HUMAN EVOLUTION

Independent age estimates resolve the controversy of ancient human footprints at White Sands

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Human footprints at White Sands National Park, New Mexico, USA, reportedly date to between ~23,000 and 21,000 years ago according to radiocarbon dating of seeds from the aquatic plant *Ruppia cirrhosa*. These ages remain controversial because of potential old carbon reservoir effects that could compromise their accuracy. We present new calibrated ^{14}C ages of terrestrial pollen collected from the same stratigraphic horizons as those of the *Ruppia* seeds, along with optically stimulated luminescence ages of sediments from within the human footprint–bearing sequence, to evaluate the veracity of the seed ages. The results show that the chronologic framework originally established for the White Sands footprints is robust and reaffirm that humans were present in North America during the Last Glacial Maximum.

Ancient footprints in White Sands National Park, New Mexico, USA (WHSA), appear to place humans in North America during the Last Glacial Maximum (*1*). The footprints and associated tracks of Pleistocene megafauna at WHSA Locality 2 are imprinted on multiple stratigraphic horizons composed of fine-grained, gypsum-rich alluvium intercalated with clay and silt that was deposited in a mosaic of wet and dry environments along the eastern margin of Paleolake Otero in the Tularosa Basin (Fig. 1). Seeds from the aquatic plant *Ruppia cirrhosa* are found in situ within thin clay laminae, either interbedded with the footprint horizons or embedded in the footprints themselves. A total of 11 aliquots of *Ruppia* seeds yielded calibrated ^{14}C ages that maintain stratigraphic order and range from ~23 to 21 ka (ka, thousand years before present; 0 years = 1950 CE) (*1*), constraining the human footprints to within the temporal bounds of the Last Glacial Maximum (~26.5 to 19 or 20 ka) (*2*).

The findings at WHSA Locality 2 push back the peopling of the Americas by thousands of years and imply that early inhabitants and megafauna coexisted for several millennia before the terminal Pleistocene extinction event (*3*). This has important consequences for archaeology and allied fields, yet there has been widespread debate as to the accuracy of the *Ruppia* ages and therefore the antiquity of the footprints. This debate is organized around two lines of reasoning. The first is that *R. cirrhosa* is an aquatic plant, so there is the potential for uptake of old carbon from groundwater, which would cause the seed ages to be too old, a phenomenon known as the "hard-water effect" (*4*, *5*). The second is that *Ruppia* seeds are physically robust and can be preserved in sediments over geologic timescales, so it is possible that the seeds were exhumed from older deposits and reworked into the sediments at WHSA Locality 2. If so, the seeds would provide only maximum-limiting ages for the human footprints (*6*, *7*).

To address the controversy regarding the ages derived from *Ruppia* seeds, we obtained radiocarbon ages of terrestrial pollen recovered from the same stratigraphic intervals as those of the seeds, as well as optically stimulated luminescence (OSL) ages of quartz grains from within the footprint horizon interval, to evaluate the chronology of WHSA Locality 2. The dating techniques, the sample types, and the accelerator mass spectrometry facility involved in this study are independent of those used by Bennett *et al.* (*1*).

Terrestrial pollen is produced by cone-bearing and fruit-bearing plants living on land and fixing atmospheric carbon and therefore is not subject to hard-water effects. However, pollen grains are extremely lightweight and are generally between 10 and 150 μm in diameter (*8*), meaning that tens or even hundreds of thousands of grains are required to achieve the mass necessary for a single radiocarbon measurement. Even though it is an exceptionally laborious process, researchers have attempted to date pollen for decades (*9*–*17*), but the results have been mixed largely because of the difficulty of isolating enough pollen grains from other organic material to produce reliable ages. The recent adoption of flow cytometry to separate pollen grains from sediment and other organic materials has overcome this

Fig. 1. Ancient human footprints found at WHSA Locality 2. Photograph showing multiple in situ footprints in track horizons TH1 (white arrows), TH2 (yellow arrows), TH3 (red arrows), and TH4 (black arrows). Their stratigraphic positions and associated chronologic data are provided in Fig. 2.

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problem, and pollen samples often approach purity after processing (*18*–*21*).

In this study, we collected large (>1 kg) samples of bulk sediment from the exact same stratigraphic levels as those of the original samples of *Ruppia* seeds from WHSA Locality 2, which yielded ages that range from 22.87 ± 0.30 to 21.13 ± 0.25 ka (Fig. 2) (*1*). The samples were subjected to rigorous chemical pretreatment and microsieving to remove as much of the host material as possible, and the pollen grains were separated from the remaining residue by means of flow cytometry (*22*). All of the WHSA Locality 2 samples contain pollen assemblages that are indicative of a climate that was much cooler and wetter than today (*22*). Arboreal taxa include abundant *Pinus* (pine) and some *Picea* (spruce), *Abies* (fir), and *Pseudotsuga* (Douglas Fir), which indicate altitudinal lowering of nearby conifer forests compared with present day and are consistent with previous findings for the Last Glacial Maximum (*23*). Nonarboreal taxa are dominated by *Artemisia*, reflecting a sagebrush steppe that is not found in the region today (*22*). For dating, we targeted conifer pollen because it is relatively large (>70 μm) and has a relatively thick exine, both of which result in increased carbon content. We measured the ^{14}C content of three different samples from WHSA Locality 2 that each contained ~75,000 pollen grains, and the resulting calibrated ages range from 23.4 ± 2.5 ka to 22.6 ± 2.3 ka (Fig. 2) (*22*).

The uncertainties associated with the pollen ages are relatively large because they required blank corrections that are approximately an order of magnitude larger than what is typically used in radiocarbon dating. Blank corrections are performed on all radiocarbon samples to account for small amounts of contaminant ^{14}C (usually modern) that is introduced to samples during the various stages of processing, including collection, handling, chemical pretreatment, CO_2 extraction, graphitization, and the isotopic measurement (*24*–*26*). To isolate the pollen grains, the samples analyzed in this study required extensive pretreatment procedures, so in order to properly correct the resulting ages, we also extracted and dated pollen from sediments that are known to be beyond the limit of radiocarbon dating for use as a procedural blank (*22*). Assuming that the same amount of contamination was introduced to all of the samples analyzed in this study, which is equivalent to an increase of ~2200 ^{14}C years or 2500 calendar years for the WHSA Locality 2 sequence (*22*), the resulting ages should be viewed as being accurate, albeit with reduced precision. Overall, the calibrated ^{14}C ages of the pollen samples from WHSA Locality 2 are statistically indistinguishable from the original seed ages (Fig. 3), which supports the original chronologic framework developed by Bennett *et al.* (*1*). Last, even had we not undertaken this

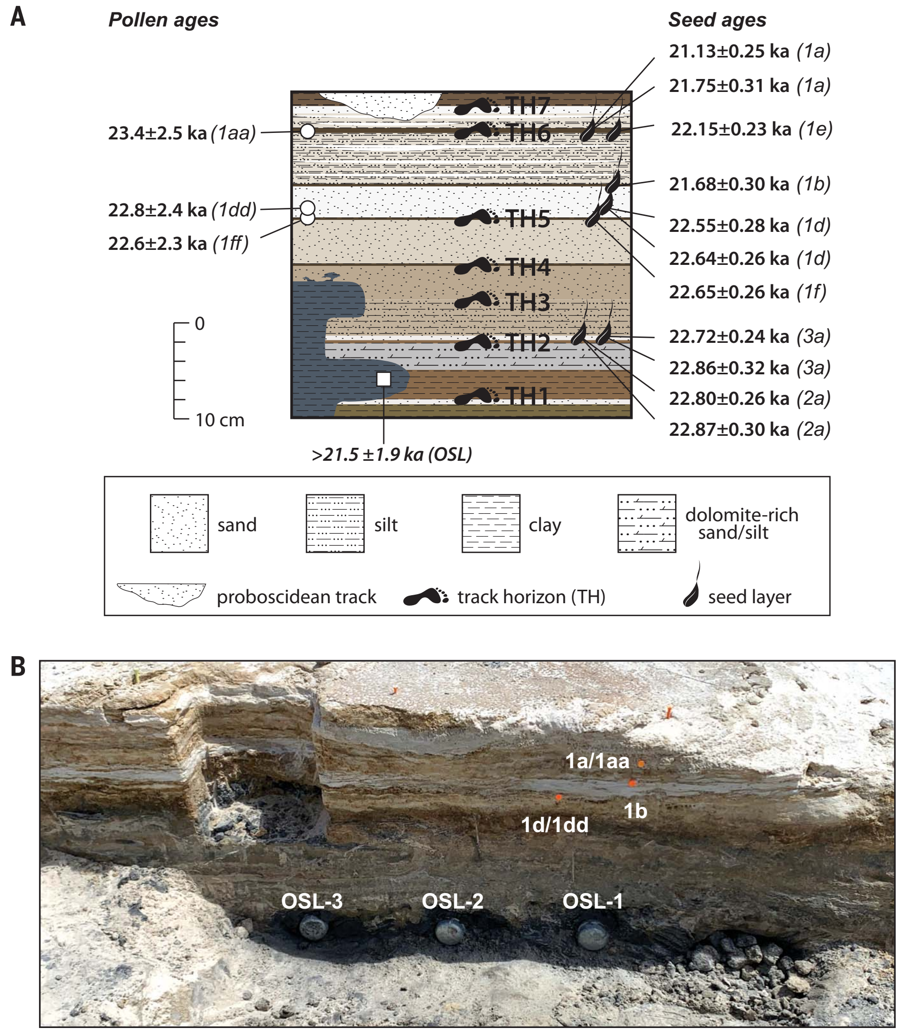

Fig. 2. Geologic context of chronologic samples. (**A**) Composite stratigraphy, calibrated ^{14}C ages, and sample numbers (in italics) of pollen and *Ruppia* seeds, as well as the minimum OSL age for sediments exposed in the trench at WHSA Locality 2. The calibrated ^{14}C ages were used to construct the age models shown in Fig. 3. (**B**) Photograph looking south of the sediments exposed in the trench at WHSA Locality 2 along with locations of radiocarbon samples for *Ruppia* seeds (1a, 1b, and 1d) and pollen (1aa and 1dd) as well as the three OSL samples (OSL-1, -2, and -3) (*22*). Pollen sample 1ff is located near the base of the trench to the east (fig. S1). The large block cut out of the exposed face on the left side of the photograph was sampled previously for U-Th series disequilibrium dating (*1*).

pollen-specific approach for the blank correction, the calibrated pollen ages would still have fallen within the Last Glacial Maximum (*22*).

In addition to radiocarbon methods, which are based on radioactive decay, we used OSL dating, which is based on the accumulation of energy stored as trapped charge within the crystal structure of a mineral and is a function of background ionizing radiation (*27*). This trapped charge is released and the geochronometer is reset when a mineral, typically quartz, is exposed to sunlight or heat. For the sediments at WHSA Locality 2, an OSL age is equivalent to the amount of time elapsed since the quartz was deposited and sealed from sunlight. Although the sediments at WHSA Locality 2 are dominated by gypsum and contain only a small amount of quartz, we were able to obtain three OSL age minima from a single stratigraphic level located just below our lowest radiocarbon age but still well within the human footprint horizons. Collectively, they show the minimum OSL age of the sampled horizon is >21.5 ± 1.9 ka (*22*). As with the pollen results, the OSL ages are statistically indistinguishable from the calibrated ^{14}C ages of the lowest *Ruppia* seeds collected for dating from the stratigraphic sequence (Fig. 2).

Both the calibrated ^{14}C ages of pollen and the OSL ages support the original ages obtained from the *Ruppia* seeds at WHSA Locality 2, but the accuracy of the age estimates from each method must be evaluated individually before they can be accepted as reliable. The most

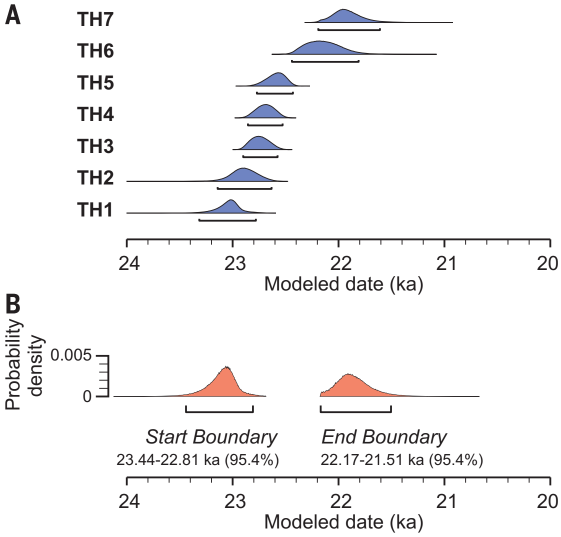

Fig. 3. Age dating and modeling results. Modeled ages for (**A**) track horizons TH1 through TH7 and (**B**) the start and end boundaries for the entire footprint horizon interval based on the calibrated ^{14}C ages of pollen and *Ruppia* seeds. Both figures were generated using the Sequence function in OxCal v.4.4.4 (*32*) and the IntCal20 calibration curve (*23*), which we accessed online 30 May 2023. Samples identified as outliers at the 95% confidence level were excluded from the analyses (*22*).

common pitfall when dating pollen is that reworking of pollen from older sediments could potentially cause the ages to be too old (*19*, *28*). To evaluate this possibility, we dated multiple aliquots of pollen extracted from sediments collected at the surface of an active playa in White Sands National Park. The pollen assemblage in the modern playa sediments is consistent with the warm, dry conditions that prevail in the Tularosa Basin today and is composed primarily of nonarboreal taxa, including Amaranthaceae, Asteraceae, and Poaceae (all flowering plants) (*22*). The ^{14}C content of the playa conifer pollen (*22*) is indistinguishable from current atmospheric ^{14}C levels (*29*), which shows that reworking of old pollen is inconsequential in this part of the Tularosa Basin today. It follows that this also holds true for the late Pleistocene, especially considering that much of the basin was covered by Paleolake Otero at that time.

Similarly, processes that take place after sediments are deposited can potentially influence OSL ages by affecting the background radiation field, causing them to be either too old or too young. Such phenomena include changes in pore water content, enrichment or depletion of radiogenic isotopes over time, changes in the flux of cosmogenic radiation, incomplete removal of trapped charge during transport (partial bleaching), and physical disturbance of the grains from bioturbation. For the WHSA Locality 2 samples, the impact of these variables is likely minimal based on the consistency of the measured pore water content between the low-permeability, clay-rich sediment samples; the similarity in radiogenic isotope values between samples; ample Sun exposure during transport prior to burial; and the intact stratigraphy at the sample locations.

Resolution of the White Sands dating controversy requires that there is no combination of physical or chemical processes that could cause the ages of three independent chronologic data sets to converge on a single age range while simultaneously being incorrect or biased. It also requires that paleoenvironmental indicators (pollen assemblages) be consistent with regional records for the period in question. These metrics are met in this study on the basis of the nature of the chronologic techniques we used and the materials to which they were applied. Combined with the previously reported geologic, hydrologic, stratigraphic, chronologic, and climatic evidence (*1*, *30*, *31*), the congruence of the calibrated ^{14}C ages of the aquatic *Ruppia* seeds, the calibrated ^{14}C ages of the terrestrial pollen grains, and the OSL ages support the conclusion that humans were present in North America during the Last Glacial Maximum.

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SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adh5007
Materials and Methods
Supplementary Text
Figs. S1 to S10
Tables S1 and S2
References (*34*–*62*)
MDAR Reproducibility Checklist

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Editor's summary
Traditionally, researchers believed that humans arrived in North America around 16,000 to 13,000 years ago. Recently, however, evidence has accumulated supporting a much earlier date. In 2021, fossilized footprints from White Sands National Park in New Mexico were dated to between 20,000 and 23,000 years ago, providing key evidence for earlier occupation, although this finding was controversial. Pigati *et al*. returned to the White Sands footprints and obtained new dates from multiple, highly reliable sources (see the Perspective by Philippsen). They, too, resolved dates of 20,000 to 23,000 years ago, reconfirming that humans were present far south of the ice sheets during the Last Glacial Maximum. —Sacha Vignieri

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