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STRUCTURE FROM MOTION PHOTOGRAMMETRY ENHANCES PALEONTOLOGICAL RESOURCE DOCUMENTATION, RESEARCH, PRESERVATION AND EDUCATION EFFORTS FOR NATIONAL PARK SERVICE AREAS

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Abstract—Structure-from-motion (SfM) photogrammetry is an increasingly common component of paleontological research and fossil resources management. The three-dimensional (3D) data and the derived products allow for novel and useful avenues to engage and problem-solve with park resource managers and stakeholders. The National Park Service (NPS) is developing a robust SfM program to support park units with resource documentation and monitoring efforts, training for staff, and building capacity for 3D data processing. We report on three case studies as examples where SfM techniques have been applied: 1) monitoring of paleontological localities; 2) documenting *in situ* fossil discoveries; and 3) digitization of fossil specimens in museum collections. The capacity within the NPS for photogrammetry to support paleontological research is also enhancing collaborative efforts resulting in new fossil discoveries in NPS areas. The case study for Curecanti National Recreation Area (CURE) is the design and testing of monitoring methods for paleontological resources subject to accelerated erosion due to reservoir management. The fossil locations at CURE are inundated by reservoir pool level changes, with loss of paleontological resources to erosion, burial and permanent submersion as the beach is reworked by wave energy due to fluctuating water level elevations. At Glen Canyon National Recreation Area a recently discovered track block with numerous vertebrate trace fossils was documented. The fossil tracks on the block appear on a bedding surface of a large vertically oriented fallen slab of Wingate Sandstone. Photogrammetry has enabled detailed 3D mapping and surface topology analysis of the slab, revealing in more detail the abundant theropod tracks and trackways. The digital nature of photogrammetric data also opens new avenues for engaging with scientists and the public. These data can be grouped into digital collections for showcasing a park's paleontological resources and are easily adapted for producing 3D replicas. Use of such models allows outreach to current and new park audiences and others who benefit from interaction with tactile elements. Rapid prototyping technology (e.g., 3D printing) employs newer materials and comes with lower costs when compared to traditional fossil replication methods. New applications for 3D data and SfM photogrammetry methods will continue to expand within paleontological research. The NPS continues to take positive strides to be at the forefront of developing SfM methods for paleontology.

INTRODUCTION

There are at least 276 units within the National Park Service (NPS) in which paleontological resources have been documented, representing a wide diversity of trace and body fossils of animals, plants, and other organisms (Santucci, 2017; Santucci et al., 2018). Some parks are expressly dedicated to promoting the preservation and study of paleontological materials, such as Dinosaur National Monument in Colorado and Utah. There are other units that include preservation of significant paleontological finds as part of their Congressional or Presidential mandate of park establishment, such as the recently re-designated (2019) White Sands National Park, New Mexico (previously a national monument) which has a wealth of Pleistocene trace fossils. In addition to these, there are parks where fossil discoveries are somewhat serendipitous, such as the large Triassic vertebrate tracks documented on historically quarried stones and incorporated into the construction of a bridge at Gettysburg National Military Park, Pennsylvania. Additionally, fossils from America's national parks can be found in the collections of most of the major museums within the United States, with special importance afforded the numerous holotypes (in excess of 2,300 specimens) derived from parks (Tweet et al., 2012, 2016). These also include fossils collected from those lands prior to the establishment of NPS status (Santucci et al., 2018) and specimens that have been obtained as part of various research efforts.

Photogrammetry literally means, measuring from photographs; digital imagery is used with structure-from-motion (SFM) and the two terms are used synonymously. The method creates an opportunity to expand the visibility of these non-renewable paleontological resources via electronic transfer of three-dimensional (3D) data. Transfer of 3D data allows researchers around the world to remotely access and study the actual specimens, or the juxtaposition of bone beds, or assess locality conditions such as erosion potential. Serial 3D investigations of sites allow comparison over time of changes to *in situ* fossils and their sites to help ascertain site and fossil stability, or loss through theft or other problems affecting those sites (Matthews et al., 2016).

The management of NPS paleontological resources also includes the conundrum of how to present material to researchers and the visiting public in such a way that facilitates engagement yet preserves the scientific integrity of specimens for future generations. Of the likely hundreds of thousands of fossils derived from NPS managed areas, a total including those on display, those held in collections, and those still *in situ*, paleontologists will only physically access a numerically small subset of these resources for study. The general public will see or interact with an even smaller fraction of this total. Moreover, there is also the need to address the loss of paleontological resources due to natural and anthropogenic causes (i.e., climate change, reservoir fluctuations), or to intentional damage (i.e., vandalism and theft). To engage with the scientific community and the visiting public, models or accurate copies are often utilized by the holding institution. Currently, model-making can be expensive and time-consuming, and not all fossil materials are amenable to traditional reproduction methods. These methods can include materials applied directly onto a fossil such as plaster of Paris, latex and resins, which may have deleterious effects on the original specimen. Additionally, some fossil materials, such as the late Pleistocene animal and human footprints found within playa lake deposits from White Sands National Park (Lucas et al., 2007; Bustos et al., 2018), cannot easily be cast without significantly altering or even destroying the original fossil in the process, even with the addition of consolidants.

Methodologies that generate 3D data and which do not require direct contact with the fossils include the use of x-rays, lasers and photographic "scanning" to document the structures, surface features and color of specimens. These techniques have become increasingly common within the paleontological research community (i.e., Bates et al., 2010; Cunningham et al., 2014; Mallison and Wings, 2014; Matthews et al., 2016; Sutton et al., 2016; Falkingham et al., 2018). Tomographic and laser scanning methods require specialized equipment to obtain data which are not always portable. Photogrammetric methods, namely those completed using digital cameras and specific software, have over the last decade become especially approachable as a field tool, as technology advances, prices drop in software, computational power of desktop systems increases, and inexpensive high-quality digital cameras have become more common (as forecast in Petti et al., 2018). Because of these changes, this equipment is now also more affordable and less technologically complicated (e.g., more user-friendly software options) for researchers and institutions.

Photogrammetric data in the geosciences can be both qualitative and quantitative in nature depending on the quality of the photography and precision of referencing. Quality data has even been obtained with a smartphone camera and processed to a 3D model using freeware (Micheletti et al., 2015). Time and again, studies have shown that systematic photogrammetric data collection can provide scientifically reproducible results for qualitative morphologic analysis and description (Petti et al., 2018 and references therein), and monitoring of *in situ* fossil specimens. The NPS Paleontology Program within the Geologic Resources Division has pursued photogrammetry to support geoscience and museum program efforts. In the realm of paleontology, these efforts are intended to enhance the mandated monitoring of paleontological resources through staff training and documentation at parks and museums. Included are collaborations with resource protection staff at parks as well as supporting the academic research community with imagery acquisition and 3D data products. Additionally, to better engage with park visitors and other members of the public, the derived 3D data can be shared remotely both as viewable models online, and as physical models (Wood and Santucci, 2014). Herein, we report on three case studies which demonstrate the above aspects and emphasize the process of data generation and the utility for derived products that meet NPS mandates and goals for the management of public fossil resources.

METHODS AND MATERIALS

Digital photogrammetry with use of consumer-grade digital photography equipment is also known as structure-from-motion (SfM) or computational photography. The range of applications that SfM-photogrammetry covers are becoming apparent and span the breadth of the geosciences. The greatest utility fall into the fields of geomorphology, specifically geologic hazards modeling and monitoring, and paleontology. There are numerous examples in paleoichnology (e.g., Falkingham et al., 2018), and morphometric and biomechanical analyses in fossil vertebrates (Giacomini et al., 2019; Miranda et al., 2019). The advent of what is being called differential, four-dimensional (4D) or change-detection, SfM-photogrammetry is of keen interest to resource management because of its use of temporally repeated datasets to ascertain change (Adams et al., 2010). The Geologic Resources Division has sought to provide national-level support to NPS units and regions, and non-NPS partners, for SfM-photogrammetry through the acquisition of equipment and software, while also providing knowledge, training and on-site assistance.

Image Processing/Software

We use the photogrammetric software from AGISoft, LLC, called Photoscan Professional, and known also (since version 1.5.1) as MetaShape Professional. This software is used to align images and generate high density point clouds, as well as for mesh and texture creation, and scaling. The software is also how larger 3D data projects are matched with geospatial information. Additional data review is completed with Applied Imagery's Quick Terrain Modeler (QT Modeler), which is a lidar exploitation software. Photogrammetric data can be rendered as a point cloud, like lidar datasets, which in turn allows for similar display and analysis. We use geospatially assigned point clouds in QT Modeler to assess slope and cross-section and, most importantly, detect change in temporally spaced data sets of the same locations.

Cameras and Associated Equipment

It has long been true that clear and well-placed photography is the principal element necessary for quality 3D data development with photogrammetry (Matthews, 2008). By this, we mean the quality of the images (i.e., exposure, clarity) and the pattern of photography needed to meet criteria (such as the image overlap) to allow the software to effectively match points (Mallison and Wings, 2014). To help meet the demands of image quality, over the course of this effort three different cameras have been used, all of which are single reflex, full-frame 35mm digital cameras with sensors in the 36 megapixel or greater range. These cameras are the Nikon-made D800, D810 and a recently acquired D850, all of which are considered consumer grade rather than the more expensive "professional" grade systems. The cameras are affixed with prime lenses. These include a 24mm f/1.4, a 28mm f/1.8 and a 105mm f/2.8; the latter was obtained for efforts in macro-photography. For objects greater than 5 cm on a given axis, we've used either the 28mm or 24mm prime lenses. Photography is accomplished in a range of light settings and has been completed with the camera handheld or mounted on a stabilizing fixture (e.g., tripod). These fixtures include a commercially available camera tripod and a camera-mast that is essentially a telescoping pole capable of extending to 8 m (Fig. 1A). The camera-mast was acquired to elevate the camera for imaging areas on the ground, as an alternative to unmanned aerial systems (UAS, also known more commonly as drones) which are restricted in NPS-managed areas (Rossi, 2017). Additionally, the camera-mast is easily adjusted; thus, an elevated position can be chosen to provide better overall image geometry for vertically oriented surfaces such as large track-bearing slabs that have fallen from the source bedrock (Fig. 1B; e.g., Francischini et al., 2019).

Scale and Spatial Data

The second most important aspect of SfM-photogrammetry for science applications, and the part that makes it a tool for both quantitative and qualitative assessment, is scale. We employ two methods depending on the overall extent of what is being photographed. The first is a local scaling which is completed with the use of control sticks and is used on all projects (Fig. 2A). These are essentially rulers in a range of precisely known lengths, with machine-readable targets printed on them. The distance between targets is constrained to values with errors of ± 0.05 mm or better. Control sticks are placed within the area to be photographed but do not need to be in every image for alignment purposes (Fig. 1B). They should however be arranged evenly, and ideally distributed throughout the area to be photographed. We consider three control sticks to be the minimum number for a project but will place five to six per project area. This ensures a level of redundancy should a scale bar be accidentally bumped or moved during photography. This source of error has occurred where controls have moved imperceptibly due to human blunders (being brushed with clothing) or even wind. The machine-readable targets utilized on our scales are supplied with the MetaShape/PhotoScan software package.

High-precision control sticks are not only important in providing scale but are also needed by the photogrammetry software to solve for the optical properties of the lens and camera. This reduces errors and pixel coordinate placement within the point cloud. We utilize photogrammetry controls with a degree of environmental stability, and therefore are minimally responsive to expansion from moisture or thermal effects (Malesa et al., 2013; Usamentiaga et al., 2017). We print the control information on sheets of Dibond®, an aluminum composite material with a plastic (polyethylene) core. The material can be printed with photographic ready artwork: a template of controls, originally developed by staff at the Bureau of Land Management and modified in Adobe Illustrator to create a design for our needs with the machine-readable targets. We have also used scales made from a plastic card stock which have non-coded but machine-readable cross-style targets on both sides, and which are useful for photography of museum specimens when precisely calibrated (Fig. 2A).

The key aspect of the required scale in photogrammetry is the precision of the measure on the control stick. For our uses, a previously measured standard (or base) set of scale bars and an independently calibrated control are used to then calibrate all subsequent controls sticks. This is simply done by photographing the new control sticks and the base set together, and then processing like any other photogrammetry project with both the known and unknown controls within the model. The photogrammetry software will calculate the distances between targets on the new scales and provide an error estimate. The independent control, which was also photographed as part of the model, is then used to verify the fidelity of the measures calculated from the software.

In addition to the above scaling method, we employ a Global Navigation Satellite System enabled global positioning satellite (GPS) system to determine geospatial coordinates for locations within a project. The criteria for the size threshold are somewhat subjective, but the GPS system is employed on projects when area is measured in the tens of meters (long axis of project area). The dataset for spatial coordinates is completed with the placement of ground control points (GCPs), which are features visible within the photography of a project area, or by recording the camera locations. We consider four GCPs to be the minimum for any project and will frequently exceed this as

FIG. 1. (**A**) Using the camera mast to photograph from an elevated position to document areas on the ground. With unmanned aerial systems restricted in National Park Service areas, this method allows for systematic low-altitude aerial imagery. (**B**) Using a camera mast to capture imagery nadir to a vertically oriented surface to ensure photograph overlap and proper spacing for a 3D model. Note the scale bars (white rectangular objects) on the surface of the track block.

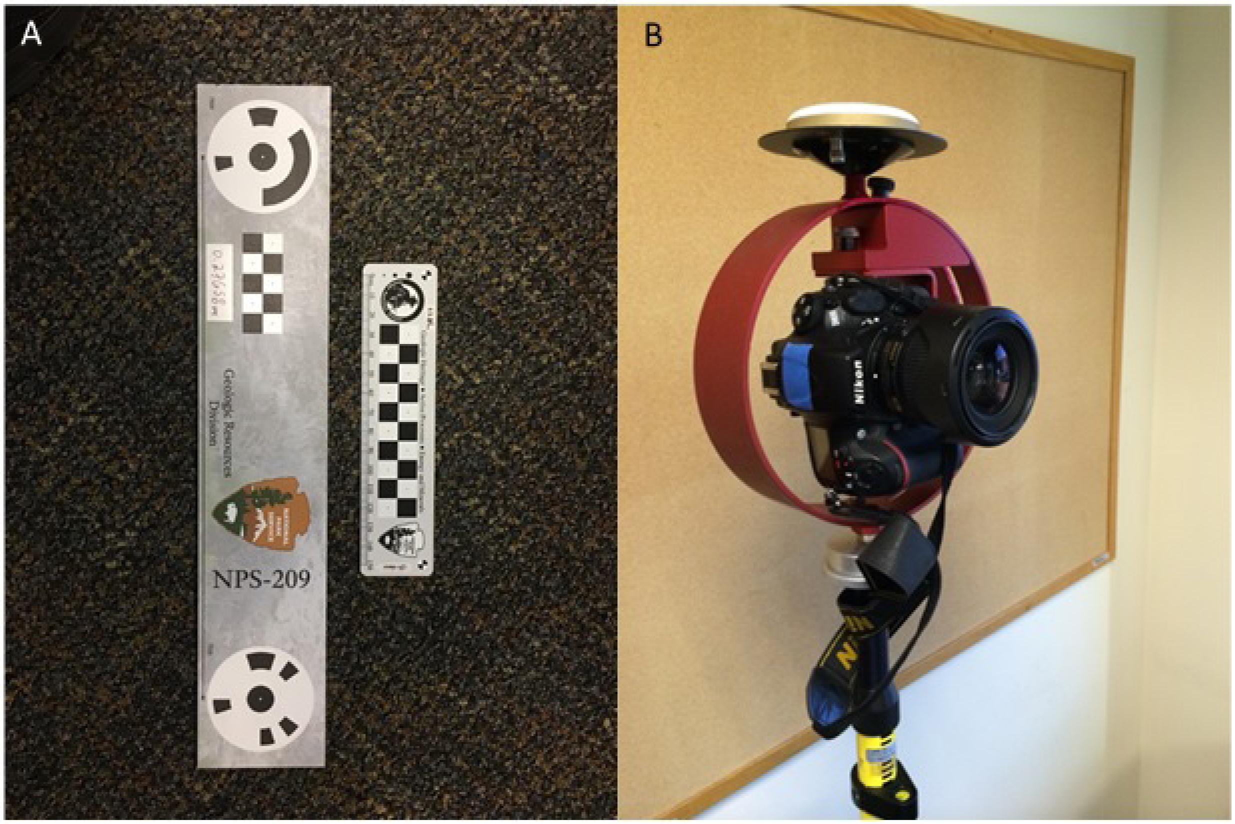

Fig. 2 – **A**) Examples of scales for use with SfM photogrammetry. The larger one, approximately 30 cm long is made from an aluminum-polymer composite material. The smaller one is 15 cm long and is printed on plastic card stock. The distance between targets at each end are precisely known, down to the 1/100 mm. **B**) Using a gimbaled camera mount allows for the focal center of the camera to remain in-line with the axis of the GPS receiver. Here we have an external antenna mounted on the top of the camera gimbal.

more points provide a better margin for errors with GPS signal strength or changes in satellite count. The GCPs can be the targets on a scale bar when used in combination with scaling, or a marker of some sort that is visible within the photography. PhotoScan/MetaShape also allows the user to assign the spatial coordinates to the position of the camera/photograph. We have used both methods (GPS on GCP or on the camera), and for improved camera placement have built a gimbaled mount with an external GPS receiver antenna over the focal plane of the camera (Fig. 2B). Using a geospatial oriented SfM-data set allows for creation of measured cross-sections and improves on differential or 4D types of analysis (Cucchiaro et al., 2018).

Model Generation, Data Rendering and Archiving

Photogrammetry data can be used as the basis for 3D printable solids and visualization of objects on several cloud-based or shareware platforms. To this end, we rely upon partners for final model hosting or 3D printing services. These services for viewing 3D models are not the archival home for data; archiving is met internally within an NPS system, the Integrated Resource Management Application (IRMA) database. This database platform allows for storage of imagery and the derived products of the photogrammetric data. It is also a secure repository for those projects related to ongoing research while also capable of providing public access. Access can be controlled; much of the paleontological photogrammetry data generated is restricted due to the innate commercial value and it often has location data associated. The latter restriction is justified by compliance with the Paleontological Resources Protection Act of 2009. Those data without location data are accessible for those with non-commercial interests. IRMA is not a data viewing system, which is why we draw on commercial platforms such as SketchFab.com or have partnered with the Smithsonian's 3D Digitization Branch to present 3D data as visual media to the public. Likewise, we have chosen to partner with commercial 3D printing services. The technology of 3D printing is still evolving rapidly in the resolution of prints, the materials available and in costs of print media and the printers. Outsourcing the 3D printing capacity allows for flexibility in end-product and in the available range of materials, and in turn allows us to focus our efforts on data capture, analysis and interpretation.

CASE STUDIES AND DISCUSSION

Case Study #1 - Shoreline locality Monitoring of Paleontological Resources

Curecanti National Recreation Area (CURE), located along the Gunnison River in southwestern Colorado, USA, is an NPS unit composed of three reservoirs and the lands surrounding them: Blue Mesa, Morrow Point, and Crystal reservoirs. To manage these resources, reservoir levels are controlled by the Bureau of Reclamation with regards to water delivery for irrigation and other downstream uses, whereas recreation and conservation aspects are coordinated by the NPS and Colorado Parks and Wildlife. Resources within the park boundary include the river and reservoirs proper, fish and wildlife therein, and diverse archeological and paleontological resources.

Along the shores of Blue Mesa Reservoir, the largest of the three lakes, rocks of the Upper Jurassic Morrison Formation are exposed, showing distinct fluvial facies. These outcrops are fossiliferous with vertebrate remains and ichnofossils. To date, there are 15 vertebrate fossil taxa known from these sites (Koch et al., 2006; Santucci et al., 2009; Foster et al., 2015), including dinosaurs, pterosaurs, other reptiles and mammals; some can be identified to genus and species, whereas others are represented by fragmentary bones and teeth. These specimens fill in a geographic gap in the known distribution of certain Late Jurassic taxa of mid-continent North America. The fossil-bearing layer at one site (referred to as South Beach; Foster et al., 2015) is a sandstone and sandstone-conglomerate mix occurring along the reservoir shore and represents a fluvial deposit; it is presently eroding into the lake, with erosion exacerbated by water level fluctuations. Vertebrate fossil fragments, both loose and in matrix (some present in blocks larger than 0.5 m^3), are scattered downslope on a wave-terraced shoreline originating from a ~3 m bluff. The other site, across the reservoir (referred to as North Beach; Foster et al., 2015), may be a stratigraphic continuation of the South Beach site due to similar lithologies and fossil specimens, as well as position (elevation and relative orientation to South Beach).

Dynamic hydro-geomorphological processes affect shoreline erosion in lakes and reservoirs. When these processes intersect fossil localities, as they do in Blue Mesa Reservoir, there is added concern for the loss and degradation of these valuable paleontological resources. Minimum and maximum pool elevations of Blue Mesa Reservoir have varied from 2,264 to 2,292 meters above sea-level since dam closure and initial filling in the mid-1960s. This fluctuation variously inundates or exposes a considerable portion of both paleontological localities. Both sites consist of a headwall and an eroding talus slope that continues beneath the water and is affected by wave energy in the water elevation fluctuation zone. Wave energy can be substantial: strong westerly winds are common with a fetch of 2–3 km that can generate waves of 1 m during storms; in winter ice cover prevents wave action but ice scour occurs along shoreline benches.

As a result of wave activity, active erosion occurs along the base of each slope on a seasonal basis, water elevation-dependent, which transports sediment offshore. Shoreline erosion dynamics can be described as a generalized cyclic pattern of erosion: loss of sediment occurs at the slope base due to wave energy and is transported offshore, which in turn increases the angle of repose. This is followed by downslope sediment movement along this now steeper slope, thus triggering a sequential series of upslope migrations from the increased angle of repose. This migration upslope ultimately reaches the bluff where it undermines the integrity of the headwall, resulting in slumping of new sediment onto the slope. The cycle then repeats, ultimately leading to landward migration of the slope. This wave-induced erosion at the slope base moves material from the site and redeposits it within the reservoir. Slumping of the fossiliferous headwall buries previously exposed fossils while potentially exposing new ones. These dynamic changes are discernable as wave terraces or beach ridges which are present at both sites. These forms (e.g., size and shape) reflect the wave hydrodynamics occurring during the incremental drawdown events at the slope-water interface and are common in reservoir systems (Joeckel and Diffendal, 2018).

Because of water regulation of Blue Mesa Reservoir, water level fluctuations not only affect erosion along reservoir slopes, they also create cycles of seasonal inundation and desiccation. This wet-dry cycle may be particularly problematic in winter or periods where daily temperatures fluctuate above and below freezing, contributing to the weathering of exposed fossils (Santucci and Koch, 2003). These effects are likely a minor contribution to fossil resource loss compared to the impacts of reservoir water elevation variability.

To better understand the effects of reservoir elevation variations, test the potential for monitoring fossil resources along the shoreline, and validate the inferred slope and sediment transport mechanisms, photogrammetry was used to document the two fossils localities. Photogrammetry has been shown as a possible method for monitoring erosion on short time scales (<5 years; Balaguer-Puig et al., 2017). Modeling the ground surface though a comparative albeit qualitative method has the potential for identifying zones of deposition and erosion resulting from wave action. Using photogrammetrically derived point clouds obtained in 2016 and in 2019 (Fig. 3A) of the ground surfaces, these data are compared using functions within QT Modeler software for change detection. The results from the two compared data sets for North Beach are colorized on a scale from red to blue (Fig. 3B). Areas of yellow to red are associated with sediment aggradation on the beach/slope. The colors green to blue are associated with degradation. The analysis shows alternating zones of aggradation and degradation from the lower to upper portion imaged on North Beach. A similar pattern of terrace formation and erosion is also apparent for South Beach. The color range of Fig. 3A is 2 m; however, changes for the most part have occurred on the cm-scale, although large blocks of stone (~0.5 m on the long axis) have been wedged from the bedrock and show the greatest beach elevation change. In areas of aggradation, several previously observed fossil specimens on the slope were buried under more than 10 cm of sediment, and in degradation areas, specimens are missing and have not been recovered. This cm-scale magnitude change has been difficult to quantify with traditional beach profiling methods but is within the realm of detection using photogrammetry.

These early results suggest that monitoring at these sites should attempt to understand the dynamic natures of both the shore and the fossils in order to develop science-based management practices for the preservation of significant paleontological resources. At a macro level, using a combination of photogrammetry and GPS, monitoring will define the nature of the site-scale changes relative to aggradation and degradation processes occurring at both upslope and downslope portions of the slopes, as well as the fate of known fossils occurring at each locality. How do the slopes change? What is the movement of fossils horizontally and vertically? How many become buried or new ones become exposed annually in this dynamic system? Finally, how many are lost annually into the deep water of the reservoir? At a micro scale, photogrammetric monitoring will help elucidate the integrity/condition of fossils through time providing insight into understanding the rate at which exposed fossils degrade at these localities. With that understanding, we will further attempt to understand how water level fluctuations affect these significant paleontological resources at both scales.

Case Study #2 - Analysis of Fossil Vertebrate Tracks at Glen Canyon NRA

The shores of Lake Powell in GLCA, like the scenario at CURE, are defined by the pool elevation of reservoir water, here behind Glen Canyon Dam. The reservoir was created within Glen Canyon of the Colorado River in Utah and Arizona, which is a steep-walled bedrock canyon dominated by thick sequences of red-colored sandstones. The dam was closed in 1963 and reached full pool in 1980. Trace fossils are common on the bedding surfaces of the Wingate Sandstone (Late Triassic-Early Jurassic), Kayenta Formation (Early Jurassic), Navajo Sandstone (Early Jurassic-Middle Jurassic), and Page Sandstone (Middle Jurassic), all key geologic strata in the park (Lockley et al., 1998, 2013; Kirkland et al., 2010, 2011; Santucci and Kirkland, 2010). Lake level variation within the reservoir affects localities where tracks can be submerged. Moreover, the remoteness of the area makes access to paleontological sites difficult for researchers and problematic for protection. These factors underscore the importance of photogrammetry as a means for documenting and remotely assessing information derived from those locations. On the other hand, boat traffic fosters access to some paleontological resources in the park (i.e., Delgalvis, 2015) and makes track and (lesser known) bone sites into interesting diversions for curious visitors. While vandalism and theft may

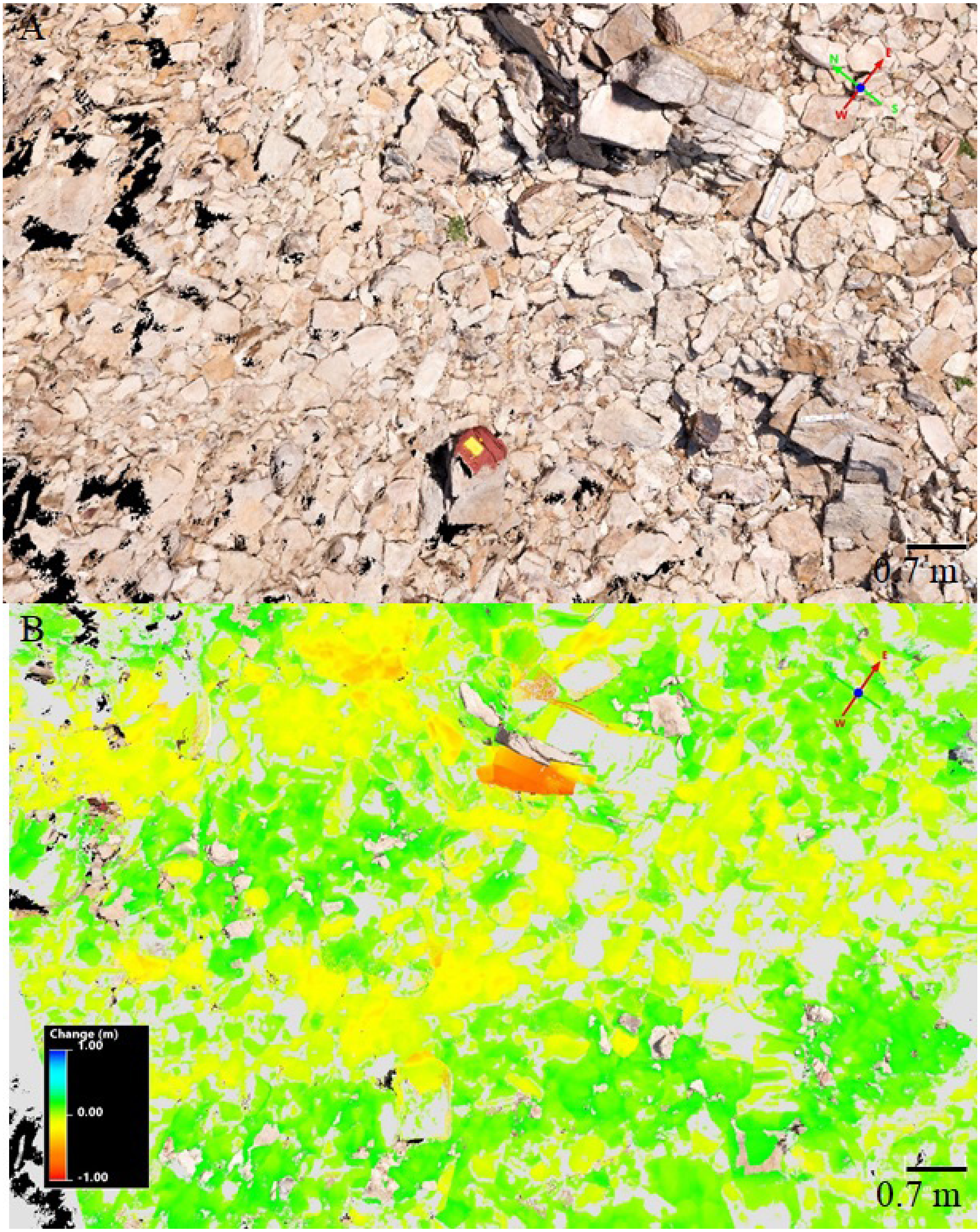

FIGURE 3. A) Natural light point cloud ortho image of North Beach at CURE derived from imagery obtained in 2019. Scale bar lower right is 0.7 m. The beach is characterized as a cobble and boulder talus slope. B) Colorized heat map of the same section of North Beach as (A). The areas of yellow to red are associated with aggradation (deposition) of material on the slope and the areas of green to blue are areas of degradation (erosion). This banded pattern is associated with the changing position of the swash from waves, reworking the beach materials as reservoir pool elevation changes.

occur, the primary concern is the wear and tear from visitation in areas not often monitored by resource or law enforcement staff, once paleontological localities are known. The monitoring of important sites above highwater is a primary objective for photogrammetry. In the cliff-dominated topography of much of the shore, the immensity and inaccessibility of difficult-to-reach track blocks can prove prohibitive to traditional means of paleoichnological analysis. SfM can be employed to document and study these sites.

In March 2017, a large, vertically orientated sandstone block with numerous tracks was reported by a park visitor. This block, termed the "Little Cave Cove" track site (locality number GLCA 377), is an 11-meter-tall float block of Upper Triassic–Lower Jurassic (Rhaetian–Hettangian) Wingate Sandstone within a steeply sloping scree field derived from a large rockfall. It is apparent that the block was part of a larger boulder that fell from the overhead cliff and then sheared along the bedding plane on impact. The block came to rest with the track-bearing, originally horizontal bedding plane oriented in a nearly vertical position. The counterpart block came to rest on the slope below the vertical slab, with the other materials of the rockfall forming a talus cave. The ceiling of this small cave shows the corresponding mold tracks from the upright block. The upright block was chosen as part of an investigation of several new reported track sites and fossil locations during 2018.

Because the near vertical orientation of the track surface makes it difficult to document the tracks and trackways properly using traditional methods, the track-bearing surface was resolved using photogrammetry. This was completed using a camera mast and taking images nadir to the surface. The visible vertical surface displays a total of 102 natural cast tracks in at least 13 identifiable trackways (Fig. 4). All tracks and trackways are attributed to theropod dinosaurs. Several trackways display different and distinct track morphologies and behavioral implications, yet they are all associated together on the same bedding surface. Additionally, some trackways were present on at least one bedding surface stratigraphically above the principle track horizon on this block. Additional beds are observed above, and below the track-bearing surface that preserve crinkled bedding, which suggests the presence of microbial mats (Noffke et al., 2001). Similar bedding surfaces were observed in the cliff face above, suggesting the potential original stratigraphic position of the track horizons.

Trackways on the surface were produced by small- to medium-sized theropod dinosaurs. Some are attributed to the ichnogenera *Grallator* and *Eubrontes* respectively. Trends of trackway directions appear to be random, although some trackways do suggest preferred orientation and possible gregarious behaviors; however, this is beyond the scope of this report. Two parallel wide-gauge trackways produced by a medium-sized theropod (cf. *Eubrontes*) have elongated metatarsal impressions and inward track rotation (Fig. 4, T1–T2; average track length including metatarsal = 60 and 71.5 cm and average track width = 27 and 24 cm respectively). These trackways may represent animals moving down a wet, slippery, and sandy slope. Trackways that tend to be of a wider-gauge (average trackway width for T1–T2= 61 and 68 cm), in association with long metatarsal traces, suggest animals that moved across slippery (induced microbial mat) surfaces (Wilson et al., 2009). In combination with other characteristics, inward track rotation behavior may suggest animals that were moving downslope or sinking into deeper sediments, however this cannot be determined since the track surface size is too small and are situated on a fallen block. Three theropod trackways (Fig. 4, T3–T5) of similar size and track depth (average track lengths = 50, 61, and 46 cm; average track widths = 33, 23, and 20 cm) have shorter metatarsal traces (or none preserved), and traveled more or less in the opposite direction to T1 and T2. These trackways do not display inward track rotation and have narrow-gauge trackways (T3–T5 average trackway width = 48, 55 narrowing to 33, and 46 cm), yet the track producers would have been similar in overall size to the producers of T1 and T2. The production of these shallower tracks (T3-T5) could be the result of a firmer substrate when compared to trackways 1 and 2.

Two shallow theropod trackways (Fig. 4, T6–T7) also produced by medium-sized theropods under natural light superficially resemble the ichnotaxon *Kayentapus*, based on narrow digits paired with wide digit divarication angles, (Piubelli et al., 2005; Lockley et al., 2011). However, using photogrammetry, we are now able to identify them as *Eubrontes*. (Note that some authors do not consider *Kayentapus* to be a valid ichnotaxon, e.g., Olsen et al., 1998). Photogrammetry shows morphological details in the tracks and trackways that would not have been recognized otherwise from field measurements. These well-preserved trackways are oriented in nearly opposite directions and display additional variations: toeing-inward in possible down-slope direction like trackways 1 and 2; and some tracks in trackways 6 and 7 show three sub-parallel digits with somewhat swim track-like morphology (see Milner and Lockley, 2016 and references therein). Additionally, some of these tracks appear more elongate due to digit drag marks as the feet were withdrawn from the substrate.

Two other trackways on the block (Fig. 4, T8–T9) show tracks similar to *Characichnos* (i.e., true swim tracks; Whyte and Romano, 2001; Milner et al., 2006; Milner and Lockley, 2016), which suggests the track-bearing surface may have been submerged to a substantial water depth prior to complete burial of the surface. These trackways show mostly single digit traces, although some in trackway 9 registered double and triple subparallel digit traces, with digit III always being the deepest and longest. Again, these trackways were produced by medium-sized theropods that would have been similar in size to producers

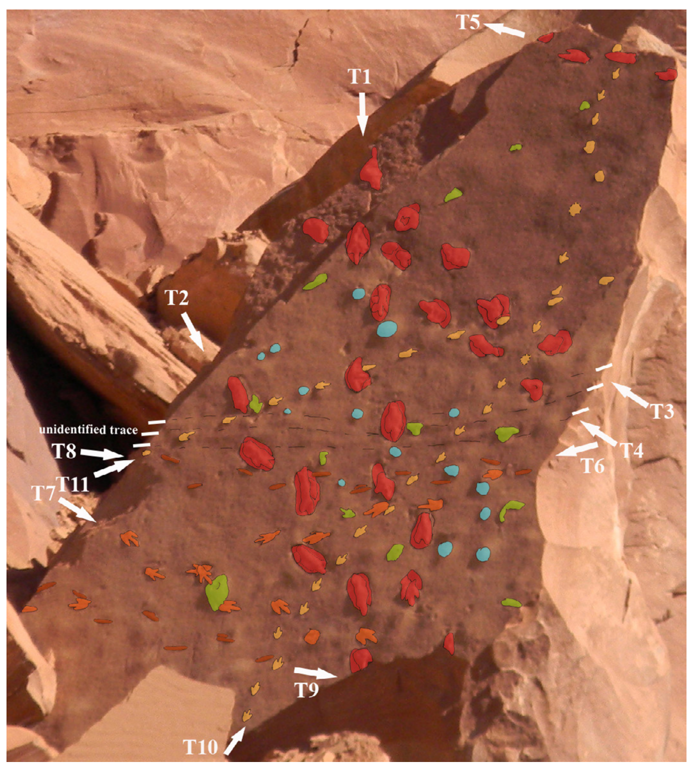

FIGURE 4. Track map of the Little Cave Cove block, derived from photogrammetric data. Trackways are denoted alphanumerically such as T1, T2, etc. and are referred to in the text. Note that the tracks of T1 are on a different bedding plane than the remaining traces (T2-11).

of trackways 6 and 7 (average trace lengths for T8–T9 = 23 and 28.5 cm respectively). We infer these animals had inward track rotation and likely represent partially penetrative tracks from a higher bedding surface that were produced in a similar manner as trackways T1–2 and T6–7. This hypothesis rules out formation of trackways 8 and 9 as the result of swimming, although some tracks are morphologically similar in appearance.

Finally, smaller coelophysoid track-producers registered at least two trackways on the block (Fig. 4, T10–T11). The longest trackway (T10) we identify as *Grallator*. Again, due to the shear face of the block in order to examine tracks closely, and limitations from natural lighting, photogrammetry allowed for proper identification of the track type. This long trackway, measuring some 10 meters in length, is somewhat meandering and consists of 25 footprints. The track-producer made slight directional changes with adjustments in stride, pace, and trackway width. A second *Grallator*-like trackway (T11) with 11 tracks is narrow-gauge and in a straight line, typical of most *Grallator* trackways.

A key aspect to note here: Tracks that were very difficult to identify using natural light have now been positively identified to the ichnogenus level through 3D manipulation, which brings out morphological details. The 3D data has led to a more complete map of the track block surface and more accurate measurements than what could be accomplished and measured or mapped at the tracksite.

Case Study #3 - Use of 3D Data for Enhanced Visitor Engagement and Outreach

The 3D data derived from SfM-photogrammetry can be used to make reproductions using rapid prototyping methods (Wood and Santucci, 2014; Wilson et al., 2017), or displayed online to create a virtual museum (Rahman et al., 2012; Cunningham et al., 2014). Additionally, the tactile nature of 3D objects provides for improved engagement and especially for visually impaired persons (Wilson et al., 2017). Public engagement through 3D printing and virtual models seems to be a logical choice. New 3D printer technology continues to become increasingly affordable, such that universities, schools and individuals are buying them and in turn seeking out, creating and modifying 3D data for pedological enhancement (Ford and Minshall, 2019). Collating 3D data into factual assemblages, known as virtual museums, allows for a novel approach to curating materials that are too delicate to otherwise display or even handle.

We created a virtual museum to showcase the paleontological resources of Grand Canyon National Park (https://www.nps.gov/articles/series.htm?id=A9E62040-AC6F-A6D7-BE564A036F1D6146 and accessed March 3, 2020). This collection of 3D data is centered on external morphologies of fossils from photogrammetry; however, it is the detail that is most approachable to the general public. This initial collection was derived from a selection of fossils, including two that are *in situ*, 12 from the park's museum collections and one fossil on loan from the Smithsonian National Museum of Natural History. This collection sample included vertebrates, invertebrates, ichnofossils, and plants, and was chosen to be representative of park major fauna and flora of the Paleozoic and latest Cenozoic. The models provide a rich media element to embed into a webpage with descriptive text that draws on information from published research and is related in clear, jargon-free language. Although this digital data is memory intensive, the versions available via the hosting service are degraded to promote rendering. The high-quality 3D data are archived on the IRMA data repository and are available for staff and researchers. There is also a public-facing entry for discoverability of data for non-NPS affiliated scientists or other stakeholders. The debut of the virtual museum was part of the 2019 National Fossil Day Celebration held at Grand Canyon National Park, which was also part of the centennial celebrations of the park. This event had staff on hand at the park to engage visitors, but also relied on photogrammetry data to showcase fossils from the Park's and the Smithsonian's collections made at the park.

We have made several prints, including tracks, scale-models of trackways and vertebrate and invertebrate remains, using them for public engagement and even as a tactile element within a display at a park museum (Wood et al., 2018). A skull of the Pleistocene vampire bat *Desmodus stocki* (NMNH 25478) was rendered as a 3D print at life scale and at 8-times scale (Fig. 5). To obtain the prints, we relied on a contract service to create the 3D models from the photogrammetry data. This important fossil was recovered from Rampart Cave during the 1930s. It has been housed at the Smithsonian collections since it was collected and has never been on display. As a 3D print, the fossil is now available for park staff to engage visitors about the animals that called the Grand Canyon home during the Pleistocene. This print was featured at the 2019 National Fossil Day Celebration. Ultimately, making 3D printable data available for the scientific community to access, furthers collaborations, reduces cost of reproductions and improves security of rare specimens or holotypes.

CONCLUSIONS

Photogrammetric methods are expanding opportunities for documenting and monitoring paleontological resources. The resulting 3D data have utility for improving engagement with members of the visiting public of national parks and enhancing scientific research of the rich paleontology found there. The range of photogrammetric applications within the geosciences is increasing rapidly, and photogrammetry is having profound effects for detecting changes, analyzing novel fossil finds and sharing data within the field of paleontology.

The changes at CURE are problematic for the preservation of shoreline fossil localities. The major observation from the photogrammetry-based differential analysis is that shore terrace formation and erosion, and talus re-working, are originating through changing wave-energy position as reservoir pool elevation fluctuates. The variable action is removing *in situ* materials into deeper water over time. Although what we present here is preliminary data, it is revealing changes in the shore area of the reservoir that likely were not detectable with shore profiling methods using only GPS. The cm-scale changes in the differential model are below the resolution of most GPS systems other than highly precise real-time kinematic systems. These real-time systems tend to be expensive and require experienced surveyors to operate. The photogrammetry used GPS as a means to geolocate the whole dataset, but this analysis relies also on the control sticks to detect and precisely quantify the observed changes. Additional analysis of the data from North and South beaches is warranted, as is a longer-term monitoring plan that uses the photogrammetric method linked with GPS.

Monitoring of trackways with photogrammetry is a proven method (e.g., Falkingham et al., 2018). Generally, photogrammetric documentation complements the traditional methods of paleo-ichnological analysis. Assessing vertically oriented blocks with tracks on their surfaces, however, is difficult with traditional means and likely near impossible in remote areas, like the canyons of Utah's national parks and monuments. An excellent example of this, as discussed above, is the "Little Cave Cove" track site. This enormous, vertically oriented slab is spectacular to view in natural light; however, it would prove to be a difficult challenge to study without the use of photogrammetry. As a result of photogrammetry: (1) fossil tracks and trackways can be accurately mapped and measured which proves extremely difficult to do in the field; (2) correct track morphologies are more recognizable unlike viewing in natural lighting conditions, therefore resulting in proper ichnotaxonomic identifications;

Fig. 5 - 3D data, once prepared for printing, can be rendered at any given scale. This bat skull was created with a 3D printer at larger than life (~8x). Inset shows the actual size of the fossil and showcases the detail that 3D printers can render for scientific model making. NPS images by JP Hodnett.

and (3) tracks and other sedimentary structures that were not visible at the site can now be readily seen and identified.

The 3D data that comes from these scientific studies can also be transformed into media for the visiting public of NPS managed lands. It is also a valuable tool for engaging with those who may not be able to visit parks. Additionally, digitizing interesting and scientifically important fossils from museum collections democratizes these holdings for the general public and scientists. For the public, this is a new avenue for learning and engaging with science. For the scientist, dissemination of digital copies of a novel specimen can provide consensus on identification and foster collaborations over distance (e.g., Cunningham et al., 2014). The National Park Service is in a unique position for collaborations in the future that involve park managed paleontological resources and leveraging digital resources for the advancement of science and public access.

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DISCLAIMER

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