Incredible discoveries and devastation of paleontological resources in a changing world preserved at White Sands National Park

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ABSTRACT

In recent years the discovery of paleontological and archaeological resources exposed because of natural disasters and rapid erosion—mostly linked to climate change—has occurred at a phenomenal rate. Each year wildfires, floods, landsides, retreating glaciers, snow melt, soil erosion, and receding lakes and reservoirs are uncovering valuable resources. Unfortunately, these same forces often lead to the loss of these resources before they can be preserved or documented. At White Sands National Park, as moisture within the soil is being reduced by persistent droughts and rising temperatures, 23,000-year-old fossil prints of people and Ice Age megafauna are being exposed—and then rapidly lost to soil erosion. Consequently, there is an urgent need to document the fossil prints before the record is lost. This is a concern not only for White Sands, but also for dry lake beds throughout the Southwest and around the world where fossil prints may not have yet been discovered but are rapidly being lost. At White Sands, we are working with an impressive team of experts to develop techniques to rapidly document these resources. The fossil resources at White Sands provides an important analogue for understanding other pluvial systems throughout the world.

INCREASING RATE OF DISCOVERY

In recent years there has been a steady increase in the number of discoveries of paleontological and archaeological resources throughout the world. Some of the reasons for the discoveries include but are not limited to: ground disturbance from the expansion of cities and infrastructure required to support growing populations, natural disasters, and improved resource recognition. Many of the new discoveries from natural disasters have been the result of resources being exposed by events such as wildfires, floods, sea level rise (Allison et al. 2017; Anderson et al. 2017), landslides, glacier retreat, soil erosion, drying of lakes and reservoirs, and dune migration. Most of these events are linked to climate change. The same forces that are exposing these scientifically valuable resources are also leading to their loss.

When resources are discovered, it is often at a moment's notice, and the optimal window of time to attempt to document or preserve them is often only days or weeks before the same processes remove them forever. At White Sands National Park, as moisture within the soil is being reduced by persistent droughts and rising temperatures, 23,000-year-old fossil prints of people and Ice Age megafauna are being exposed—and then rapidly lost to soil erosion. For the fossil prints at White Sands the optimal time to document them is within the first few hours of

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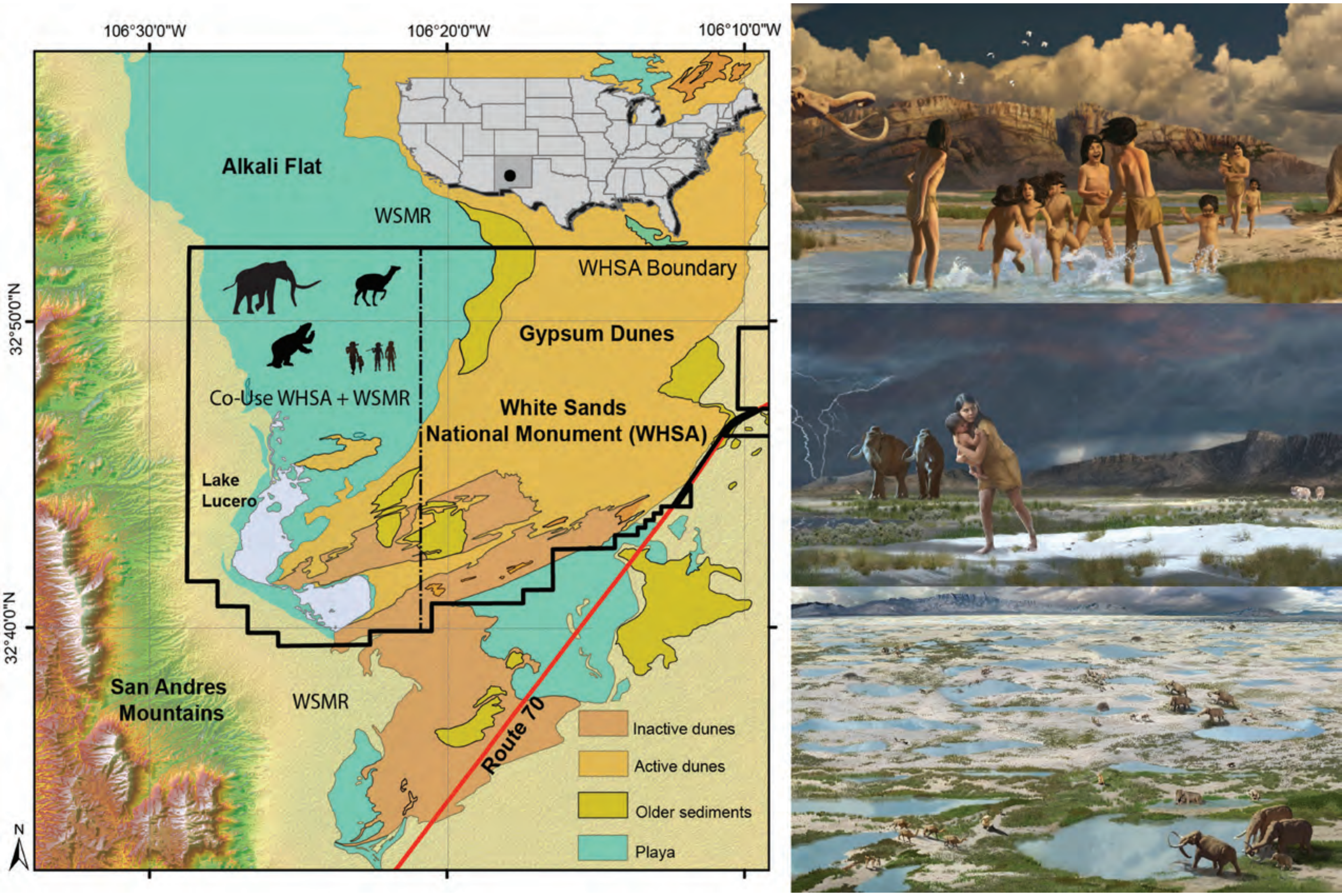
exposure before they dry out and/or are covered by a fine layer of salt. When new resources are exposed there is a need for immediate documentation, but the required equipment, personnel, procedures, compliance, and knowledge may not be ready before they are lost. The preservation of priceless natural and cultural resources that hold significant value for future generations is at the core of the National Park Service (NPS) mission in an ever-changing world fueled by climate change and the stressors needed to support a growing population.

White Sands National Park (formerly White Sands National Monument) is considered a small park due to its limited budget and staffing, but it has big-park issues and incredible resources of national and international significance. When camel and mammoth prints were first found in 2006 the park did not have the staffing or expertise to know where to begin or the equipment to properly archive and document the prints. With the help of the NPS's Intermountain Region and Washington headquarters physical science and paleontological program, the park was able to formalize the process to document trackways and borrow the equipment to start the process. By 2014, the park was recognized as a megatracksite, with the greatest concentration of Cenozoic fossil prints in the Americas. By 2016, with help from park staff and interns, and assistance from the Bureau of Land Management (BLM) and US Geological Survey (USGS), fossil megafauna trackways had been documented across the park's 32,357 hectares (80,000 acres) (Figure 1). With help and assistance from the New Mexico Institute of Mining and Technology, University of Arizona, Environmental Planning Group, and New Mexico Museum of Natural History and Science, the park began to gather baseline data on

FIGURE 1. Geological and locational context of White Sands National Park (WHSA). The study sites reported are located throughout the park in the gypsiferous lake sediments. Note that the precise locations are not indicated, in accordance with National Park Service (NPS) protocol and US law. WHSA is bounded by White Sands Missile Range, Holloman Air Force Base, and BLM (Bureau of Land Management) land. This is the homeland of many Tribes and Pueblos that visited and lived in the area over thousands of years. Artwork by Karen Carr depicts White Sands during the Pleistocene.



the megafauna fossil trackways and lake sediments where prints were being found and established general ages for the former (Figure 2).

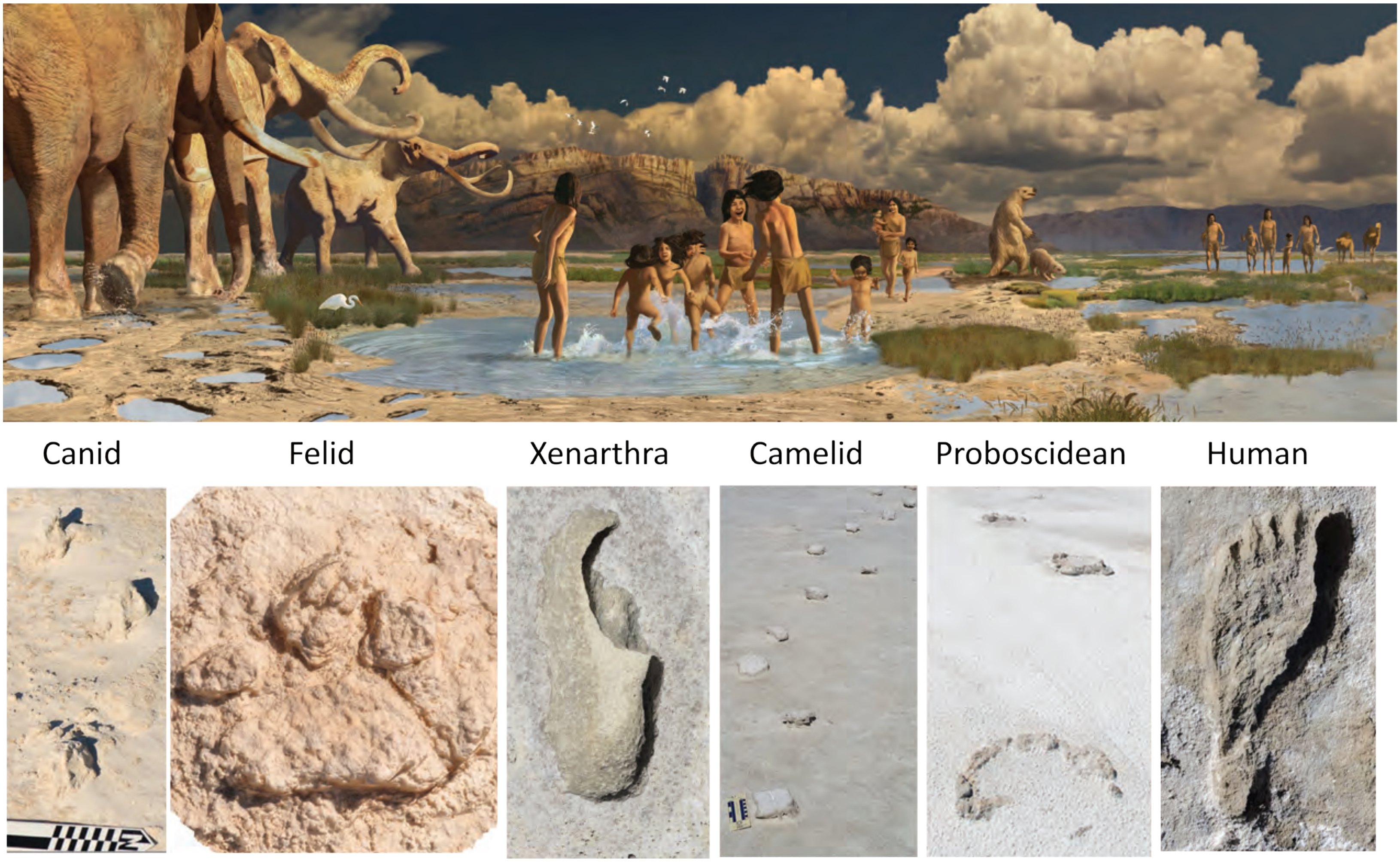
ANALOGUE FOR OTHER PLUVIAL SYSTEMS

We now know that these footprints are found in a pluvial lake system called Lake Otero, an Ice Age lake that was teeming with life during the Last Glacial Maximum 20,000 years ago (Allen et al. 2009). The long episodic dry and wet events seem to be ideal for preserving fossil footprints, not only of Ice Age megafauna, but also of people who lived in the area at least 23,000 years before present.

At White Sands thousands of fossil prints have been documented, making it a great analogue for sites in other dry-lake bed pluvial systems. Throughout the Southwest similar former large wetlands and lakes that once teemed with life can be seen in the form of barren salt flats. These dry lake beds, also known as playas, have done an excellent job of preserving records of past life from colder and wetter times— records that, if preserved, offer educational stories for future generations (Bennett et al. 2021). These records include rich organic layers that contain pollen, shells, and fossil prints of people and megafauna. In recent years we have learned that fossil trackways are not unique to White Sands but are present in other dry lake beds throughout the Southwest, and park staff have assisted other managers in documenting fossil prints on their lands.

For early American history the key questions that have repeatedly been asked are: (1) When did people arrive in the Americas?; (2) What route did they take?; and (3) Did they cause the die-off of the great Ice Age megafauna? We don't know the date when people first arrived, but we now have evidence, repeated throughout the park, that people were

FIGURE 2. Examples of some of the trackmakers and prints from White Sands National Park. Artwork by Karen Carr depicts White Sands during the Pleistocene.



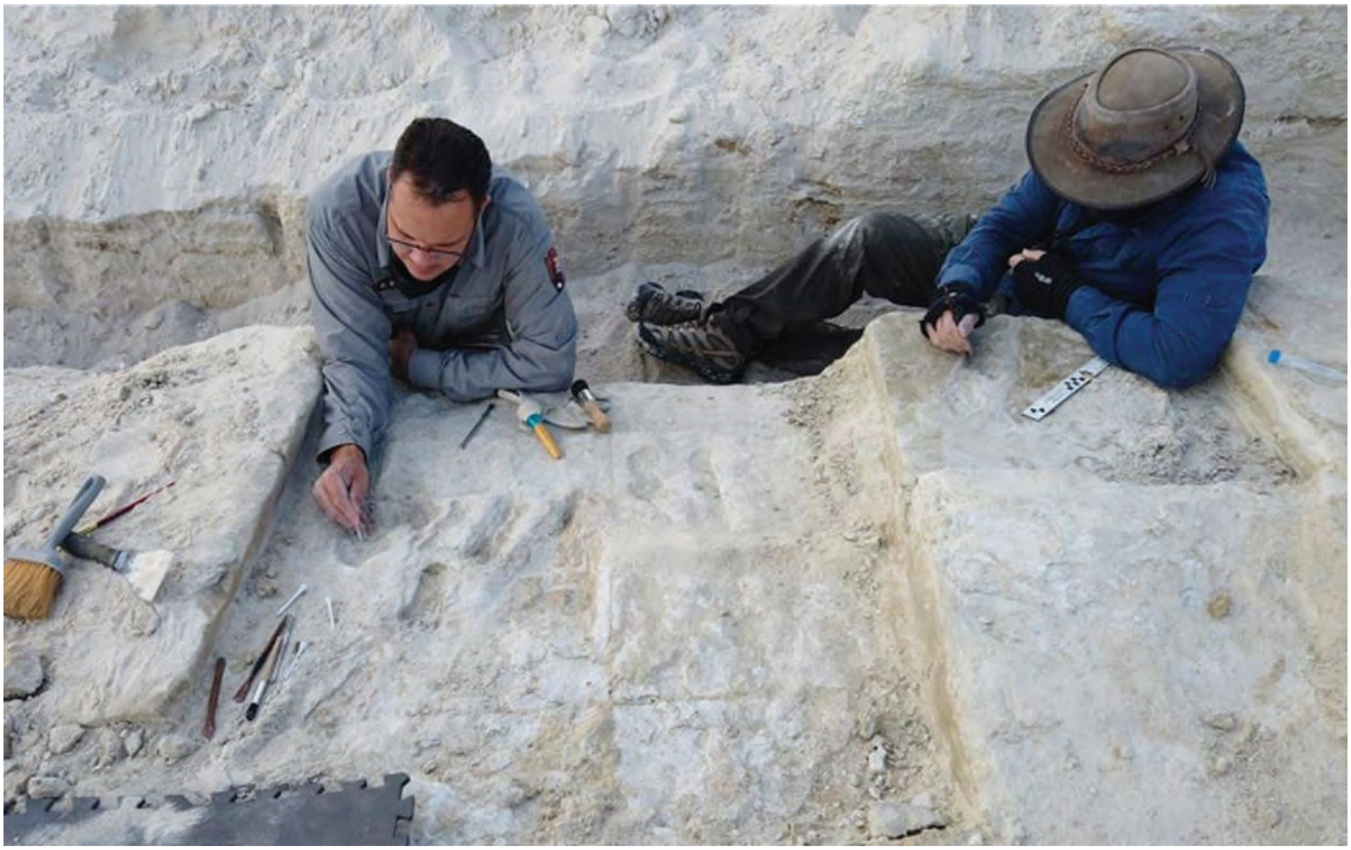
present at White Sands at least 23,000 years ago. We do not know the exact route people traveled, but we are finding additional trackways in other pluvial systems throughout the Southwest. This is exciting because pluvial lake systems are found in both North and South America (Orme 2008). In time, additional evidence from these pluvial lake systems may suggest migration routes and the direction of travel (Anderson and Gillam 2000). Finally, we also now have evidence that people lived alongside megafauna for thousands of years, beginning at least from 23,000 to 21,000 years before present (Bennett et al. 2021) (Figure 3).

URGENCY TO DOCUMENT DISCOVERIES

Over the last two decades there have been severe droughts in the Southwest that have led to large-scale soil erosion. Three scenarios have been predicted for the next 50 years for how the local environment will be affected by climate change. These scenarios are "dry and hot," "wet and hot," and "no change in precipitation and warm" (Table 1); the one thing that they all share is that there will be a net loss of soil moisture (Benjamin et al. 2020). Early studies in dune migration conducted by Dr. Eddie McKee of USGS found that as the sand dries it moves exponentially with a given velocity of wind. These events are caused by long periods of drying, followed by heavy winter and spring winds. In recent years winds have exceeded 130 km/hr (80 mi/hr) in the park and 166 km/hr (103 mi/hr) at a nearby mountain pass, causing complete white-outs and plumes of white gypsum dust. Images of this phenomenon can be found using the keyword search "White Sands dust from space": The dust is so thick that it can be seen from the International Space Station. During such storms the sands leave the vicinity of the park and can travel beyond Oklahoma, a distance of some 1,300 km (800 mi) (Figure 4).

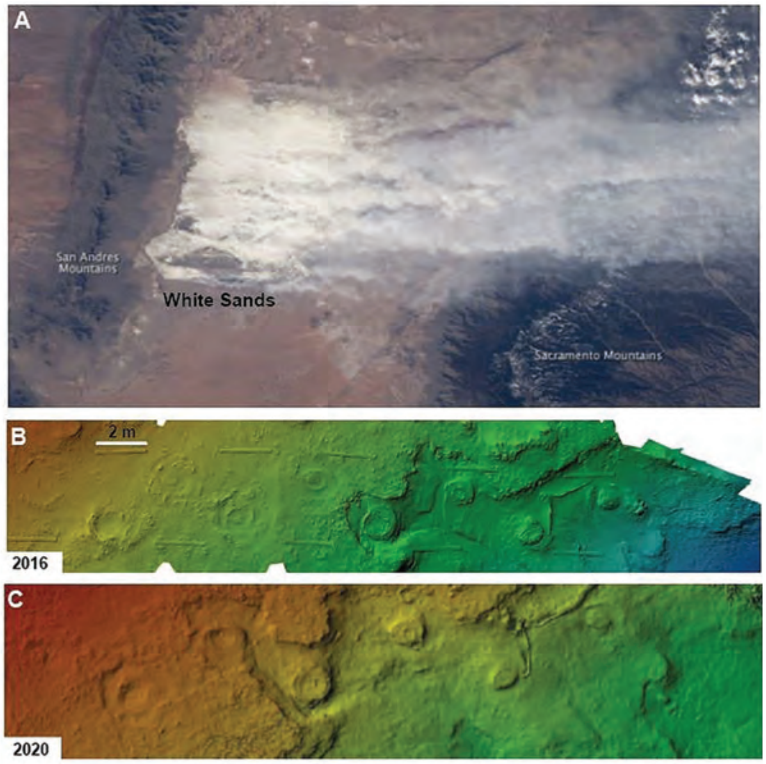
These large-scale removal events are causing rapid sediment loss, exposing trackways and then putting them on a countdown to disappearance. The primary modes of erosion and weathering include flaking, wind abrasion, and boring of holes. Loss differs in response to sediment type (Figure 5), depositional environment, and levels of current environmental and climatic stress (Zimmer et al. 2018). At White Sands we have documented that it takes anywhere from a few months to a couple of years from initial discovery to complete erosion and loss depending on print type,

FIGURE 3. Team working on brushing out and documenting trackways from multiple trackway horizons within a trench. Eleven horizons were found from the top to the bottom of the trench, all with human prints and some megafaunal prints.



	Warm/Rain-No Change	Hot/Wet	Hot/Dry
	Common across scenarios: warming in all seasons		
Warming	Degree of warming: ~2.7 °C (1.5 °F) 26 days > 38°C (100 °F) (+6 days)	Degree of warming: ~7.4 °C (4.1 °F) 36 days > 38°C (100 °F) (+16 days)	Degree of warming: ~7.4 °C (4.1 °F) 42 days > 38°C (100 °F) (+22 days)
	Variable		
Precipitation	No change	5 cm (2 in) annual increase concentrated in Jul/Aug (+66%)	3.8 cm (1.5 in) annual decrease evenly distributed across June–Dec
	Common across scenarios: increasing soil moisture deficit		
Water Balance	Annual soil moisture deficit increases 7%	Annual soil moisture deficit increases 12%	Annual soil moisture deficit increases 27%

▲ **TABLE 1.** Climate change scenarios.



▶ **FIGURE 4.** Large-scale erosion and gypsum dust plumes. The photo is from the International Space Station (NASA Earth Observatory, February 28, 2012; courtesy of NASA); dust can be seen spreading as far as Oklahoma.

where it is located, and the mineralogy of the preserved prints (Table 2). Specifically, we have seen rates of erosion that exceed 1.5 cm/year (0.6 in/year) and have documented the loss of entire sedimentary horizons containing human and megafauna prints.

At White Sands severe soil erosion is signified by the root zone of plants being exposed, which in places involves up to 28 cm (11 in) of sediment loss, along with large-scale vegetation die-off and exposed trackways across hundreds of acres (Figure 6). The rate of erosion and sediment loss varies across the park with a close correlation to elevation and sediment type. Exposed root zones and sediment loss can also be seen in other playa systems where fossil trackways have recently been found.

A POWERHOUSE TEAM COMES TOGETHER

With the confirmation of human trackway contemporaneous with Ice Age megafauna prints, an impressive multi-disciplinary team came together to implement and deploy a rapid set of techniques to capture information from the fragile fossil prints before they were lost. The same strategies deployed at White Sands can be used at other sites where paleontological and archaeological resources have been recently exposed or are at risk to rapid loss. To preserve as much information as possible, a framework has been implemented to document resources at the surface and subsurface, conduct print analysis, establish the geological context and age, determine print distribution, and assign a risk factor based on location and composition. In addition, the team is working with representatives from Pueblos and Tribes and anthropologists to better understand the stories that are told in the fossil prints.

At White Sands all work begins with surface documentation to establish ground control, utilizing ground photographs for photogrammetry, lidar, aerial photography, and ground surveys. The way in which a site is documented depends on its size (Figure 7). For small sites ranging from 1–3 m^2 (11–32 ft^2), a standard camera can be used to complete photogrammetry (a process that uses overlapping photos to generate orthomosaics and dense point clouds to create exact 3D digital replicas), or else a handheld laser scanner can be used to create 3D models from dense point clouds and

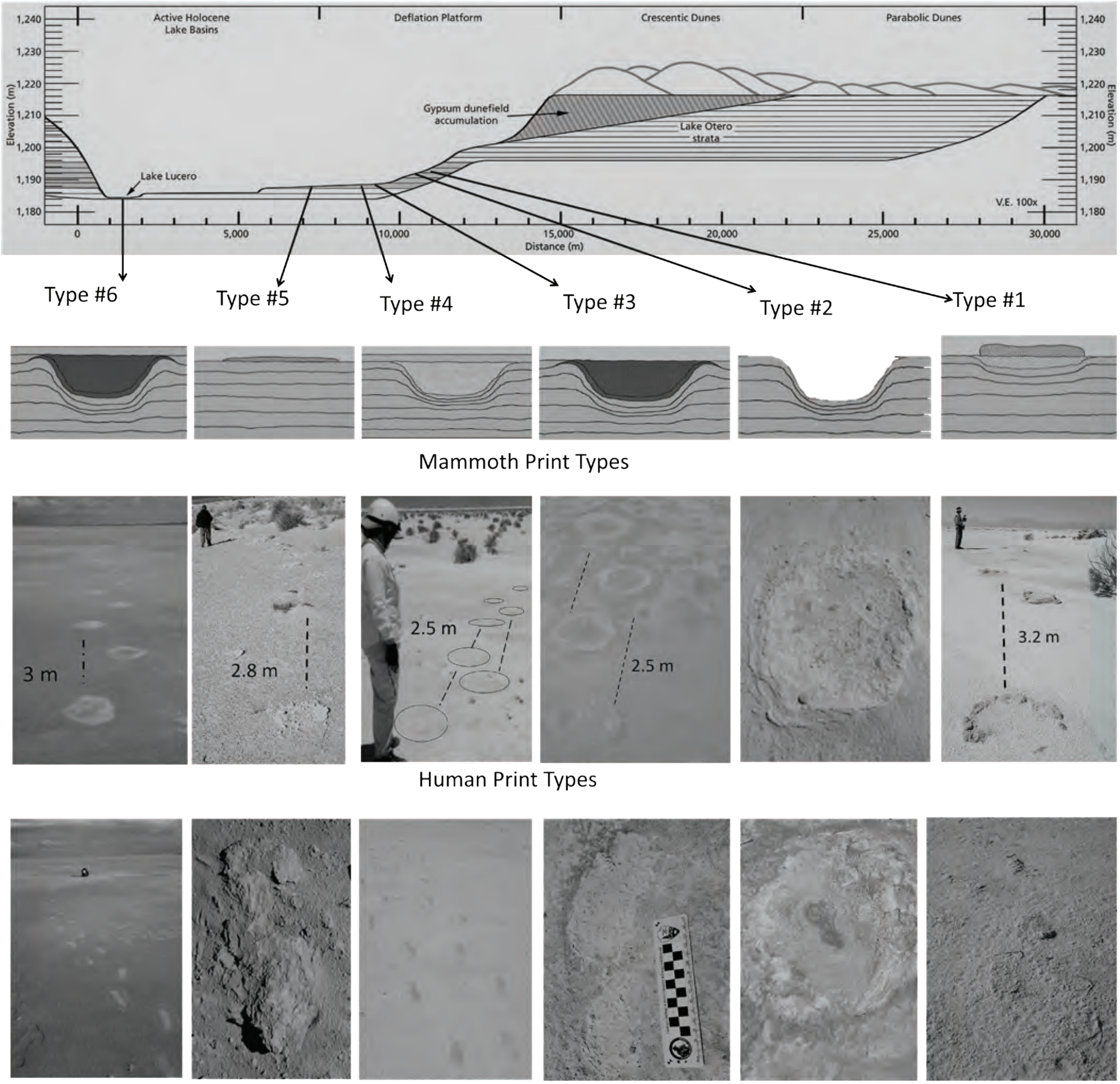
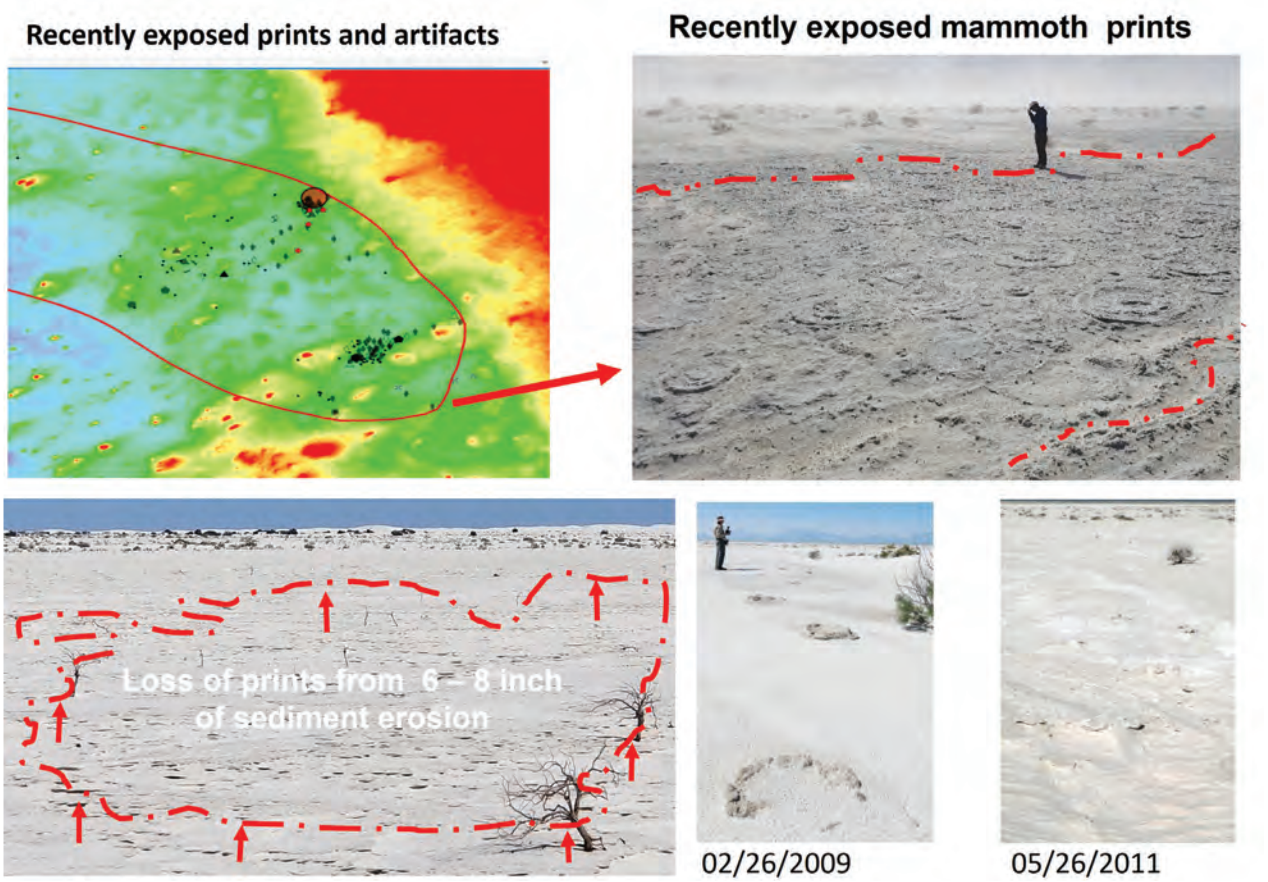


FIGURE 5. ABOVE Conceptual model of the White Sands Dune Field aeolian gypsum sand and lake bed. BELOW Previous work, which recognized erosional shorelines within the basin (Langford, 2003; Kocurek et al. 2007, Szykiewicz et al. 2010), revealed mammoth and comparative human print types. Prints change in composition, mineralogy, and structure with soil type and elevation. For comparison only, mammoth prints were used to represent megafauna prints, but this could also have been done using ground sloth or camel. Type #1 prints are made of clay; Type #2 are prints that are not filled; Type #3 are filled with sand and not covered; Type #4 are filled with fine sand and covered with silt or clay; Type #5 are made of dolomite; Type #6 are deep, coarse-grain-filled prints covered with silt.

orthomosaics. Each point that is generated is a measurement; it is very common for most 3D-model point clouds to have millions of points. For sites that range from 4–15 m^2 (43–161 ft^2), a camera mounted on a gyroscope with a 1-second timer affixed to a high pole, kite, or balloon works well, or else the camera can be part of an unmanned aerial system (UAS; i.e., a drone). For sites greater than 15 m^2 (161 ft^2), either a UAS or fixed-wing aircraft capable of taking true color photos and lidar scans is preferred (Figure 8). From these images the paleontological and archaeological resources can be easily located and precise measurements taken. From the air it is often possible to see patterns of trackways and archaeological structures that can be difficult to see from the ground. Repeated cyclic surveys can also be used to identify vulnerable areas or ongoing large-scale sediment loss and calculate rates of erosion. Documentation from the ground is conducted by park staff and the core research team. UAS and fixed-wing aerial surveys have been conducted by USGS with the approval of and close coordination with the US Army to fly in the otherwise restricted airspace over the park.

Trackmaker	Adult Mean Print Size	Juvenile (small body) Mean Print Size	Sediment Class
Humans	23 x 8 cm (9 x 3 in)	12 x 5.5 cm (5 x 2 in)	Sand, clay, silt, stone (dolomite)
Proboscideans (mammoths and mastodons)	53 x 45 cm (21 x 18 in)	32 x 34 cm (13 x 13 in)	Sand, clay, silt, stone (dolomite)
Camelids (camels)	20 x 18 cm (8 x 7 in)	**	Sand, clay, silt, stone (dolomite)
Folivorans (sloths)	38 x 18 cm (15 x 7 in)	25 x 10 cm (10 x 4 in)	Sand, clay, silt, stone (dolomite)
Felids (cats)	15 x 19 cm (6 x 7 in)	**	Clay
Canids (dogs)	12 x 10 cm (5 x 4 in)	**	Clay, silt, stone (dolomite)

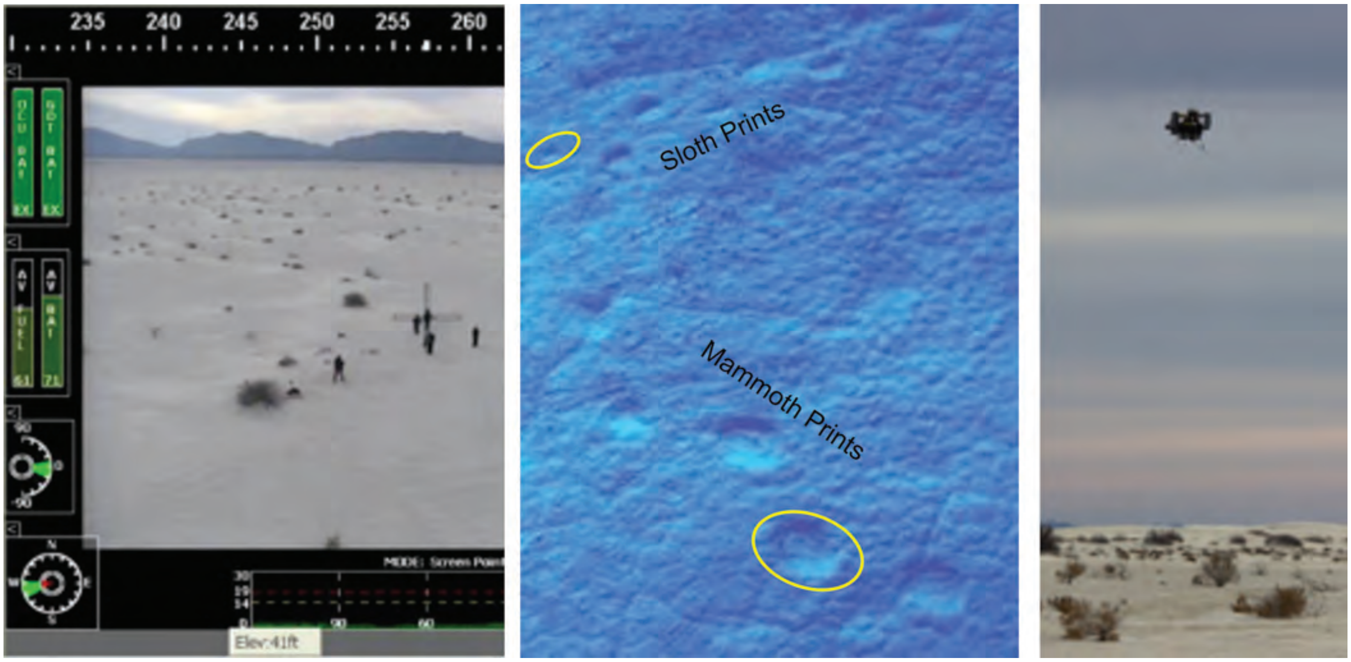


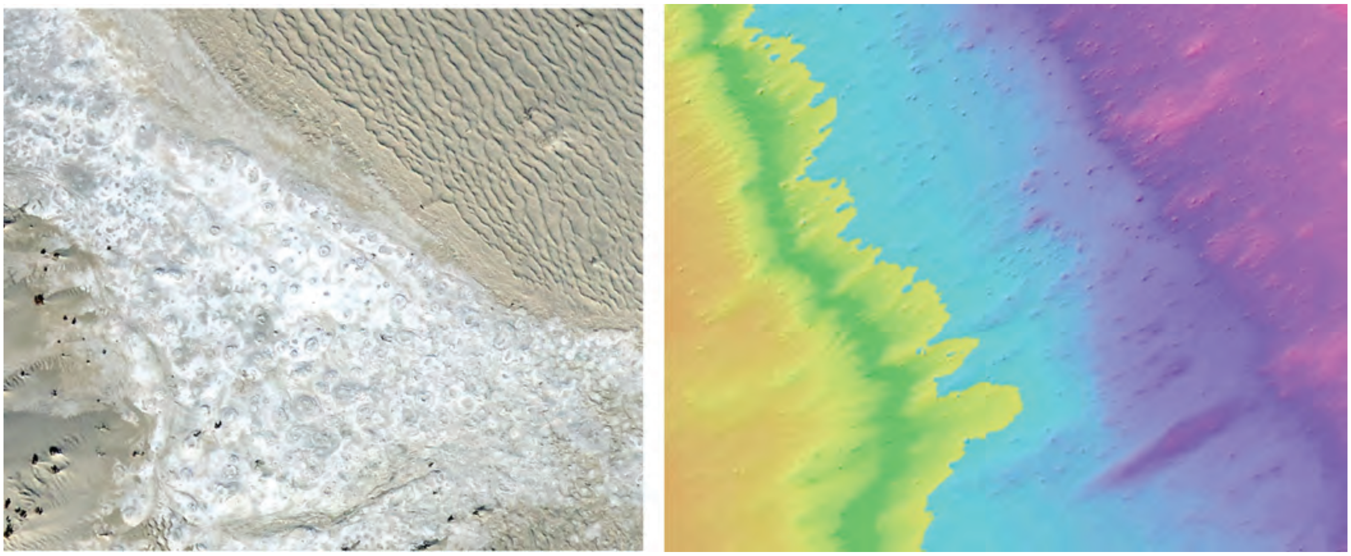
▲▲ **TABLE 2.** Variation of adult and young trackmakers' prints and sediment class that are composed of. ** indicates no known juvenile prints for that trackmaker. Size is listed as (print length) x (print width) in centimeters.

▲ **FIGURE 6.** Large-scale erosion causing thousands of prints to be lost across thousands of acres.

The subsurface surveys have been led by Dr. Thomas Urban of Cornell University (Ithaca, New York), a specialist in the field of geophysics. Urban has refined the use of ground-penetrating radar (GPR) and magnetometers to identify fine and large-scale prints in the subsurface. He has also pioneered new techniques to survey in dry, wet, and hypersaline soils (Urban et al. 2019, 2020). At White Sands, prints in the subsurface often present anomalies at the surface because the infill of the prints is different from the surrounding sediments. From the visual perspective prints will appear as wet or dry spots or a halo of salt, and disperse at the surface as soil moisture changes throughout the year. When surveyed with GPR or a magnetometer, a shadow or outline like Superman seeing a blurry figure through a concrete wall can be seen (Figure 9). At White Sands the GPR and magnetometer often detect many more prints, and from additional trackmakers, than can be seen at the surface. For example, mammoth prints may be visible at the surface, but GPR will also detect human and giant ground sloth prints that could not be seen by the unaided eye at the surface.

Professor Matthew Bennett of Bournemouth University (Poole, UK) is a leader in the study of ichnology and one of the world's foremost experts in fossil human footprints. He led the discovery of the first prints at White Sands that demonstrated that humans and megafauna were contemporaneous with one another, and the analysis of





▲▲ **FIGURE 7.** Photos of trackways and 3D models taken by the US Geological Survey UAV program

▲ **FIGURE 8.** DEM and image from LiDAR using a fixed-wing aircraft. Thousands of prints have been exposed and are rapidly eroding.

the human and megafauna prints throughout the park. Dr. Sally Reynolds, also of Bournemouth University, is an expert in human evolution, the study of mammalian fauna, and past environments, and has led the analysis of the anthropogenic information they provide for the first people of the Americas. From 3D scans of the prints thousands of measurements are used to confirm that a particular print has been properly identified. Cross-sections of prints are used to determine the order in which they were laid down, how the substrate was altered, and what traces are left behind (Bennett et al. 2019). From the diversity of prints, trackmakers can be identified (mammoth, giant ground sloth, dire wolf, human, etc.), and demographics can be analyzed for size, sex, and age of trackmakers (Bennett et al. 2020). From the prints, interactions can be seen between trackmakers, and new information on early American history can be learned from the stories the prints tell.

Previous studies have assigned the human and megafaunal track-forming window to the Late Pleistocene (Bustos et al. 2018). To better define the age based on geochronologic data, Dr. Jeff Pigati and Dr. Kathleen Springer, geologists with USGS, joined the team. They are two of the foremost experts in wetland chronology and dating of geological profiles (e.g., Springer and Pigati 2022). They led the mapping stratigraphy and sedimentology of the sediments at an extremely fine resolution (centimeter to sub-centimeter) and measured the individual footprint horizons so they could be placed in a firm stratigraphic context (Bennett et al. 2021; Pigati et al. 2022a, 2022b, 2023). For dating, they used a combination of radiocarbon dating of organic matter, radiocarbon dating of pollen, and luminescence dating to establish the ages of the horizons that contain the human footprints and megafauna trackways.

White Sands has had the honor and privilege to work with the Pueblos and Tribes on whose homeland the park is located, through consultation and site monitoring. Many of the groups have relayed that they have oral histories of the great megafauna and words for them in their own Native languages. Many of these groups have an ancestral memory going back thousands of years. Representatives of several tribal Nations are actively participating in efforts to design interpretive trails and exhibit content within the park, and NPS works to facilitate tribal access to areas of White Sands. In 2023 a schedule of quarterly calls was initiated to bring Indigenous representatives and the footprint team together on a regular basis.

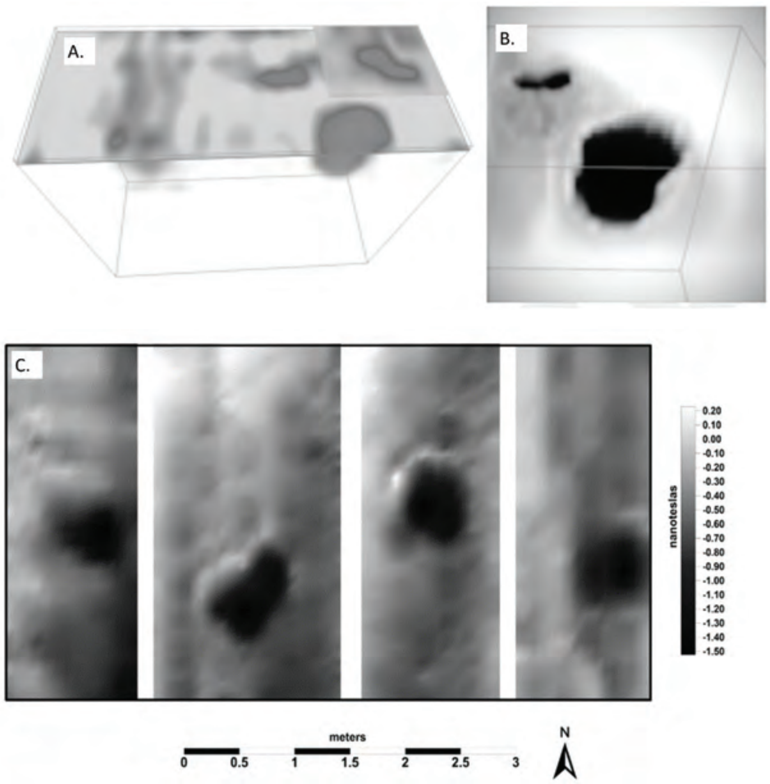


FIGURE 9. Tracking subsurface ghost tracks with GPR and magnetometry. (A) GPR amplitude slice (2.0 to 4.0 ns) of mammoth, human, and sloth prints. Giant ground sloth tracks that could not be seen at the surface are identifiable and were confirmed when the prints were excavated. (B) GPR amplitude slice (2.0 to 4.0 ns) of a mammoth and human. (C) Magnetometry of a mammoth trackway within the subsurface (adapted from Urban et al. 2018, 2019).

The new discoveries from this work and interest in the preservation of these fossil prints of international significance provided strong justification to support the legislation that redesignated White Sands National Monument as White Sands National Park in December 2019. Under this legislation, the park now seeks to "protect, preserve, and restore its scenic, scientific, educational, natural, geological, historical, cultural, archaeological, paleontological, hydrological, fish, wildlife, and recreational values and to enhance visitor experiences" (Public Law 111-11, Title VI, Subtitle D; Public Law 116-92, Subtitle E, Sec. 2851[b]). Through the new legislation, a permanent archaeologist and paleontologist are being hired for the park to carry on these efforts into the future.

CONCLUSIONS

Throughout the world, important discoveries of archaeological and paleontological resources are being found at an increased rate, while at the same time the stressors of climate change and other natural and anthropogenic factors are leading to rapid losses of paleontological resources and records of the early history of people including in the Americas. At White Sands, many of these discoveries are being made in pluvial systems (now dry lake beds), and the same processes that appear to have preserved these important records at the park also appear to have preserved early records at other pluvial systems around the world.

In the race to preserve early archaeological and paleontological records, White Sands is working with a core multi-disciplinary team of experts to refine a series of techniques to rapidly capture data from sites before they are lost. The park is also consulting with a wide range of Indigenous colleagues whose knowledge, when added to that of the core team, is producing a deeper understanding of the significance of the paleontological resources. White Sands can serve as an analogue for other Late Pleistocene sites around the world, and many of the techniques that are being developed for White Sands can be implemented at sites with similar preservation needs.

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