3 and spiked with a ^{229}Th-^{236}U tracer that was calibrated against gravimetric solutions prepared from high purity U and Th metal pieces. U and Th were pre-concentrated by Fe co-precipitation following Edwards *et al*. (1988). U-Th ion exchange separation using TRU and UTEVA resins followed Potter *et al*. (2005). U isotope ratios were measured on a Triton thermal ionization mass spectrometer (TIMS). Samples were loaded as a nitrate onto previously outgassed zone refined double Re filament assemblies. ^{234}U ion beams were measured using a secondary electron multiplier (SEM) behind a retarding potential quadrupole (RPQ) energy filter to eliminate tailing effects of higher mass peaks on ^{234}U. External reproducibility of ^{234}U/^{238}U in CRM 112a as measured with SEM+RPQ was c. 0.2%, more than twice the typical external precision achieved on this instrument using the SEM without the RPQ (Condon *et al*. 2010). SEM/Faraday gain was monitored during analysis using ^{235}U/^{236}U ratios measured by both SEM - Faraday and Faraday - Faraday. Mass fractionation correction factors were based on those observed for CRM 112a standard runs. Thorium isotope ratios were measured on a Nu HR ICP mass spectrometer in static mode employing standard-sample bracketing using an in-house ^{229}Th-^{230}Th-^{232}Th reference solution calibrated against U isotope standards. Data were processed using an in-house spreadsheet following Ludwig (2003a) using functions and graphics routines in Isoplot 3.0 (Ludwig, 2003b) and the decay constants of Cheng *et al*. (2000). Correction for detrital Th contributions for the NIGL data used the bulk earth value, as with the Bristol data above. Age, concentration and activity ratio uncertainties are quoted at the 2σ level and are propagated from measured analytical uncertainties, detrital Th correction uncertainty, and the external reproducibility of replicate measurements of a powdered aliquot of the McMaster speleothem 76001 (n=11) during the period when the tufa analyses were obtained. Two analyses of speleothem 76001 processed with the tufa samples yielded an average $^{230}Th/^{234}U$ age of 47.7 ± 2.3 ka, within error of the published TIMS U-Th age of 47.6 ± 2.4 ka (Li *et al*. 1989).

U-Th data from both sites, including calculated ages and initial $^{234}U/^{238}U$ activity ratios, are presented in Table 1. Date reporting conventions: we quote U-series dates as a (years before chemical separation, Bristol data before year 2007 AD, NIGL data before year 2010 AD), uncalibrated radiocarbon dates as ^{14}C yr BP (radiocarbon years before present, the present being the year 1950 AD), and calibrated radiocarbon dates as cal a BP (calibrated years before year 1950 AD).

Table 1

All of the subsamples of the Museo del Desierto isolated footprint tufa have $^{230}Th/^{232}Th$ activities >43.0, indicating that contamination with ^{230}Th bearing-detrital material was relatively low. Isochron analyses using five coeval samples from the base of the tufa give a detrital $^{230}Th/^{232}Th$ activity indistinguishable from the bulk earth value of 0.8 ± 0.4 (2σ). This value was used to correct for detrital contamination. The error weighted mean of detrital Th-corrected U-series dates from the uppermost layer yield an age of 10.55 ± 0.03 ka) and for the lowest layer we obtain an age of 10.66 ± 0.04 ka. These results are in stratigraphic order indicating that the results are robust and the 2 cm thick tufa section formed rapidly. The detrital corrected result for sub-sample i (10.59 ± 0.07 ka) represents a mixed age of bottom and top section. The date of formation of the uppermost layer at 10.55 ± 0.03 ka is the most relevant to the time when the impressions in the tufa were made and is taken to therefore effectively represent the date of the Museo del Desierto human footprints.

The top surface of the Tierra Blanca Quarry tufas, representative of the material that the *in situ* trackway is preserved within, is dated at 7.24 ± 0.13 ka based on an average of the two top surface ages for 036521-7-4 and 036521-5. The depth profiling data for tufa samples

036521-7-1, 036521-7-2 and 036521-7-3 shows that age systematically increases with depth, with a 7.89 ± 0.12 ka near-surface porous layer, an intermediate porous layer at 7.97 ± 0.13 ka, and lowermost layer at 8.46 ± 0.12 ka respectively (Fig. 4b). Although this is not proof of closed system behaviour, it is consistent with it. $^{230}Th/^{232}Th$ activity ratios for the profiled portions 036521-7-1, 036521-7-2, 036521-7-3 and the upper surfaces of pieces 036521-7-4 and 036521-5 range from 29.3 to 44.1. These values are less than those of the isolated footprint tufa samples but sufficiently high so as to result in accurate corrected ages and acceptable final propagated age uncertainties. Three other upper surface samples, however, have much lower [$^{230}Th/^{232}Th$] activity ratios and therefore are not used here to date the tufas. Uranium concentrations in the *in situ* footprint tufa are consistent at c. 2 µg/g, very similar to the isolated footprint tufa. The two footprint site tufas also have similar initial [$^{234}U/^{238}U$], suggestive of similar uranium source characteristics.

3.2. Stable isotopes and pollen

$\delta^{13}C$ and $\delta^{18}O$ were analysed on bulk tufa samples from the Tierra Blanca site. The tufa samples were ground in agate and an equivalent of 10 mg of carbonate was reacted with anhydrous phosphoric acid *in vacuo* overnight at a constant 25˚C. The CO_2 liberated was separated from water vapour under vacuum and collected for analysis. Measurements were made on a VG Optima mass spectrometer. Overall analytical reproducibility for these samples is normally better than 0.2‰ for $\delta^{13}C$ and $\delta^{18}O$ (2σ). Isotope values ($\delta^{13}C$, $\delta^{18}O$) are reported as per mil (‰) relative to the VPDB scale using a within-run laboratory standard calibrated against NBS standards.

Figure 5

The stable isotope data (Fig. 5) show that $\delta^{13}C$ remains relatively constant throughout the section with the highest value of –0.4‰ occurring at three depths: 27 cm, 24 cm and 5 cm. The lowest value of –1.1‰ occurs at 25 cm (mean –0.6‰, *n*=10). $\delta^{18}O$ decreases from –2.9‰ to –6.2‰ from 32 cm to 0 cm (mean –3.9‰, *n*=10), with a 2‰ shift occurring between 5 cm and 0 cm (footprint layer tufa) and is the largest $\delta^{18}O$ shift in the sequence.

Two samples from the pit were taken for pollen analysis and described here as TB-1 (0 cm) and TB-5 (5 cm). These samples (20-50 cm^3) were pulverized in a mortar and pestle and Lycopodium tables (spores = 13,911) added prior to dissolution. Samples were then dissolved in 1,000-2,500 ml of 20% HCl for 48 hours prior to a light (3 min) H_2SO_4-based hot acetolysis controlled by glacial acetic acid. No KOH was employed as no humus was present. Where gypsum was detected it was dissolved in a hot 0.2 M EDTA salt solution. Care was taken to minimize potential adverse effects on pollen exines resulting from high pH solutions. No HF was employed, as almost all non-organics were removed *via* EDTA (sulphates). After cleaning and ETOH-based dehydration, samples were dyed in a safranine and alcohol solution and finally mounted in silicone oil for light microscopy.

The two tufa samples contain a similar range of pollen taxa, including more commonly *Pinus*, *Cupressaceae*, *Quercus*, *Carya*, *Poaceae*, *Chenopodiaceae*, *Asteraceae*, *Ambrosia*, *Ephedra* and *Leguminosae*. Also present are less common pollen types such as *Potamogeton*, *Cyperaceae*, *Rhus*, *Myrica*, *Salix*, *Alnus*, *Acacia*, *Centaurea*, *Geranium*, *Agave*, *Opuntia* (fragmentary) and an indeterminate trizonocolporate type (*Leguminosae*). The pollen data shows a change towards the top of the Tierra Blanca tufa sequence from TB-5 to TB-1 (5 cm to surface). Regional upland taxa – *Pinus* and *Quercus* – increase from 20 to 254 grains/cm^3 and 13 to 22 grains/cm^3 respectively whereas grasses (*Poaceae*) are seen to decrease from 17 to 6 grains/cm^3. The CCB floor taxa such as *Poaceae* and *Cheno-Ams* can be misleading however, as observed by Meyer, (1973) and Minckley and Jackson, (2008), where abundances can indicate local pollen rain rather than regional vegetation types.

4. Discussion

4.1. Early human occupation in Mexico

The Cuatrociénegas footprint ages represent the oldest directly dated human footprints in Mexico and show that human activity in the CCB began at least 10.5 ka, and there is then human presence at 7.2 ka. The former are comparable to some of the oldest directly dated humans from Central Mexico (e.g. 10.7 ± 0.07 ka BP Peñon Woman III found in Mexico City; Gonzalez *et al*. 2003) and 9-11 ka BP skeletons from the flooded caves of the Yucatan Peninsula (Gonzalez *et al*. 2006).

Very few sites with unambiguous human footprint evidence have been documented from the Americas. The oldest isolated human footprint is dated at ~14 cal ka BP from the Monte Verde II site in Chile (Dillehay *et al.* 2008), while well documented and dated human tracks from Managua (Nicaragua) (Lockley *et al*. 2009; Schminke *et al*. 2010a, b), California and Monte Hermoso in Argentina (Aramayo, 2009) are much younger (between 2.5 to 7.0 cal ka

BP). The new Cuatrocienegas human footprint ages are therefore an important addition to this limited inventory of directly dated archaeological evidence of the early periods of Palaeoindian occupation of the Americas. In Mexico, the suggested human and animal tracks from Valsequillo have generated a debate (see the discussion in Gonzalez *et al*. 2006; Huddart *et al*. 2008; Renne *et al*. 2005) but are now recognised as being created by quarrying marks modified by natural weathering and sheet flow erosion (Mark *et al*. 2010; Morse *et al*. 2010).

4.1.1. NE Mexico: Cuatrociénegas

The oldest previously reported human fossil evidence from the CCB is 8.9 ± 0.8 cal ka BP on a fossil coprolite from Frightful cave (Taylor, 2003). Although the cave deposit is well stratified, the Frightful cave chronology is largely based on vegetal fragments that are possibly not associated with human occupation. With the oldest dates from the Ciénegas and Coahuila complexes being 9.9 ± 0.9 cal ka BP and 10.4 ± 0.2 cal ka BP respectively, from fragments of cut wood, the chronology developed by Taylor (1956, 1966, 2003) can be ambiguously interpreted (see Introduction). The footprint horizon at 10.55 ± 0.03 ka (this study) is the oldest archaeological evidence of human presence in the CCB to date and evidence such as this removes some of the previous ambiguity, confirming the presence of humans in the basin during the early Holocene.

4.2. Palaeoenvironment

The tufa has relatively constant and high $\delta^{13}C$ values between −1.1‰ and −0.4‰ throughout the sequence analysed (Fig. 5). In contrast, the range of modern dissolved inorganic carbon $\delta^{13}C_{DIC}$ values (–21.6‰ to –9.2‰) from the CCB suggests modern tufa depositing waters have varying proportions of organic versus inorganic carbon sources in comparison to the early Holocene tufas (Andrews *et al*. 1993, 1997). Especially important might have been the degassing and equilibration with atmospheric CO_2 as this process leads to high $\delta^{13}C$ in tufas especially as the spring mound structure and associated tufa dams suggest higher energy, turbulent waters where equilibration may be enhanced (e.g. Pedley *et al*. 2003). Wolaver *et al*. (2013) have shown that up to ~30% of the carbon in the C-AA waters is sourced through dissolution of the aquifer limestone, with high $\delta^{13}C$ values for the Cretaceous limestones surrounding the CCB (+2 to +4.5‰) (Bralower *et al*. 1999). The low $\delta^{13}C$ of modern water TDIC suggests that the CCB is not the only/main (current) source of C, and suggests mixing between the C-AA and an additional, localised karst aquifer with low $\delta^{13}C$, or soil derived carbon.

The oxygen isotope ($\delta^{18}O$) composition of tufa is dependent on surrounding hydrological conditions and largely reflects the $\delta^{18}O$ composition of the meteoric source water (Andrews *et al*. 1997) and subsequent evaporation (Rank *et al*. 1992; Carrillo-Rivera, 1993). The Tierra Blanca trackway is located on top of a fossil tufa spring mound and would have required a constant hydrostatic head pressure (Pentecost, 2005). The head pressure likely came from precipitation in the high peaks surrounding the CCB and not directly in the basin. The $\delta^{18}O$ values of the Tierra Blanca tufas are high (–2.9‰ to –6.2‰) in comparison to modern weighted meteoric water (precipitation) values of –8.3‰ (Wassenaar *et al*. 2009) even allowing for small changes in temperature. The $\delta^{18}O$ composition of the Tierra Blanca tufas is consistent with the $\delta^{18}O$ range of modern water samples within the basin (see section 2.2.). However, $\delta^{18}O$ values of surface waters higher than –6‰ in the CCB generally indicate waters that have been modified through evaporation, with values lower than –6‰ more indicative of surfacing groundwaters (Felstead, 2012; Johannesson *et al*. 2004).

Therefore, differences in Tierra Blanca tufa $\delta^{18}O$ are likely to be the result of differences in evaporation, the lower part of the tufa forming under more arid conditions than the upper most sample, suggesting an increase in humidity (Fig. 5). Published lake records in the Chihuahuan region of northern Mexico (Castiglia and Fawcett, 2006; Metcalfe *et al*. 1997) report conditions wetter than the present existed up to ~7 ka, despite post-glacial warming and aridification of northern Mexico, with periods wet enough to support pluvial lake formation ~8.5 to ~8 ka and ~7 to ~6 ka. Stronger NAM conditions have been suggested as a contributing factor of these wetter conditions. Barron *et al*. (2012) suggest warming of Gulf of California (GoC) SSTs between 8 and 6.2 ka may have caused low-level moisture surges, strengthening summer NAM circulation, consequently causing greater advection of moisture from the GoM. Increased summer precipitation over the northern Mexico region, which recharges the regional C-AA, during this time period may explain the deposition of the footprint bearing tufa spring mound ~8.5 to ~7 ka, in an otherwise drying region.

4.2.1. Pollen and midden records

Van Devender and Burgess (1985) and Van Devender (1990) report that late-glacial piñon-juniper woodland began to withdraw from the uplands around the CCB ~14.5 ka, being replaced by Chihuahuan desert scrub and succulents without the woodland elements. Conditions of more effective moisture apparently persisted into the early Holocene and the remains of small mammals suggest that spring marshes were present into the mid-Holocene in the basins of the southern Chihuahuan desert. Pollen data from this study indicate the presence of specific vegetation types ~8.5 to ~7 ka. *Pinus* values, which approximate 50% in sample TB-1 and only 8% in sample TB-5, rise toward the surface of the Tierra Blanca tufa sequence. It is assumed that a major event such as an extensive fire, or a sustained period of drier climate (or both) suppressed *Pinus* values in the latter sample. Gonzalez *et al*. (2009) report large amounts of charcoal at 9-15 cm depth in their tufa stratigraphy, just before the suppressed *Pinus* values, perhaps indicating burning by humans, although charcoal is not observed in our stratigraphy (Fig. 5).

With increased water availability from the C-AA and high (>3000 m a.s.l) surrounding mountains, it is likely that CCB would have become a desert refugium until ~ 7 ka when drier conditions prevailed. Hickory/pecan (*Carya*) and willow (*Salix* sp.) pollen is present in the footprint tufa TB-1 at Tierra Blanca, although in low numbers of 5 and 4 grains respectively. This supports increased water availability, as these are temperate, deciduous species that will have grown at the side of the pools in the CCB. Pecan and willow species are currently present in very sheltered, moist canyons of Coahuila (Badino *et al*. 2004; Minckley, 1969; Taylor, 2003). Their presence ~7.2 ka as basin floor taxa is certainly indicative that much wetter or more humid conditions than today prevailed in the CCB at this time, corroborating stronger NAM circulation.

4.3. Summary: Human dispersion and activity of hunter-gatherers

The footprint age of 10.5 ka of the Museo del Desierto specimens extends the boundary of the Ciénegas complex by ~500 a and confirms the presence of humans in the CCB ~1.5 ka earlier than previous published dates. Faunal remains from Frightful cave (Gilmore, 1947; Taylor, 2003) corroborate regional climate and environmental data (Meyer, 1973; Van Devender and Burgess, 1985; Van Devender, 1990) indicating the CCB was most likely cooler and wetter than today at the time the footprints formed. This is consistent with the previous environmental interpretation of the Ciénegas complex given in the Introduction.

The 7.24 ka *in situ* human footprint trackway straddles the boundary of the Ciénegas and Coahuila complexes (~8 cal ka BP, see Introduction).The CCB provided a desert refuge with abundant water and vegetation rich in desert succulents and fruit bearing trees. Increased moisture/humidity is indicated by lower $\delta^{18}O$ values, particularly between ~8.5 and ~7 ka (5cm – 0 cm, Fig 5), and presence of *Pinus*, *Salix* and *Carya* species in the footprint tufa layer. The additional presence of desert succulents *Opuntia* and *Agave* allude to a transitional environment in the CCB. *Opuntia* (prickly-pear cactus) is a fruit-bearing desert succulent, consumed by the Coahuiltecas, flowering in late spring/early summer (Badino *et al*. 2004; Bryant, 1975; Taylor, 1966, 2003). The presence of this pollen in the footprint tufa suggests hunting-gathering activities may have occurred at this time of year, along with cave occupation - as coprolites from Frightful cave show the presence of *Opuntia* pollen in the Ciénegas complex (~9 to ~7 cal ka BP) along with a variety of other fruits, leaves, bulbs and seeds (Bryant, 1975). The presence of grindstones (Taylor, 1966) found in the same cave site indicates the activity of grinding seeds and nuts (*Carya* and *Pinus*) of which there would have been both local and regional supply (Bryant, 1975, 1977).

5. Conclusions

The CCB has had at least two periods of human occupation in the early Holocene with two sets of footprints preserved in tufa dated to 10.55 ± 0.03 ka and 7.24 ± 0.13 ka. The former, Museo del Desierto specimens, represent the oldest directly dated human footprints in Mexico. The dating results suggest that the Tierra Blanca Quarry *in situ* footprint tracks and the Museo del Desierto footprints originate from different locations. We put the Tierra Blanca Quarry footprints into some palaeoenvironmental context with the stable isotope and pollen data. The fossil-spring tufa deposition episodes of the two footprint horizons at 10.5 ka and ~8 to~7 ka does suggest fault controlled spring activity during much wetter, early/mid-Holocene pluvial phases in the Chihuahuan desert. Our results indicate that periods of increased effective moisture in the early/mid-Holocene Chihuahuan desert region, possibly due to stronger NAM circulation, recharged the C-AA, allowing the deposition of a tufa spring mounds during continued post-glacial aridification, possibly allowing an area of refuge for late glacial vegetation to develop. As the ancient nomadic hunter–gatherers needed to adapt to the increasingly hostile desert conditions that subsequently developed through the Holocene, they expanded their ability to find resources, leading to longer cycles of nomadism and possibly the expansion of their unique desert culture right into the 18th Century when they finally become extinct after the arrival of the Europeans.

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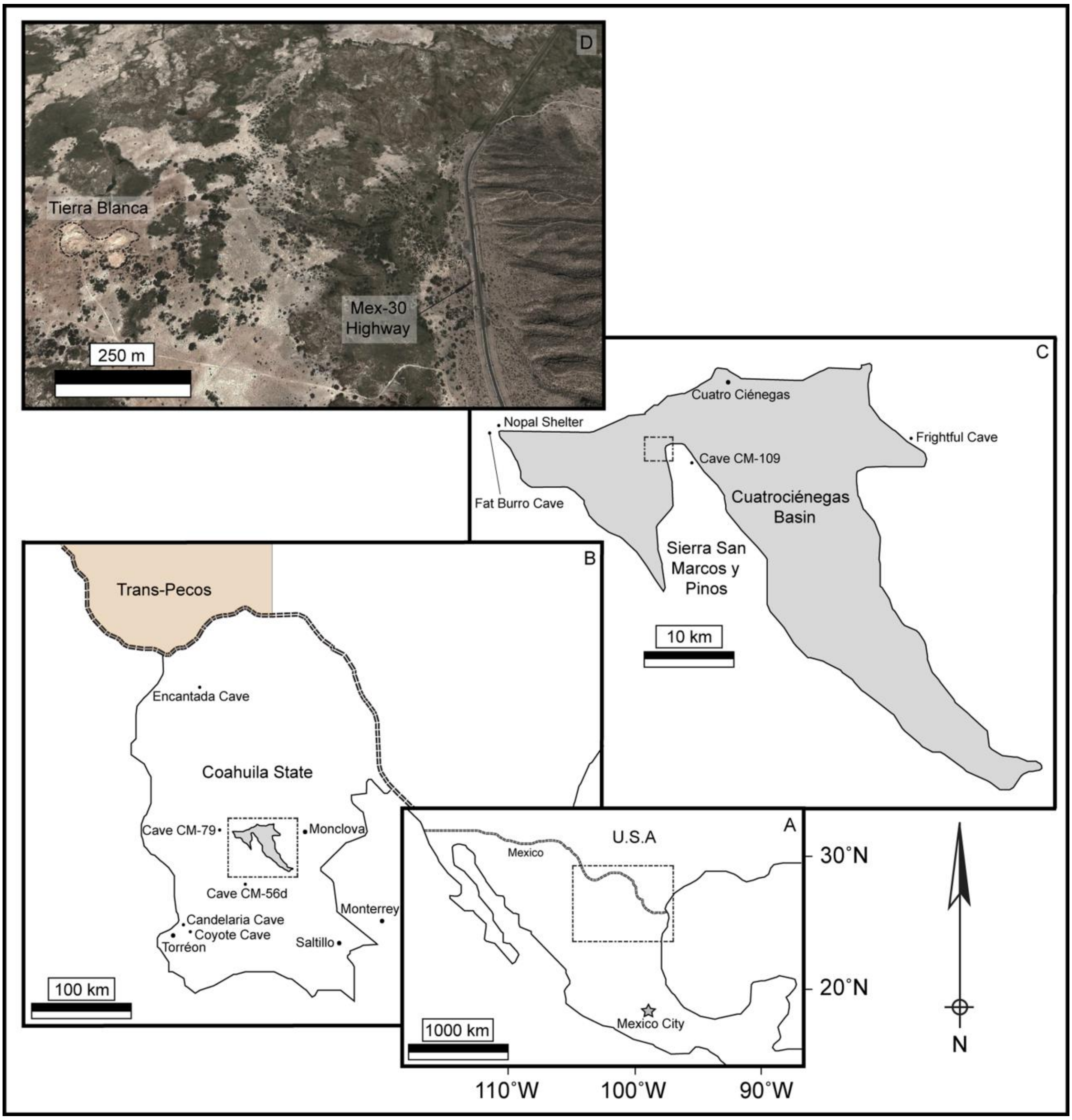

Figure 1: A. Location of the CCB in NE Mexico. B. Location of the CCB in Coahuila State. Major cities and cave sites outside the basin are shown along with the Trans-Pecos region of SW Texas. C. Location of the *in situ* human footprint trackway within the CCB. Important cave sites within the surrounding mountains are also shown. D. Proximity of the *in situ* footprint trackway to the Mex-30 highway where the set of Museo del Desierto footprints were found in 1961 (image from *google.co.uk/earth*). **Colour reproduction on the Web only and black and white in print.**

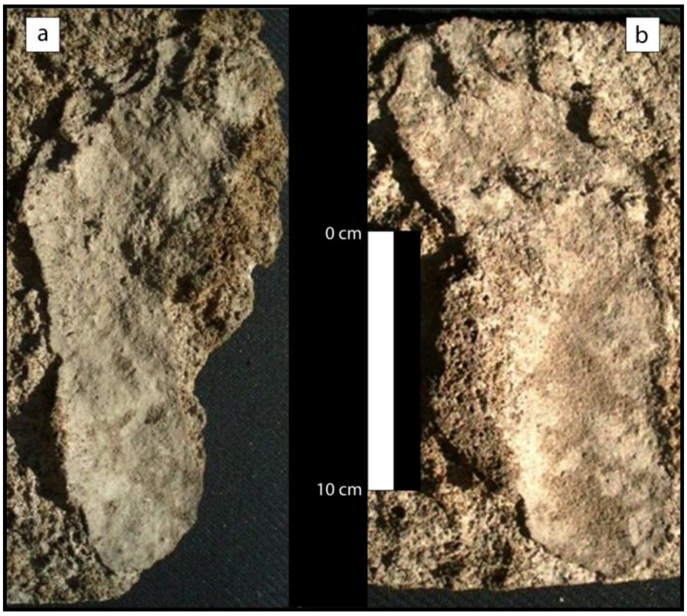

Figure 2: (a) The left and, (b).Right human footprints preserved in tufa found in 1961, currently on display at the Museo del Desierto in Saltillo, Coahuila (after Gonzalez *et al*. 2009). **Colour reproduction on the Web only and black and white in print.**

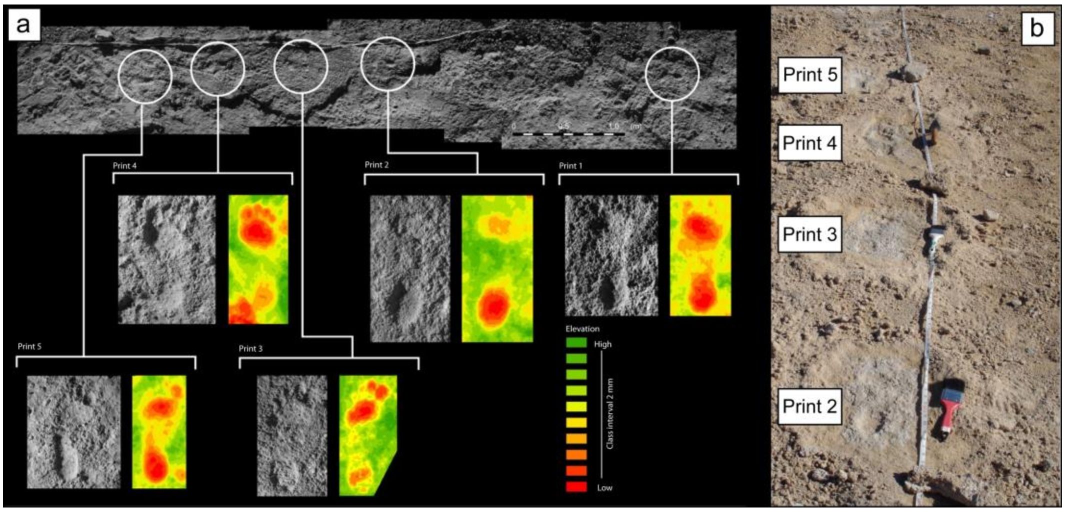

Figure 3: a) Laser scanned map of the *in situ* human footprint trackway at the Tierra Blanca Quarry. Well preserved prints are designated 1-5 on the diagram whilst eroded prints are not numbered. Three prints (L-R-L sequence) are missing between prints 1 and 2 and a further three (R-L-R sequence) are missing after print 5 (after Bennett *et al*. 2009). b) Photograph showing prints 2-5 of the trackway. **Colour reproduction on the Web only and black and white in print.**

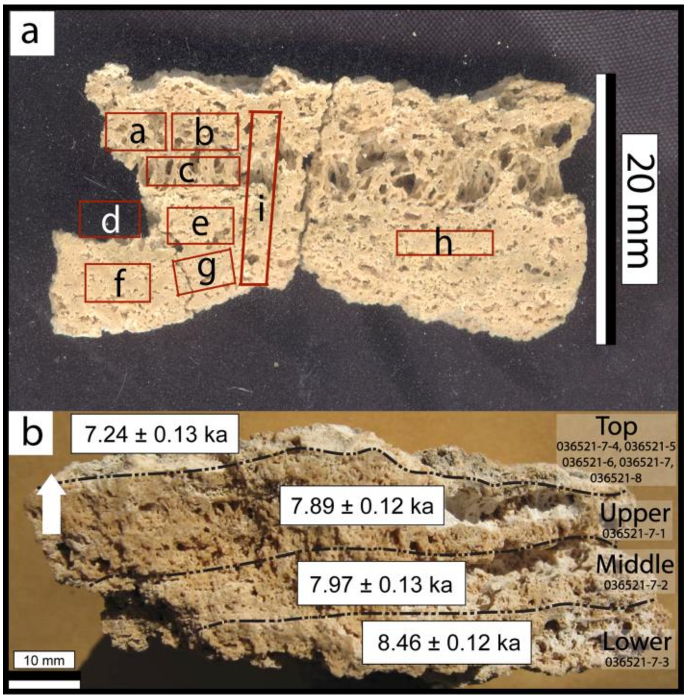

Figure 4: (a) Samples taken for U-series dating from the Museo del Desierto left isolated human footprint. (b) U-series samples taken from the Tierra Blanca *in situ* footprints, showing where the samples were taken and the ages obtained. **Colour reproduction on the Web only and black and white in print.**

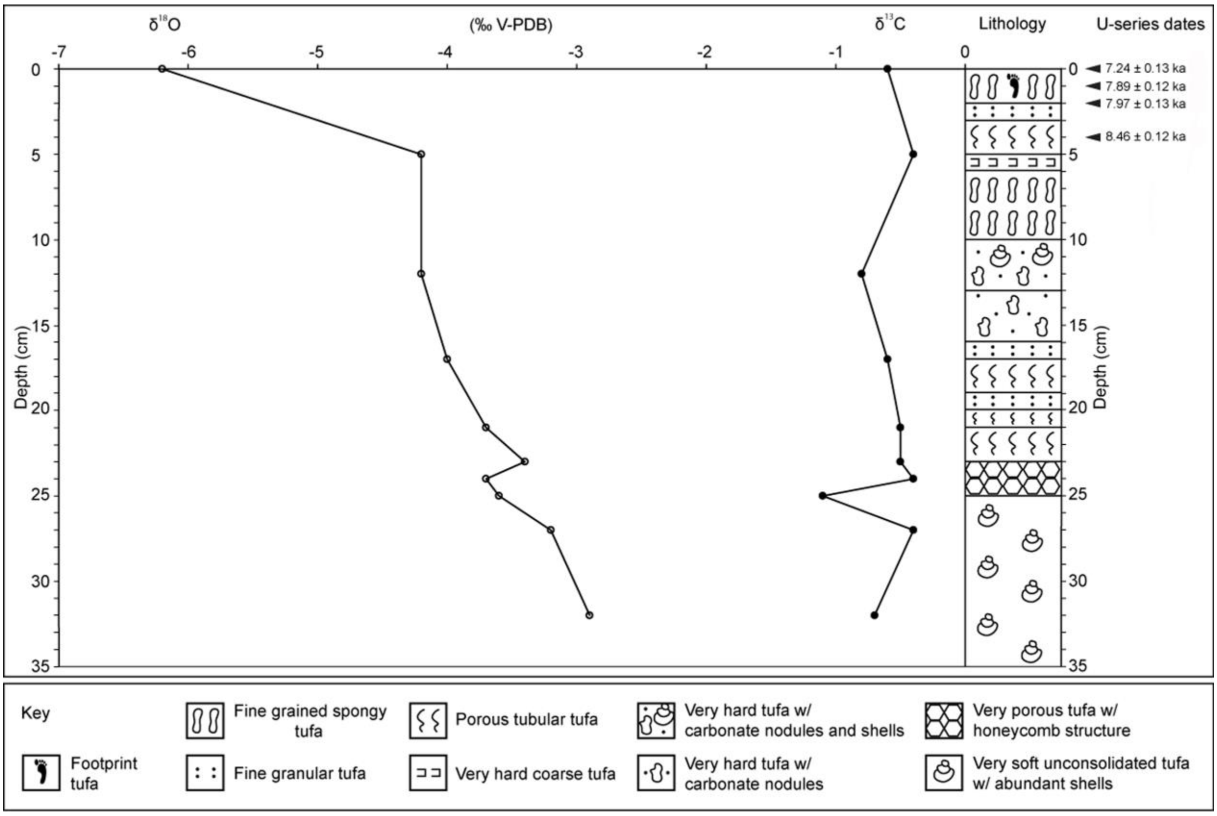

Figure 5: Preliminary $\delta^{18}O$ and $\delta^{13}C_{DIC}$isotope data for the Tierra Blanca tufa samples shown alongside pit stratigraphy and U-series dates

Sample	^{238}U [ng/g]	^{232}Th [ng/g]	Measured $[^{234}U/^{238}U]$	$[^{230}Th/^{238}U]$	$[^{230}Th/^{232}Th]$	U-Th age [ka]	Corrected $[^{230}Th/^{238}U]^{*+}$	$[^{234}U/^{238}U]^*$	U-Th age* [ka]	$[^{234}U/^{238}U]^*_{initial}$
BIG-UTh-A314-a	1931.1 ± 7.1	9.81 ± 0.03	1.880 ± 0.003	0.175 ± 0.001	105.2 ± 0.3	10.59 ± 0.05	0.174 ± 0.001	1.881 ± 0.003	10.51 ± 0.06	1.907 ± 0.003
BIG-UTh-A330-b	2112.0 ± 6.3	9.49 ± 0.06	1.887 ± 0.003	0.177 ± 0.001	120.3 ± 0.5	10.68 ± 0.04	0.176 ± 0.001	1.888 ± 0.003	10.61 ± 0.05	1.915± 0.003
BIG-UTh-A334-c	2172.0 ± 10.3	8.79 ± 0.06	1.886 ± 0.003	0.175 ± 0.001	132.5 ± 0.7	10.58 ± 0.06	0.175 ± 0.001	1.887 ± 0.003	10.52 ± 0.06	1.914 ± 0.003
BIG-UTh-A298-d	2177.6 ± 13.2	18.16 ± 0.09	1.880 ± 0.003	0.178 ± 0.001	65.2 ± 0.1	10.78 ± 0.06	0.176 ± 0.001	1.882 ± 0.003	10.66 ± 0.08	1.909 ± 0.003
BIG-UTh-A331-e	2171.2 ± 6.6	18.07 ± 0.11	1.873 ± 0.003	0.178 ± 0.001	65.2 ± 0.3	10.80 ± 0.05	0.176 ± 0.001	1.875 ± 0.003	10.68 ± 0.07	1.902 ± 0.003
BIG-UTh-A316-f	2390.5 ± 7.8	18.97 ± 0.06	1.870 ± 0.003	0.177 ± 0.001	68.4 ± 0.2	10.81 ± 0.05	0.176 ± 0.001	1.871 ± 0.003	10.69 ± 0.07	1.898 ± 0.004
BIG-UTh-A332-g	2202.3 ± 5.9	27.42 ± 0.16	1.878 ± 0.003	0.179 ± 0.001	43.9 ± 0.2	10.85 ± 0.05	0.176 ± 0.001	1.881 ± 0.003	10.66 ± 0.10	1.908 ± 0.003
BIG-UTh-A333-h	2230.6 ± 38.2	21.19 ± 0.40	1.872 ± 0.003	0.177 ± 0.001	56.9 ± 0.3	10.75 ± 0.07	0.175 ± 0.001	1.874 ± 0.004	10.61 ± 0.10	1.900 ± 0.004
BIG-UTh-A315-i	2100.4 ± 5.3	17.65 ± 0.04	1.878 ± 0.003	0.177 ± 0.001	64.3 ± 0.1	10.72 ± 0.07	0.175 ± 0.001	1.880 ± 0.003	10.59 ± 0.07	1.907 ± 0.003
NIGL- 036521-7-1 upper	2060.5 ± 10.4	23.27 ± 0.12	1.898 ± 0.004	0.136 ± 0.001	36.9 ± 0.3	8.062 ± 0.08	0.134 ± 0.002	1.900 ± 0.005	7.888 ± 0.12	1.921 ± 0.005
NIGL- 036521-7-2 middle	2079.0 ± 10.5	24.44 ± 0.13	1.894 ± 0.004	0.138 ± 0.001	35.8 ± 0.4	8.153 ± 0.10	0.135 ± 0.002	1.897 ± 0.004	7.970 ± 0.13	1.917 ± 0.004
NIGL-036521-7-3 lower	1979.9 ± 10.0	20.72 ± 0.11	1.899 ± 0.004	0.146 ± 0.001	42.5 ± 0.4	8.621 ± 0.09	0.143 ± 0.002	1.902 ± 0.004	8.459 ± 0.12	1.924 ± 0.004
NIGL-036521-7-4 top	2062.7 ± 10.6	17.72 ± 0.09	1.895 ± 0.006	0.124 ± 0.001	44.1 ± 0.4	7.327 ± 0.08	0.122 ± 0.002	1.898 ± 0.006	7.194 ± 0.10	1.916 ± 0.006
NIGL-036521-5 top	2056.1 ± 11.0	27.28 ± 0.14	1.902 ± 0.008	0.127 ± 0.001	29.3 ± 0.2	7.489 ± 0.08	0.124 ± 0.002	1.905 ± 0.009	7.284 ± 0.13	1.924 ± 0.004
NIGL-036521-6 top	1997.9 ± 22.6	62.97 ± 0.73	1.901 ± 0.006	0.168 ± 0.003	16.3 ± 0.3	9.972 ± 0.20	0.160 ± 0.005	1.909 ± 0.007	9.486 ± 0.31	1.933 ± 0.007
NIGL-036521-7 top	2123.3 ± 11.0	83.16 ± 0.45	1.897 ± 0.005	0.174 ± 0.002	13.6 ± 0.2	10.404 ± 0.17	0.165 ± 0.005	1.906 ± 0.007	9.799 ± 0.35	1.932 ± 0.007
NIGL-036521-8 top	1988.7 ± 10.1	79.30 ± 0.56	1.895 ± 0.004	0.175 ± 0.007	13.4 ± 0.5	10.477 ± 0.42	0.166 ± 0.008	1.905 ± 0.007	9.860 ± 0.52	1.931 ± 0.006

Table 1: Uranium and thorium concentrations, activity ratios and detrital Th-corrected U-Th ages for the left human footprint now at the Museo del Desierto, Saltillo, Coahuila (BIG samples), and the *in situ* human trackway (NIGL samples). $^*[^{230}Th/^{238}U]_{activity} = 1 - e^{-\lambda 230\, T} + (\delta^{234}U_{measured}/1000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](1 - e^{-(\lambda 230 - \lambda 234)\, T})$, where T is the age in years. Decay constants (λ) are 9.158×10^{-6} a^{-1} for ^{230}Th, 2.826×10^{-6} a^{-1} for ^{234}U and 1.551×10^{-10} a^{-1} for ^{238}U (1,2). $^+$Corrected for detrital Th contamination using an initial $[^{238}U/^{232}Th]_{act.} = 0.8 \pm 0.4$ (2σ).