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Title: Evidence of humans in North America during the Last Glacial Maximum

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Abstract: Archaeologists and researchers in allied fields have long sought to understand human colonization of North America. When, how, and from where did people migrate, and what were the consequences of their arrival for the established fauna and landscape are enduring questions. Here, we present evidence from excavated surfaces of *in situ* human footprints from White Sands National Park (New Mexico, USA), where multiple human footprints are stratigraphically constrained and bracketed by seed layers that yield calibrated ^{14}C ages between ~23 and 21 ka. These findings confirm the presence of humans in North America during the Last Glacial Maximum, adding evidence to the antiquity of human colonization of the Americas and providing a temporal range extension for the coexistence of early inhabitants and Pleistocene megafauna.

One Sentence Summary: *In situ* fossil footprints show that humans were present in North America during the Last Glacial Maximum.

Main Text:

The late Pleistocene expansion of human populations into the Americas is the latest chapter in the 'Out of Africa' migration of modern humans (*1*). The earliest evidence for dispersal and occupation remains controversial *(2*). Hypotheses range from those that favor Clovis as the earliest occupation (~13 ka) (*3*) to those that favor older ("pre-Clovis") sites dating to ~16.5 ka (i.e., post Last Glacial Maximum [LGM]; 26.5 to 19-20 ka; *4*) or even older (*5*). Viable migration routes from Asia depend on timing and associated environmental conditions and could have occurred via an inland route through the Ice-Free Corridor (*6, 7*), the Pacific Coastal Route (*8, 9*), or both, although notably these routes would have been closed or at least unlikely during the LGM (*10*).

Most early sites in North America, defined here as early post-LGM or older, are questioned due to either their dating (*3*) or uncertainty about the association of humans and purported artifacts (*11*). Fossil human footprints provide an alternative source of evidence for human presence when excavated from an *in situ* sedimentary sequence with good chronological control (e.g., *12-14*). Unlike cultural artifacts, modified bones, or other more conventional fossils, footprints have a primary depositional context and are fixed on the imprinted surface.

In this context, we report the discovery of a series of human footprints from White Sands National Park (WHSA Locality 2; Fig. 1A) in south-central New Mexico that occur on multiple stratigraphic horizons interbedded with seed layers. Our results indicate that humans were present on the landscape by at least ~23 ka with evidence of occupation spanning approximately two millennia. These data provide definitive evidence of human occupation of North America south of the Laurentide Ice Sheet during the LGM.

WHSA lies within the Tularosa Basin, a topographically closed basin that encompasses an area of about 14,000 km^2. The floor of the basin contains a gypsum playa (Alkali Flat, Figs. 1A and S1) created by eolian deflation of late Pleistocene lake beds following the desiccation of pluvial Lake Otero. The precise history of Lake Otero is not currently known but it was the largest of several perennial lakes that filled the basin between ~36 and 19 ka (*15*). Throughout this time, changes in the hydrological budget in the Tularosa Basin led to a range of water levels and therefore lake/wetland extents associated with fluctuations in precipitation, groundwater input, and inflow/outflow. Ichnofossils of extinct late Pleistocene fauna occur widely on the margins of the playa and include tracks of Proboscidea (mammoth), Folivora (ground sloth), Carnivora (canid and felid), and Cetartiodactyla (bovid and camelid), most of which are associated with human footprints (*16-18*).

WHSA Locality 2 is located on the eastern side of Alkali Flat on a shallow (<6 m) erosional scarp formed between the current playa and the White Sands gypsum dune field. A sedimentary sequence exposed by trenching consists of 1.25 m of lacustrine clays and silts intercalated with thinly bedded gypsiferous and siliciclastic sands, silts, and clays, which represent a transition from a lacustrine ecosystem to an alluvial regime in response to changing hydroclimate conditions during the late Pleistocene (Figs. 2 and S2). Endocarps of ditch grass (*Ruppia cirrhosa*) occur as discontinuous layers throughout the sequence. Footprints (humans, proboscidean, and canids) occur at all levels both in cross section and on excavated surfaces adjacent to the trench (Figs. 1B-E, 2, S4-S11). A total of 61 human tracks have been identified and documented.

Human footprints reported from all surfaces have good anatomical definition (i.e., visible heel impressions, medial longitudinal arches, and toe pads) consistent with modern humans when compared to other Pleistocene footprint sites and the ichnotaxa *Hominipes modernus* (*19, 20*). A geomorphometric comparison of a sample of WHSA tracks with a set of modern (N=356) and fossil footprints from Namibia (N=78; supplemental text) shows broad similarity (Fig. S3). The WHSA tracks, like the fossil tracks from Namibia, are flatter footed than the modern samples, similar to what is commonly reported for habitually unshod individuals (e.g., *21*). The WHSA footprints also have longer toe pads that we suggest are associated with slippage of the foot during locomotion (*18*).

Seven footprint surfaces (track horizons [TH]; TH1-7) and one multi-surface, track-bearing package (TH8) are present. All footprint surfaces, including TH4 with 37 tracks, have been excavated, but we draw particular attention to TH1 and TH5 through TH7, which occur at depth in the base of trenches. TH1 is the stratigraphically lowest footprint horizon and is exposed in the north-south side trench where it exhibits several human tracks, including a two-step trackway (TH1; Figs. 2, S4, and S5). TH5 occurs as a surface at the western end of the site but can also be traced laterally 9.35 m onto the floor of the main east-west trench where two footprints occur with different orientations, separated vertically from one another by a few centimeters of sediment (TH5 and TH6, Figs. S2 and S10). An additional footprint was also found in the base of the trench approximately 32 mm higher and 350 mm to the east (TH7, Fig. S2). Inferences of stature, track-maker age, and walking speeds are summarized in Figure 2B, although caution is required due to the uncertain anthropometric affinity of the track-makers' population. Many tracks appear to be those of teenagers along with children; large adult footprints are less frequent. One hypothesis for this is the division of labor, in which adults are involved in skilled tasks whereas 'fetching and carrying' are delegated to teenagers. Children accompany the teenagers and collectively they leave more footprints that are preferentially recorded in the fossil record. This pattern is common to all excavated surfaces.

We established chronological control for the footprint-bearing sediments using radiocarbon dating of *in situ* layers of macroscopic seeds of the aquatic plant *Ruppia cirrhosa* (*20*). Seed layers were sampled from throughout the sedimentary sequence (Figs. S11-S14) and yielded calibrated ages that range from 22.86 ± 0.32 to 21.13 ± 0.25 ka (N=11) and maintain stratigraphic order within the uncertainties between TH2 and TH6 (Fig. 2). Radiocarbon dating of aquatic material, such as *R. cirrhosa*, may be subject to hard-water (or reservoir) effects that could conceivably make these ages too old, so we explored the potential for these effects at WHSA Locality 2 using three lines of evidence (*20*). First, the geologic and hydrologic settings along the shallow lake margin that hosts the human trackways make it unlikely that stands of emergent aquatic plants would harbor significant hard-water effects. Second, our calibrated ^{14}C ages maintain stratigraphic order even when samples were separated by centimeter(s), which would not be the case if hard-water effects were large and variable. Finally, we evaluated independent chronologic data from the Tularosa Basin (*15*) and found that terrestrial and aquatic material yielded concordant ^{14}C ages between ~44 and 25 ka, which demonstrates that hard-water effects in Paleolake Otero were less than a few hundred years during this period (Fig. S15). In our view, an improbable series of events would be required to introduce a large hard-water effect by ~23 ka when for the previous ~20 kyr they were minimal. For these reasons, we conclude our radiocarbon-based chronology is robust.

To determine the underlying distribution of the calibrated ^{14}C ages from WHSA Locality 2, we applied the kernel density estimation (KDE) model (`KDE_Model`) function of OxCal4.4.2 (*22, 23*). In addition, we used the OxCal `Boundary` function to determine the start date and end date represented by the calibrated ages and the `Interval` function to determine the amount of time these track horizons represent (*20*). Our data and the modeling results show that the ages of TH-2 through TH-6 span from ~23 to 21 ka (Figs. 3 and S13), placing humans in this part of North America for approximately two millennia during the LGM. The presence of proboscidean tracks in TH8 places an additional constraint on the upper age of the sequence that shows it does not extend beyond the late Pleistocene.

The depositional sequence reported here exhibits a potential paleoclimate signal in which lacustrine conditions were succeeded by alluvial sedimentation that occurred in temporal correspondence with abrupt warming during Dansgaard-Oeschger event 2, beginning at ~23.3 ka (*24*). This drying event resembles sequences observed in other paleohydrological records in the southwestern U.S. (*25, 26*). In the Tularosa Basin, the lowered lake levels would have exposed a wide area along the lake margins where humans and megafauna traversed.

The evidence presented here confirms that humans were present in North America *before* the glacial advances of the LGM closed the Ice-Free Corridor (*9, 27*) and Pacific Coastal Route to human migration from Asia (*7*). The overlap of humans and megafauna for at least two millennia during this time suggests that if people were hunting megafauna, the practices at least initially were sustainable. This also raises the possibility of a human role in poorly understood megafauna extinctions previously thought to predate their arrival (*28, 29*) and makes 'early' sites in the Americas appear more plausible. However, exactly when people first arrived in the Western Hemisphere and when continuous occupation was established are still both uncertain and contested. What we present here is evidence of a firm time and location when humans were present in North America.

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Data availability: Downloadable files of the data presented in the Supplementary Information (Tables S1-S8) can be found at https://doi.org/ 10.5066/P9ABZEM9. The 3D footprints models are available at: https://doi.org/10.18746/bmth.data.00000186.

Supplementary Information: Supplementary text on methods and materials, supplementary references (*30-73)*, Figures S1 to S19, and Tables S1 to S8.

Figure 1: Study area and ancient footprints found at WHSA Locality 2. A. Map showing approximate location of the study site. Note that in accordance with the Archaeological Resources Protection Act of 1979, National Parks Omnibus Management Act of 1998, and the Paleontological Resources Preservation Act of 2009, the precise location of the site is withheld. Interested parties may contact the National Park Service for this information given a legitimate reason. **B.** Human footprints on track horizon 4 (TH4). **C.** Human footprint on track horizon 5 (TH5) located in the base of the main trench. **D.** Surfaced 3D model of part of the main trench showing three human footprints on different surfaces in the floor of the trench. **E.** Human trackways on surface TH4.

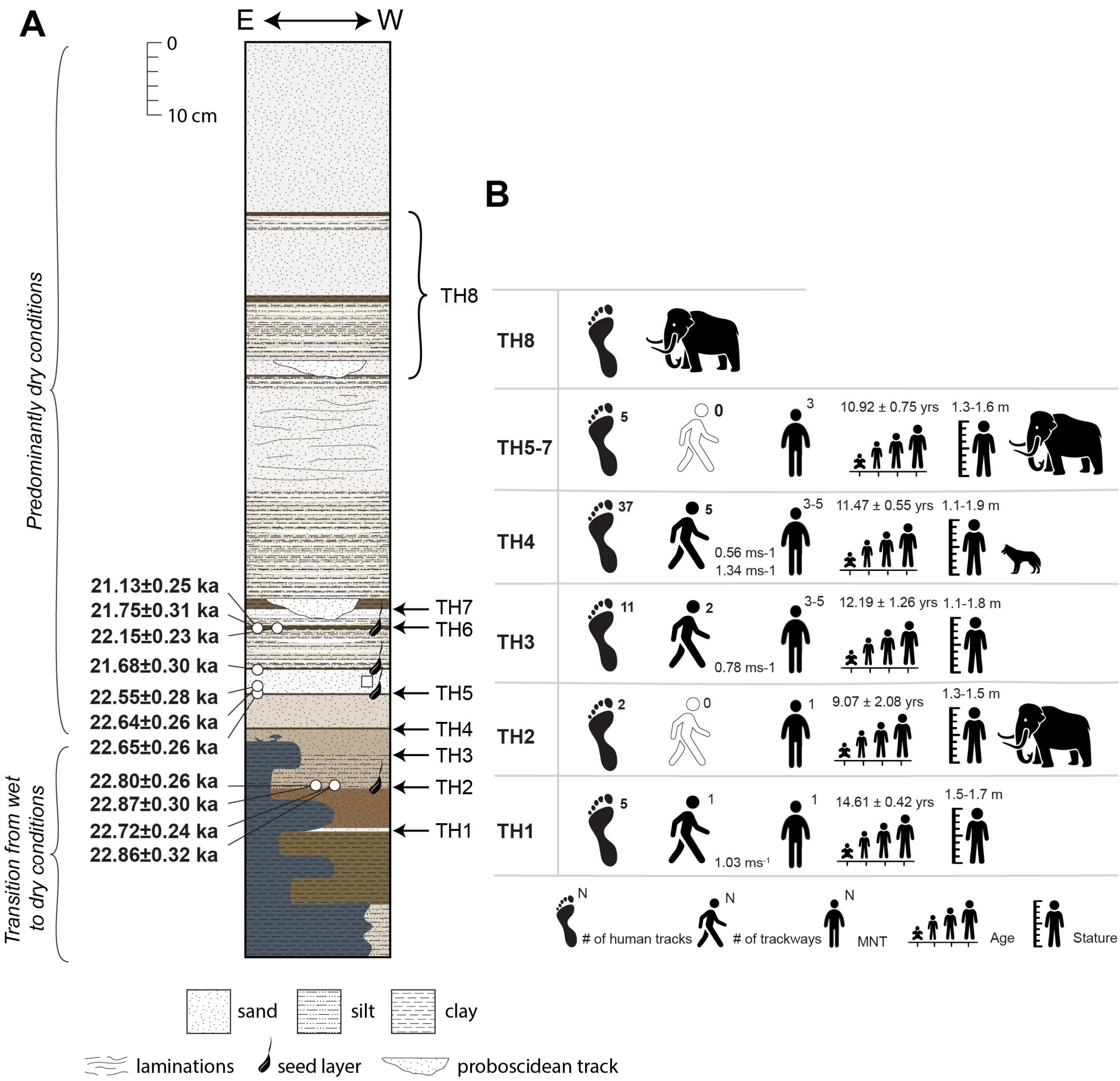

Figure 2: Geologic context and trackmaker demographics. A. Composite stratigraphy, calibrated ages, and dominant hydrologic regime for sediments exposed in the trench at WHSA Locality 2. Filled circles denote ^{14}C samples; filled square denotes uranium-series sample. The calibrated ^{14}C ages were used to construct the age models shown in Figure 3. **B.** Summary of footprint evidence on each horizon [number of human tracks, number of trackways, minimum number of track makers (MNT), track-maker age, stature, and fauna]. For additional details see (*20*).

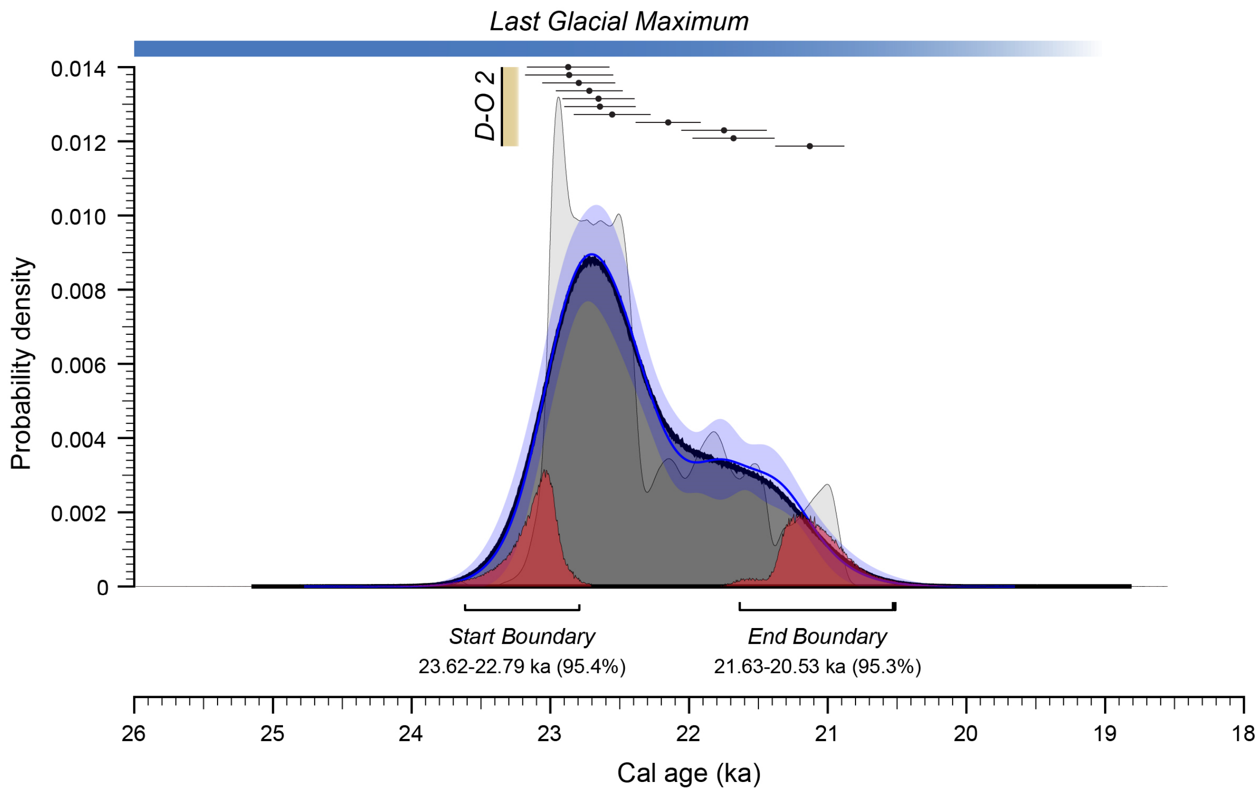

Figure 3: Age dating and modeling results. Kernel density estimate (KDE) modeling results for the 11 calibrated ages corresponding to TH2 through TH6. The dark gray distribution outlined in black is the KDE distribution. The blue line and lighter blue band overlying this show the mean and ±1σ for snapshots (n=1000) of the KDE distribution, which give an indication of the significance of any features. The light gray distribution is the Sum distribution for reference, and the red distributions are the start and end of the Boundary distribution. Generated using the `KDE_Model` and `Boundary` functions in OxCal v.4.4.2 r:5 (*22*) and the IntCal20 calibration curve (*23*); accessed online 12/08/2020. Timing of the last glacial maximum (26.5 to 19-20 ka; *3*) shown by horizontal blue bar; timing of Dansgaard-Oeschger event 2 (D-O 2; beginning at 23.3 ka; *24*) shown by vertical tan bar.