Beyond the Square Hole

Application of Structure from Motion Photogrammetry to Archaeological Excavation

Charles W. Koenig, Mark D. Willis, and Stephen L. Black

In archaeological excavations, two of the most critical pieces of information we record are the three-dimensional (3D) context and provenience of artifacts, samples, features, excavation units, excavation layers, and, in some cases, sites themselves. Accurate and precise recording of these data is imperative because spatial data become the core dataset from which archaeologists begin analysis and interpretation. The standard procedures for how we collect these data have remained largely unchanged for decades, particularly in North America, and especially in cultural resource management archaeology (exceptions for sites with architecture and stark stratigraphy notwithstanding). To document 3D information, the standard methodology is to: (1) establish site datums and

ABSTRACT

The accurate and precise collection of three-dimensional (3D) context and provenience data is of critical importance for archaeologists. Traditional square-hole methods are being augmented by new digital techniques to increase the accuracy and precision with which 3D data are collected. Structure from Motion (SfM) photogrammetry is an emerging digital technique that is becoming more widespread for collecting 3D data of archaeological sites and features. We are using handheld digital cameras and ground-based SfM to record accurate and precise 3D context and provenience data at the scale of the excavation unit and profile during rockshelter excavations in the Lower Pecos Canyonlands of Texas. By combining SfM with traditional excavation methods, we collect 3D data on excavation units, layers, features, and profiles without excavating in grid-bound square units. SfM provides a straightforward and flexible method to excavate based on the stratigraphy and logistical pragmatics, which further aids in assigning precise context and provenience to recovered artifacts and samples. This article describes how ground-based SfM serves as a basic recording tool during excavation and shows that, by applying ground-based SfM methods to excavation, archaeologists can collect more, and more accurate, data than with traditional square-hole methods.

La colección exacta y precisa del contexto y de los datos de procedencia en tres dimensiones (3D) de objetos y rasgos es de importancia crítica para la arqueología. Los métodos tradicionales a base de unidades cuadradas están siendo aumentados por nuevas técnicas digitales que tienen el objetivo de mejorar la exactitud y la precisión con las que se recogen los datos en 3D. La fotogrametría de estructura a partir del movimiento (Structure from Motion; SfM) es una técnica digital emergente que está cada vez más generalizada para recoger datos en 3D de sitios y rasgos arqueológicos. Utilizamos cámaras digitales portátiles con SfM terrestre para registrar los datos en 3D exactos y precisos de contexto y procedencia a la escala de la unidad de excavación y del perfil durante las excavaciones de abrigos rocosos en los cañones del Lower Pecos, Texas. Mediante la combinación de SfM con los métodos de excavación tradicionales, recogemos los datos en 3D de unidades de excavación, capas, rasgos y perfiles sin excavar en unidades limitadas por una cuadricula tradicional. La SfM proporciona un método sencillo y flexible para excavar basado en la estratigrafía y las consideraciones prácticas, lo que ayuda aún más la asignación de contexto preciso y procedencia a los materiales culturales y muestras recuperados. En este artículo se describe como la SfM terrestre sirve como una herramienta básica de grabación durante la excavación, y como por medio de la aplicación de métodos de SfM terrestre a la excavación, los arqueólogos pueden recoger datos más abundantes, y más precisos, de lo que se puede recoger con los métodos tradicionales usando las unidades de excavación cuadradas.

Advances in Archaeological Practice 5(1), 2017, pp. 54–70

DOI:10.1017/aap.2016.8

create a measured, usually arbitrary grid; (2) establish square excavation units (traditionally 1 × 1 m); (3) excavate these units in arbitrary levels (often 5 or 10 cm thick); (4) use string and a line level and/or a total data station (TDS) to record the elevation of artifacts, samples, and the final excavation level floor within each unit; and (5) create measured illustrations on graph paper showing artifact locations, prominent features, and stratigraphic interfaces within each excavation level (see Kelly and Thomas 2013:81–89). This is a tried and true approach—one that will continue to produce quite serviceable archaeological data and remain appropriate in many settings. New digital documentation techniques and technologies, however, are helping archaeologists to move beyond the square hole. Structure from Motion (SfM) photogrammetry (Agisoft LLC 2014, 2015) is one of these technologies and is an emerging technique for collecting 3D data and producing highly accurate and precise 3D maps and orthophotos of archaeological sites and architectural features at a fraction of the cost and time of lidar and TDS mapping (e.g., Green et al. 2014; McCarthy 2014; Verhoeven et al. 2012; Willis et al. 2016). This article serves to further the application of Structure from Motion (SfM) photogrammetry to excavation and demonstrates the feasibility and suitability of using ground-based SfM for 3D data collection and documenting archaeological excavations.

Ground-based SfM is a method for collecting 3D data from surfaces using a handheld digital camera. De Reu et al.'s (2013, 2014) recent articles demonstrate the effectiveness of combining ground-based SfM with traditional excavation methods for collecting precise 3D data at the scale of the excavation unit and profile. As part of the Ancient Southwest Texas (ASWT) research project, we are conducting a multiyear investigation of several rockshelter sites in the Lower Pecos Canyonlands of Texas (Figure 1). Because of the challenging and complex cultural and natural stratigraphy often housed within rockshelters (e.g., Farrand 2001), we began using ground-based SfM as one of the core methodologies of our excavation strategy. By combining SfM with our traditional excavation methods, we collect and maintain precise 3D provenience on all excavation units, layers, and profiles without excavating in square units. SfM provides us the flexibility in documentation to be able to excavate based on the rockshelter stratigraphy, which further aids assigning context and provenience to subsequent artifacts and samples.

This article has four main objectives: (1) briefly review SfM and examples of how archaeologists have applied the technique; (2) introduce ground-based SfM for the field archaeologist; (3) describe how ground-based SfM can be used as a basic recording tool during excavation, using our ASWT investigations as a case study; and (4) argue that the application of ground-based SfM methods to excavation provides a viable way for archaeologists to spend less time while collecting more, and more accurate, data than traditional square-hole methods.

ONGOING INVESTIGATIONS OF SEVERAL ROCKSHELTER SITES IN THE LOWER PECOS CANYONLANDS

Situated around the confluence of the Pecos and Rio Grande Rivers, the Lower Pecos Canyonlands of southwest Texas and northern Mexico (Figure 1) is one of the most distinctive archaeological regions in North America (Turpin 2004:266). Physiographically and ecologically, the Lower Pecos is located at the junction of the southwestern edge of the Edwards Plateau, the eastern edge of the Chihuahuan Desert, and the northern edge of the Tamaulipan Scrub (Dering 2002:Figure 2.5). Here the numerous canyons incised into the Cretaceous age limestone bedrock contain hundreds of rockshelters used by humans. This arid region is famous for the 3,000-year-old Pecos River–style pictographs and amazing organic preservation afforded by the numerous rockshelters and caves (Boyd 2003, 2016; Turpin 2004). Due to the excellent preservation, the archaeological record of the Lower Pecos has one of the longest records of hunter-gatherer lifeways in North America (Dering 2002:3.1). The archaeology and cultural history of the Lower Pecos has been well characterized in widely available sources, including Black and Dering (2001), Boyd (2003), Shafer (1986, 2013), and Turpin (1995, 2004).

Since 2013, the ASWT project of Texas State University has been working in Eagle Nest Canyon, a short tributary to the Rio Grande located just east of historic Langtry, Texas (e.g., Basham 2015; Castañeda 2015; Rodriguez 2015). The canyon, also known as Mile Canyon, has several prominent rockshelters, the most famous of which is Bonfire Shelter (41VV218), arguably the oldest and southernmost bison jump site in North America (e.g., Byerly et al. 2007; Dibble and Lorrain 1968; Prewitt 2007). The canyon has been the scene of intermittent archaeological excavation for over 80 years (e.g., Bement 1986; Davenport 1938; Ross 1965; Sayles 1935), but apart from the work at Bonfire, previous work in Eagle Nest Canyon focused either on the recovery of artifacts for museum display (1930s) or on establishing a cultural chronology for the region (1960s; see Black 2013). The current ASWT investigations are the first to apply twenty-first-century archaeological methods to investigate rockshelters in the Lower Pecos (e.g., Rodriguez 2015). Our ongoing work in Eagle Nest Canyon is focused on four rockshelters: Kelley Cave (41VV164), Skiles Shelter (41VV165), Horse Trail Shelter (41VV166), and Eagle Cave (41VV167) (see Figure 1). Our most intensive excavations are those at Eagle Cave, a large rockshelter with deeply stratified deposits representing over 9,000 years of hunter-gatherer occupation (see our blog, aswtproject.wordpress.com). Conceptually, ASWT research centers on hunter-gatherer

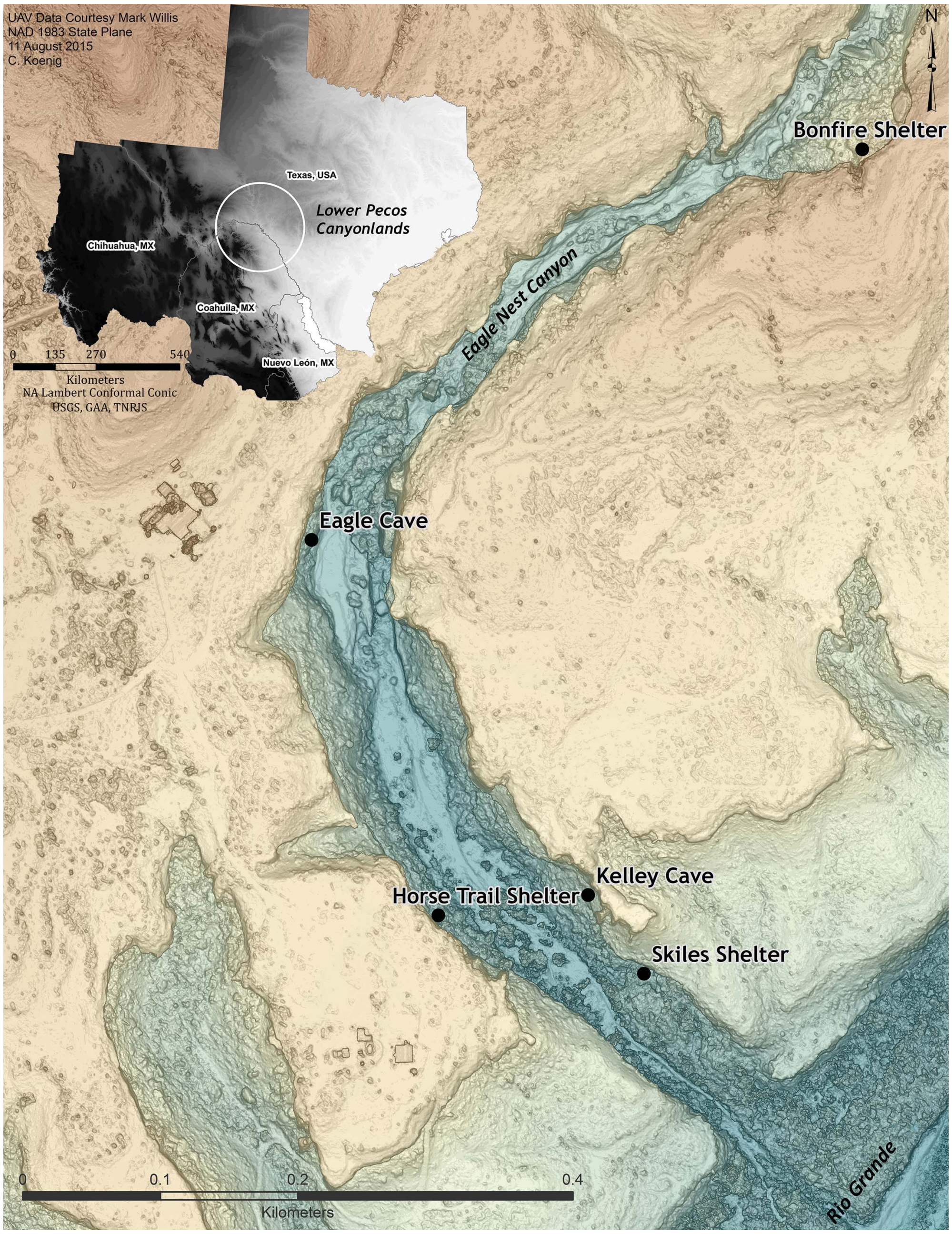

FIGURE 1. Location of the Lower Pecos Canyonlands (inset), with close-up of Eagle Nest Canyon and major sites discussed in the text. Unmanned Aerial Vehicle data for Eagle Nest Canyon collected by Mark Willis in January 2014 and processed using Agisoft Photoscan. The digital elevation model resolution is 15 cm per pixel.

landscape use intensification and the dynamics of cultural and natural formation processes.

Across the world, rockshelters are challenging sites to excavate because of the complex cultural and natural stratigraphy often housed within (e.g., Farrand 2001; Goldberg and Macphail 2006). We knew the sites in Eagle Nest Canyon would be no different, and we wanted to implement an explicitly stratigraphic approach allowing us to document, excavate, and sample each stratigraphic unit (strat) individually (e.g., Harris 1989). However, we realized a stratigraphic excavation strategy required a methodology that would allow us to be flexible in terms of unit sizes, orientations, and the depth of the excavated layers, while at the same time maintaining precise 3D provenience and context of all strats, artifacts, and samples. Having been introduced to SfM by Willis in 2009 (Willis et al. 2016), and after employing SfM on various projects in the Lower Pecos (e.g., Basham 2015; Campbell 2012; Koenig 2012; Rodriguez 2015), we realized that developing a method using ground-based SfM as our primary recording technique would be the best way to map everything from the overall site to the stratigraphic layers. Further, because of the fragile nature of rockshelter deposits, SfM would allow us to quickly document exposures and features threatened by potential wall collapse and rapid weather changes (e.g., severe thunderstorms). The timely publication of De Reu et al.'s (2014) article describing the use of ground-based SfM in an excavation context also gave us a starting point for how to apply the methodology. The major methodological benefit we saw for using SfM, aside from collecting precise and accurate 3D data, was that it would give us the flexibility during excavation to place our units and excavate our layers based on the geology, archaeology, and logistical pragmatics, not arbitrary measurements or grid systems.

STRUCTURE FROM MOTION

Structure from Motion (SfM) is a digital photography processing technique for capturing highly detailed, three-dimensional data from almost any surface using digital cameras. Using SfM, archaeologists can produce topographic maps, orthophotos, digital elevation models (DEMs), and 3D renderings of landscapes, features, excavation units, stratigraphic profiles, buildings, cave walls, or countless other surfaces. Although archaeologists working in Europe had begun using methods similar to SfM in the late 1990s and early 2000s (e.g., Pollefeys et al. 1998; Pollefeys et al. 2001; Pollefeys and van Gool 2002), we were first introduced to SfM by Willis in 2009 when he posted a short video on YouTube of a 3D model of a prehistoric stacked-stone circle in West Texas (http://youtu.be/TuHJUS2olyc). The video went viral, and over the following months Willis and other "geeks" from across the world continued refining the process using archaeological data (Willis 2010). Companies such as AutoDesk and Agisoft quickly developed commercial products that made the process more user-friendly and widely applicable. SfM is becoming more widespread within archaeology (including underwater [Drap 2012; Fulton et al. 2016]) in part because SfM is cheaper to implement than lidar scanning, even though both methods can produce similar results (see Barsanti et al. 2013; Brutto and Meli 2012). Examples of projects using SfM come from the United States (e.g., Douglass et al. 2015; Graves et al. 2013; Kenmotsu et al. 2012; Liebman et al. 2013; Miller et al. 2012; Miller and Graves 2009), South America (e.g., Brown et al. 2010), Mesoamerica (e.g., Houk 2013); Polynesia (e.g., Willis and Jalandoni 2011), Asia (e.g., Lin et al. 2011), Middle East (e.g., Howland et al. 2014; Reinhard 2012), and Europe (e.g., De Reu et al. 2013; De Reu et al. 2014; McCarthy 2014; Verhoeven et al. 2012).

The basic principle behind Structure from Motion is similar to traditional softcopy photogrammetry but requires significantly less positional control and does not require a detailed calibration report for the camera used (Chandler and Fryer 2005). To create a 3D model of any surface, dozens or hundreds of overlapping photographs are taken of the subject using a digital camera. Due to innovations in digital photography and aerial photographic systems, these photographs can be taken from virtually any platform, from the ground or suspended above the ground on a pole, kite, balloon, blimp, or unmanned aerial vehicles (e.g., Verhoeven 2009). Once the photographs are collected, they are loaded into a photo-processing software program such as Agisoft Photoscan (Agisoft LLC 2015; Verhoeven 2011).[1] Photoscan uses a scale-invariant feature transform (SIFT) algorithm to detect and triangulate the locations of similar features in each image (Lowe 1999; see also McCarthy 2014). The similarities are then used to determine the basic shape of the subject and the vantage point from which each photograph was taken. To dramatically increase the number of points in the resulting 3D model, a patch-based multi-view stereo (PMVS) algorithm is applied to the dataset (Furukawa and Ponce 2007). This decomposes the input images into a set of image clusters of a manageable size for processing. Once the 3D surface is computed, the "texture" or color values from each photograph are combined into a two-dimensional (2D) mosaic that can be projected back onto the model to create a high-resolution, seamless image. The resulting model can then be viewed fully textured as a 2D image, or as a 3D model in MeshLab or similar 3D viewing software. Advances in software have made this series of seemingly complex steps possible in just a few mouse clicks (Agisoft LLC 2014). The end products are fully 3D-formatted files (e.g., Alias Wavefront OBJ), texture maps of the surface, digital elevation models (DEMs), and ortho imagery. These can be virtually manipulated, measured, compared, etc., and the textured surfaces can be enhanced using GIS, D-Stretch, or other processing software (e.g., Adobe Photoshop).

The focus of this article is not on basic SfM methodology. Several published articles on archaeological applications of SfM focus on the methodology and provide step-by-step instructions for the collection of photographs and processing of 3D models using a variety of software packages (e.g., De Reu et al. 2014; Douglass et al. 2015; Kjellman 2012; Willis et al. 2016). However, we will point out that SfM does need relatively stable scenes to create 3D models. In other words, strong changes in lighting conditions (e.g., transitioning from sunny to shaded subjects), movement within the scene (e.g., vegetation moving in the wind), or unstable footing for the photographer (e.g., taking blurry photographs) can cause distortions in the 3D model. With planning, practice, and a fast lens, such problems can be minimized, and the photographer is left to focus solely on taking enough photographs of the entire subject to create the 3D model (see also Willis et al. 2016).

Ground Control Points

SfM technology requires the use of ground control points (GCPs) in order to georeference or position the photos (and subsequently, the SfM model) in real space (e.g., De Reu et al. 2014; Douglass et al. 2015).[2] These points can range from temporary markers placed on the ground (such as paper plates), to "X" marks on rocks, to excavation unit nails, to other more permanent datums. Once GCPs are established, they must be shot in, often with a Total Station or high precision GPS (see De Reu et al. 2014:253; McCarthy 2014:Figure 3). However, archaeologists can also use measuring tapes, builders squares (Castañeda 2015), or grid points established with tape and line level in order to georeference the 3D models (see Douglass et al. 2015:145).[3] The only criteria are that all of the GCPs are visible in multiple photographs (three photographs are the absolute minimum) and are part of a known three-dimensional coordinate system. The coordinates can be real-world values (like UTM or latitude and longitude, and elevation above mean sea level) or arbitrary such as an excavation-specific grid system. Without GCPs, you can still produce 3D models, but they will lack scale and cardinal orientation and are not suitable as a primary documentation method.

ARCHAEOLOGICAL APPLICATIONS OF STRUCTURE FROM MOTION

In the past several years, Willis and the ASWT project have used SfM techniques to document a variety of open and sheltered hunter-gatherer sites and features, including individual earth ovens (e.g., Basham 2015; Campbell 2012), large plant-baking facilities (burned rock middens; Graves et al. 2013; Koenig 2012:285–287, 305–306; Roberts and Alvarado 2011), rockshelters (Kenmotsu et al. 2012; Koenig 2012:260–262; Rodriguez 2015), rock art panels (Boyd et al. 2012; Miller et al. 2012), bedrock features (Castañeda 2015), and entire landscape segments (e.g., Willis et al. 2016). Depending on the specific research goals, site settings, and available technology for each project, SfM photographs were collected from a variety of platforms, including Unmanned Aerial Vehicles (UAVs), kites and blimps, poles, and ground-based cameras. Each platform is useful for acquiring photographs at different resolutions and angles. For instance, the use of UAVs for acquiring SfM photos is best suited for producing high-resolution 3D models of landscapes (e.g., Liebman et al. 2013; Lin et al. 2011; Willis 2013). The use of kites or blimps for aerial photography is useful for mapping smaller areas (such as single sites) and can be flown at a variety of altitudes to acquire higher-resolution data (Miller and Graves 2009; Reinhard 2012; Roberts and Alvarado 2011; Verhoeven 2009, 2011; Verhoeven et al. 2012). Archaeologists have also used Pole Aerial Photography. As the name suggests, this technique involves attaching a camera to a long pole to take photographs from a very low altitude (3–5 m), and generally photographing a smaller area than UAVs, kites, or blimps (Campbell 2012; De Rue et al. 2014; Graves et al. 2010; Houk 2013; Manaugh 2013; Verhoeven 2009; Willis 2010). Most of these techniques are used to capture photographs taken perpendicular to the ground surface, but acquisition method choice will depend on the desired resolution and logistics of collecting the photos.

One of the most revolutionary aspects of SfM documentation is that only a basic handheld digital camera is required to produce excellent data at the excavation level. Like aerial methods, ground-based SfM is accomplished by simply taking hundreds of overlapping photographs while maneuvering around a feature or other subject (e.g., Douglass et al. 2015). A distinct advantage of this approach is that much heavier and higher-quality cameras can be used, as the other techniques lend themselves to the lightest cameras possible (see Kim et al. 2013). Ground-based SfM also allows for the documentation of vertical surfaces and, because the photographer is closer to the subject, can produce sub-millimeter resolution ortho-imagery and DEMs (e.g., De Reu et al. 2014; Douglass et al. 2015). This technique is well suited to documenting relatively small areas, such as excavation units or features (e.g., Douglass et al. 2015), but we have also used this method to document large, complex excavation areas (see Willis et al. 2016).

THE USE OF GROUND-BASED SfM IN EAGLE NEST CANYON: A CASE STUDY

Within Eagle Nest Canyon, we are using ground-based SfM as the primary documentation method to precisely document excavation units, stratigraphic layers, features, and profile exposures. The technique of acquiring photos is similar as reported elsewhere (e.g., De Reu et al. 2013; De Reu et al. 2014; Douglass et al. 2015; Kjellman 2012; McCarthy 2014; Willis et al. 2016), but we have developed general methodological guidelines specifically for photographing small units and exposures.

SfM Data Acquisition in Eagle Nest Canyon: Some Considerations

Whenever taking SfM photographs, the photographer must be sure to photograph the subject from a variety of angles. The best photos for producing SfM models are those that are taken with the camera held perpendicular to the surface being photographed, which is why aerial platforms are so effective at the site level (see also Agisoft LLC 2014:5-6). Unlike data collected from an aerial perspective, however, the ground-based photographer must be aware that the closer you are to the targeted surface, the faster the perspective will change from photograph to photograph. The surfaces that are perpendicular in several successive images are no longer perpendicular as you move the camera around the excavation unit. For instance, if you are photographing around a corner of a unit you will need to take additional head-on photos of the corner to ensure that the software can match the photographs.

When taking photographs, we prefer the "snake" method, also called "leading with the camera," where each photograph is taken in a logical succession rather than randomly across the surface. In general, our rule of thumb for maintaining sufficient overlap is 40–60 percent both horizontally and vertically. In other words, each photograph should share between 40–60 percent of the points with the photos before and after. For the majority of our work, we use an Olympus OM-D E-M5 camera with a 12–55 mm lens but have also used Nikon Coolpix, Canon SLRs, and Panasonic Lumix point-and-shoot cameras with good to acceptable results.

Prior to taking each set of SfM photographs, we make certain that at least six ground control points (GCPs), three being the absolute minimum, will be visible in the planned overlapping image set. Our GCPs are generally small Xs drawn onto fire-cracked or natural rocks, but we also use nails driven into the ground surface, profile, or excavation unit corners (Figure 2). Each GCP is shot in with a total data station (TDS), using an arbitrary coordinate system established for the entire canyon (Table 1), linked via GPS to UTM coordinates. When the models are georeferenced using six GCPs, our average error (see Green et al. 2014) is very small (<1 cm). To maintain accuracy as the excavations progress, we occasionally re-shoot the GCPs to be sure that the positions have not changed. Requiring six GCPs ensures that each SfM model can be georeferenced, further allowing us to maintain precise provenience information for each excavation unit or profile. For most excavation units ranging from approximately 50 × 50 cm to

TABLE 1. Ground Control Point Coordinates and Associated Error Values for 3D Model of Unit 73, Layer 6C from Eagle Cave.

	Values from TDS			Calculated Error in Photoscan
Ground Control Points	**X (m)**	**Y (m)**	**Z (m)**	**Error (mm)**
GCP243	2790.183	5316.556	977.776	3.46
GCP248	2790.265	5316.732	977.496	2.64
GCP301	2789.09	5316.79	977.928	3.06
GCP302	2789.465	5316.75	977.83	4.63
GCP306	2788.886	5317.112	977.915	3.22
GCP318	2789.522	5316.807	977.526	3.08
Total Error				3.41

Note: Error value for ground control points is RMS.

1 × 1 m we take between 40 and 200 photos to completely photograph the floors and walls. The total number of photos taken depends on the complexity of the targeted surface and overall shape and size of the unit (e.g., the more uneven the surface and the deeper the unit, the more photos required).

Once the photos have been taken, we process the photos using Agisoft Photoscan (Agisoft LLC 2015). Although freeware and other 3D-modeling software packages can be used, for our purposes, Photoscan is straightforward and allows us to easily complete the process from photography to georeferenced 3D models. The computer we use is a custom-built 64-bit system running Windows 7 with dual Intel Xeon E5-2630V2 (2.6 GHz, 15MB, 12C) processors, dual NVIDIA GTX 650Ti BOOST 2 GB graphics cards, and 128 GB Crucial DDR3 (8 × 16 GB) memory. This system allows us to build 3D models with over 3,500 photographs, but a machine this powerful is not necessary for most models. The more powerful the system the more photos you can process, but laptops with far less processing power and RAM can successfully process 3D models with fewer photographs. Once the 3D models are processed in Photoscan, we can export fully textured 3D models (Figure 3), as well as orthographic photos and digital elevation models (DEMs) of the surfaces with sub-millimeter resolution and import these into ArcGIS (Figure 4). We are then able to overlay any artifacts and samples shot in with the TDS (Figure 4b). Generally, we are able to process overnight the SfM sets from a single day of excavation so that we have the orthographic images available to take to the field the next day.

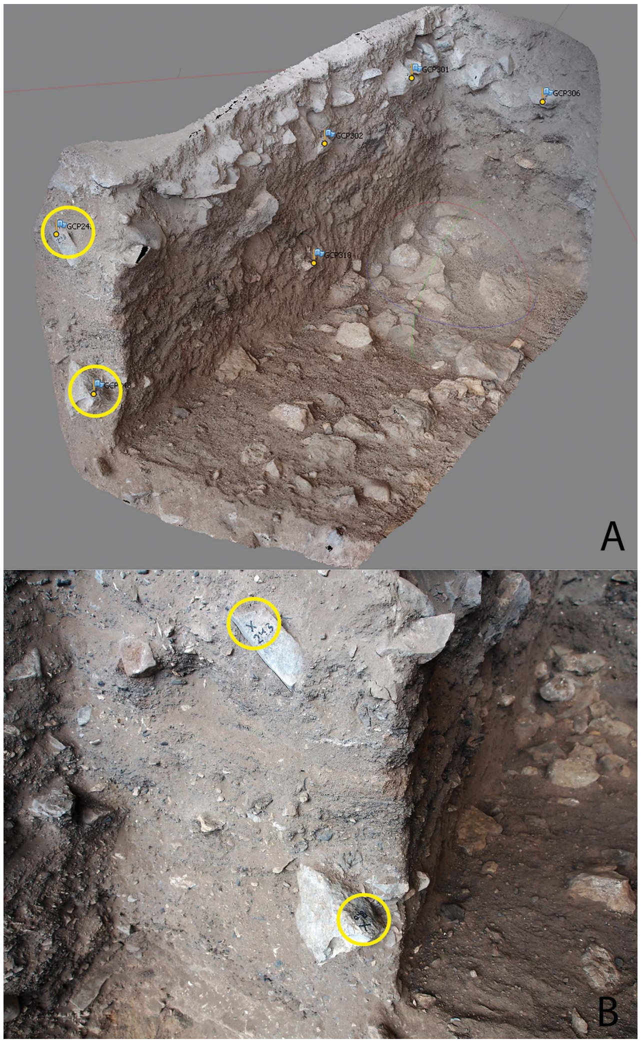

FIGURE 2. A minimum of three Ground Control Points (GCPs) are used to reference SfM models to real-world coordinates in Photoscan. Six GCPs were used to reference 3D model of Unit 73, Layer 6C from Eagle Cave (a), and a photograph (b) of the GCPs taken as part of the SfM photographs. The circles highlight the same GCPs in each image.

Layer by Layer SfM Excavation Methodology at Eagle Cave

As mentioned, rockshelters contain some of the most complex stratigraphy of any archaeological sites; Eagle Cave is a good case in point (Figure 5). This site has up to 5 m of cultural and natural deposits (Ross 1965). The lowest stratigraphic units are mostly coarse-textured, naturally occurring sediments (e.g., rock spall or eboulis layers), but as you progress vertically up the profile, the sediments become nearly 100 percent anthropogenic in nature.[4] Adding to the complexity, the uppermost 2 to 3 m of deposits have been subject to considerable anthropogenic mixing in the form of cooking pits and latrines, as well as extensive bioturbation (especially small animal burrows) (Figure 6). Previous excavations at the site occurred in 1935–1936 by the Witte Museum of San Antonio (Davenport 1938) and in 1963 by the Texas Archeological Salvage Project at the University

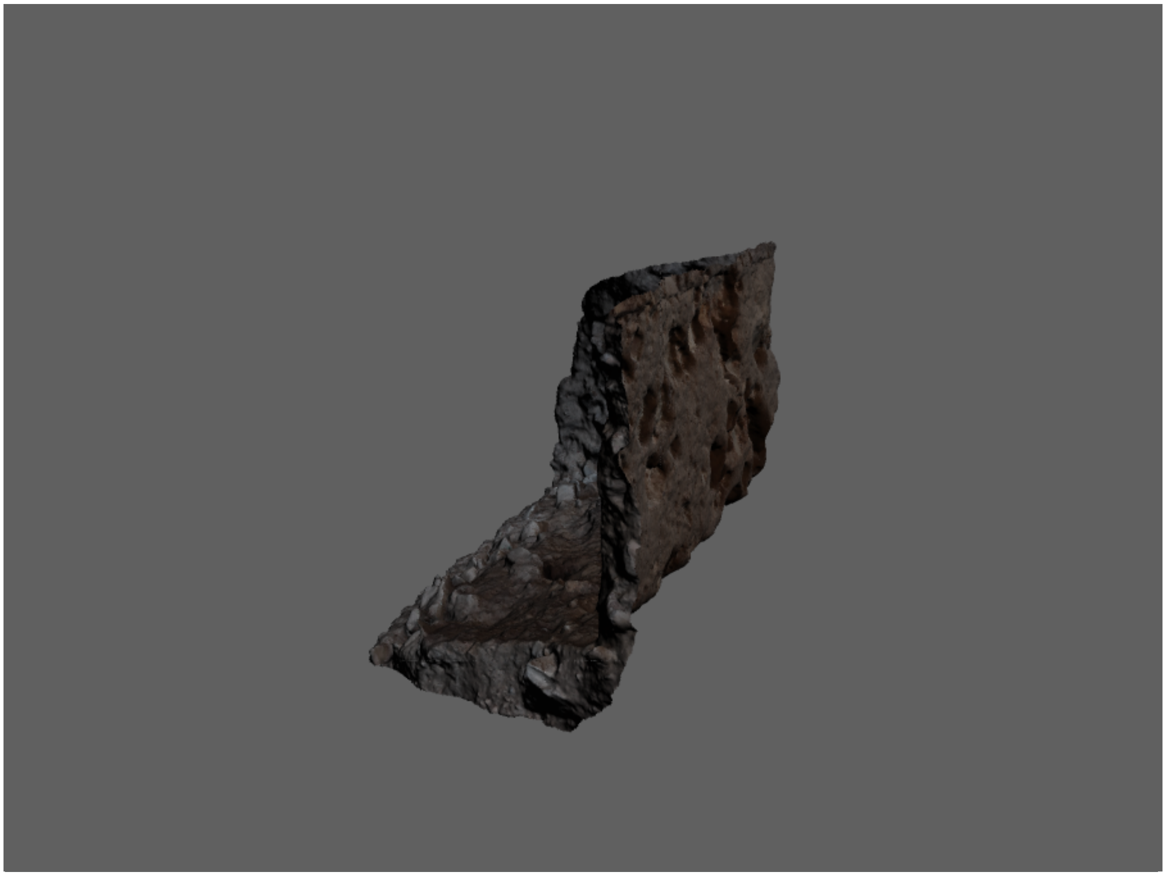

FIGURE 3. 3D model of Unit 73, Layer 6C from Eagle Cave generated from 137 photographs. This model can be rotated, measured, and otherwise manipulated by clicking the image. Due to size constraints, the texture resolution is only 25 percent of the original.

of Texas (Ross 1965; the University of Texas units from 1963 are plotted in Figure 5). The Witte and University of Texas excavations were concentrated in a major trench spanning nearly 25 m from the dripline to the rear wall through the center of the site. This 2- to 3-m-wide trench was only partially backfilled after the 1960s work, and through the decades the once-vertical trench faces gradually slumped into a large U-shaped depression nearly 10 m wide in the center of the site.[5]

The goals of the ASWT work in Eagle Cave are to expose, sample, stabilize, and backfill the trench to prevent additional destruction to the extant intact deposits and gain a twenty-first-century understanding of the 9,000-plus years of hunter-gatherer occupation. We use the motto "Low Impact, High Resolution" to describe our excavation strategy. Rather than open up large horizontal exposures (e.g., excavation blocks), we focus on taking advantage of the slumping trench walls to create a vertical, stepped profile that damages the extant intact deposits as little as possible (Figures 7 and 8). We remove the disturbed material from the sloping surface and then use small excavation units to expose clean faces (profile sections) of intact deposits. Because we are using SfM to capture the provenience data, our units do not need to be square or conform to an arbitrary grid. The only pragmatic orientation requirement is that the south walls of each unit (we are working on the south wall of the main trench) are roughly parallel so that, once we finish excavation, we have connected stratigraphic exposures spanning the entire site (Figure 8). SfM is especially important when dealing with a site containing substantial amounts of disturbed fill because it gives us the flexibility to target the areas with intact deposits regardless of location or orientation.

As excavations progress, we use SfM to document *at minimum* the exposed horizontal and vertical surfaces of each natural layer/stratigraphic unit (Figure 9). Occasionally, we take multiple sets of SfM for each layer as we excavate, especially in thicker, rocky stratigraphic layers to document how the layer changes, capture rock morphology, or record other ephemeral detail. Although not as dramatic as watching architecture grow out of an excavation unit (see De Reu et al. 2014), subtle features can be graphically documented as they become fully exposed. We still take traditional overview or record shots with a chalkboard and north arrow, but because of their accuracy and clarity, the orthophotos created from the SfM models generally become the official record shots.

We excavate following the natural stratigraphy, and, by using SfM, we are able to document and link stratigraphic units while we excavate regardless of whether these layers slope, are discontinuous, or do not extend across the entire excavation. As

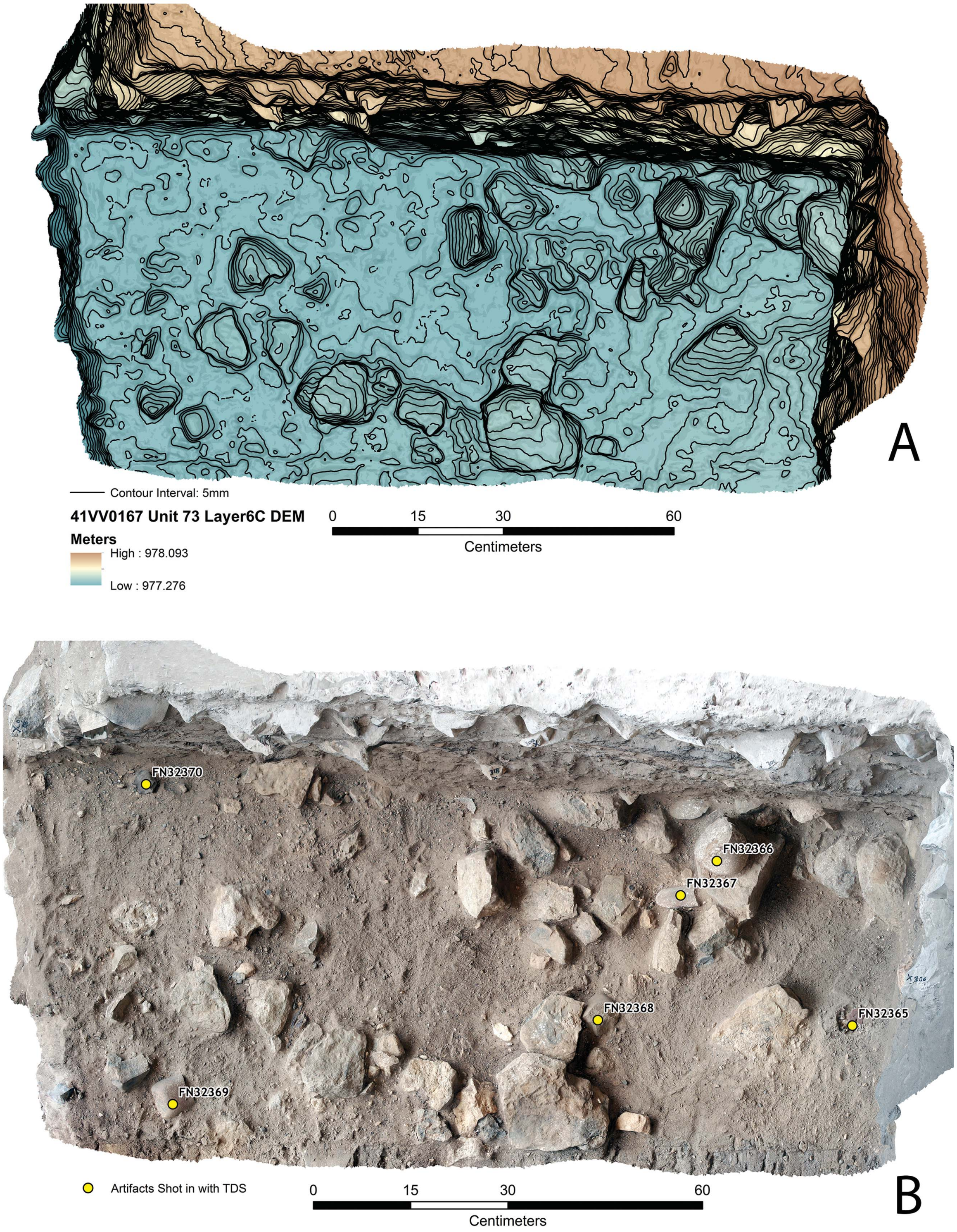

FIGURE 4. Digital elevation model (a) and orthophoto with total data station points (b) of Unit 73, Layer 6C from Eagle Cave. The digital elevation model has a pixel resolution of 1 mm and has 5-mm contour lines interpolated over the surface. The orthophoto has a resolution of .5 mm. Orthophotos and digital elevation models can be readily exported directly from Photoscan and loaded into GIS software, and total data station points showing locations of artifacts and samples can be overlaid onto the ortho or digital elevation model.

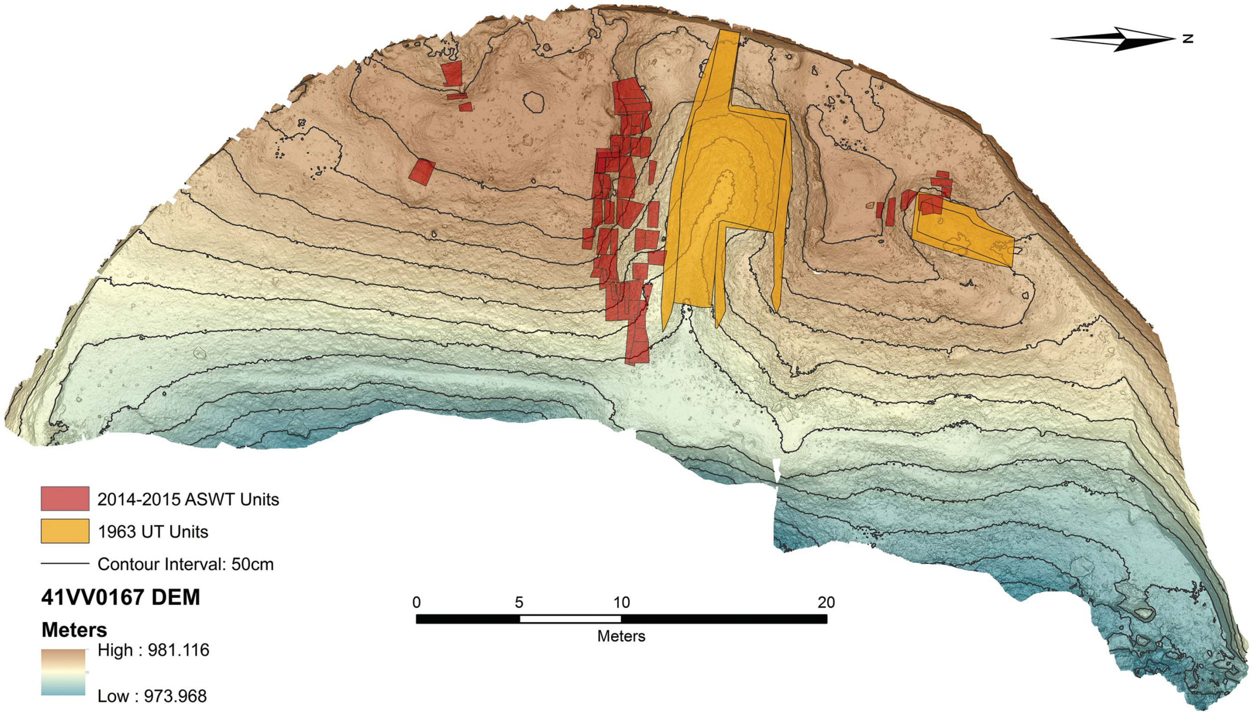

FIGURE 5. Plan map of Eagle Cave showing the ASWT excavation units in comparison to the 1963 UT work at the site. The underlying digital elevation model was created in Photoscan using 1,800 photographs collected using Pole Aerial Photography. The digital elevation model was exported with a pixel resolution of 4 mm, and the contour interval is 50 cm.

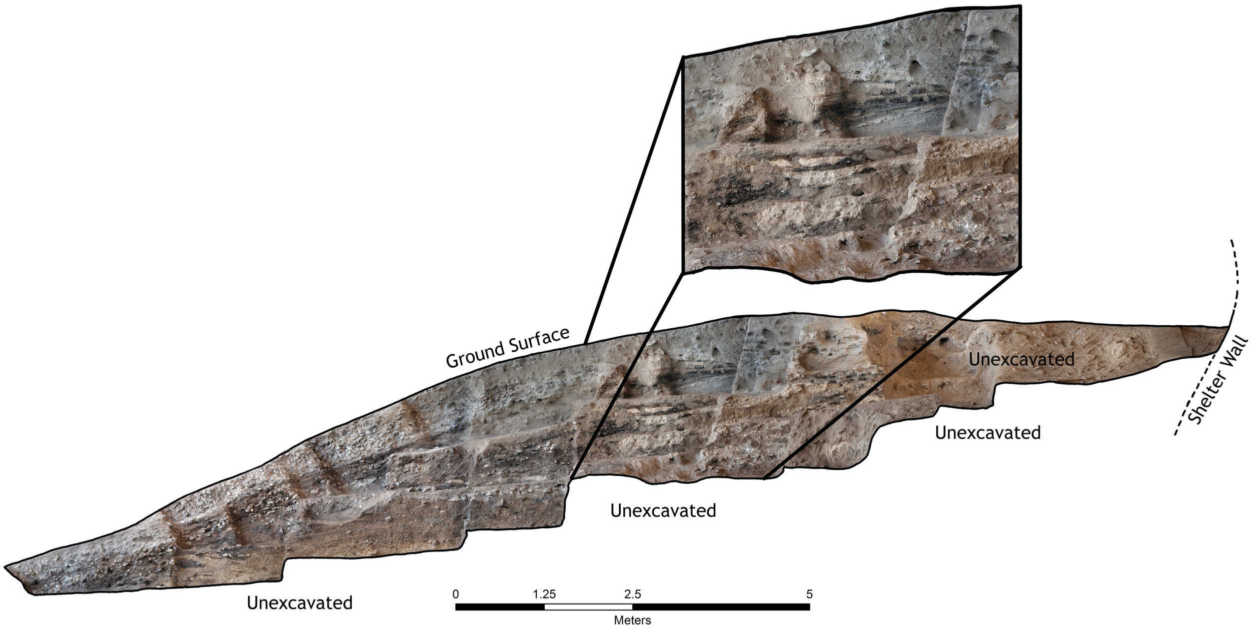

FIGURE 6. Profile view of the south wall of the main trench in Eagle Cave as of May 16, 2015. The underlying 3D model was created from 1,300 photographs, and the orthophoto has a pixel resolution of .5 mm. The upper portion of the site has been disturbed by bioturbation and historic sheep ranching. The inset image shows a sample of the microstratigraphy present at the site.

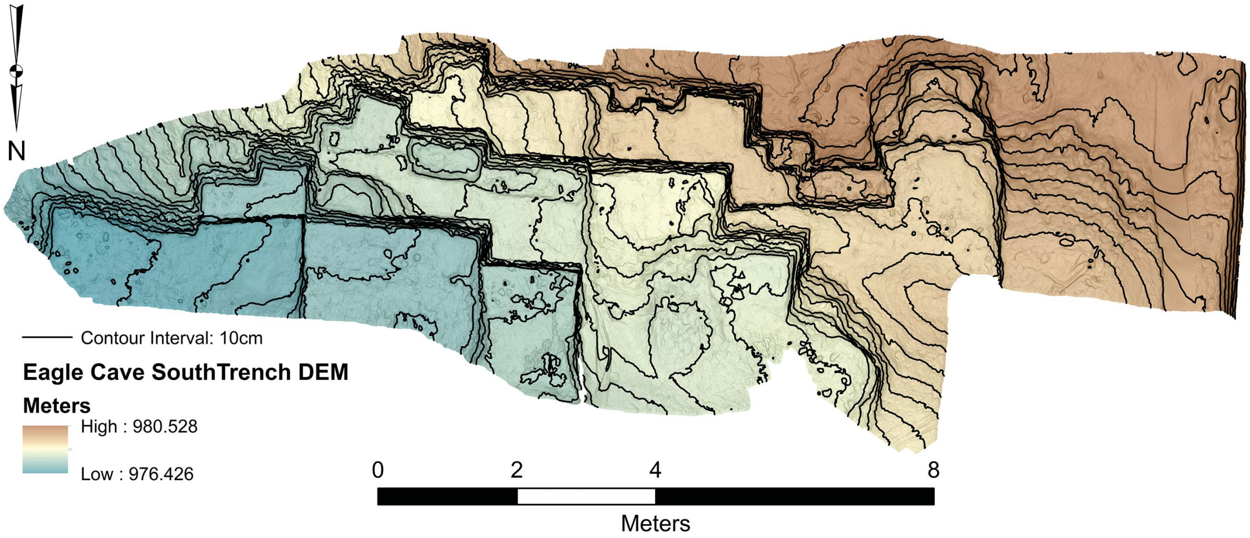

FIGURE 7. Plan view of the south wall of the main trench in Eagle Cave as of May 16, 2015. The digital elevation model has a pixel resolution of 1 mm. The excavations are stepped to stabilize and preserve the site.

FIGURE 8. 3D model of the south wall of the main trench in Eagle Cave as of May 16, 2015. Model generated from 1,300 photographs and referenced with 26 GCPs. This model can be rotated, measured, and otherwise manipulated by clicking the image. Due to size constraints, the 3D surface has been decreased in size from 5.4 million faces to 1 million, and the texture resolution is 25 percent of the original.

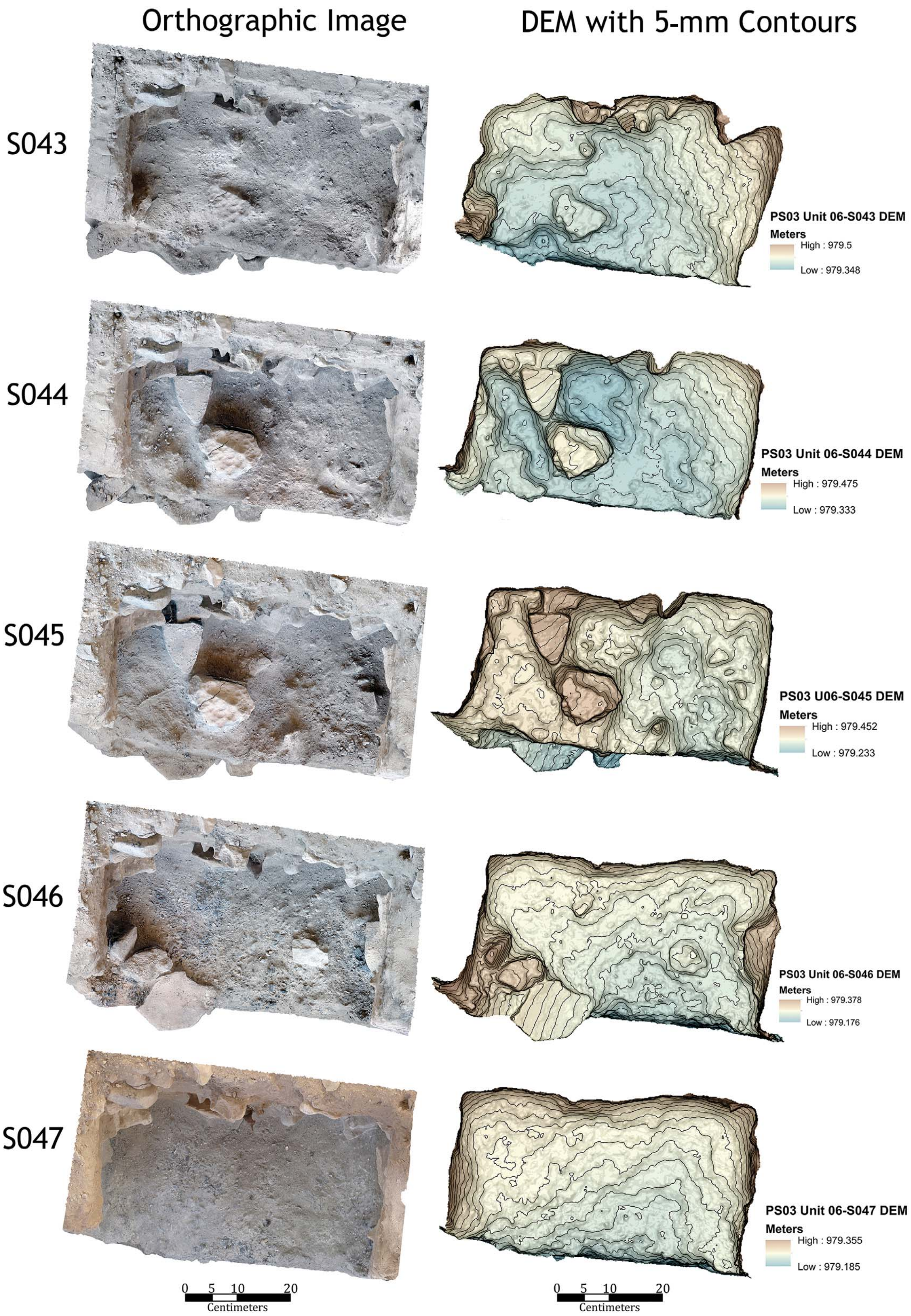

FIGURE 9. Layer by layer SfM excavation of Unit 6, strats S043-S047 from Profile Section 3. Each image shows the top surfaces of the excavated strats. The images on the left are orthophotos exported with resolution of .5 mm, and the digital elevation models on the right exported with 1 mm resolution with 5-mm contour lines overlaid. The digital elevation models were cropped to display only the bottom of the unit. These digital elevation models were used to calculate volumes in GIS using the Cut-Fill tool.

TABLE 2. Total Excavated Volume of Strata from Unit 6, Profile Section 3 in Eagle Cave Calculated Using Cut-Fill in ArcGIS Compared to Volume of Matrix Collected for Analysis.

Strat Sampled	Cut-Fill Volume Calculation		Matrix Collected	Percent Difference
	m^3	L	L	
S043[a]	.0058	5.79	6.3	9%
S044	.0050	4.95	3.8	−23%
S045	.0107	10.73	10	−7%
S046[b]	.0015	1.55	0	0

Note: Cut-Fill Volume Calculation is total excavated matrix (including burrowed or disturbed fill), and Matrix Collected is only undisturbed sediment collected for analysis.

[a] Cut/Fill volume calculated without "void" left by rock in upper right DEM of S043.

[b] S046 consisted only of fire-cracked rock; therefore, no matrix was collected.

our research progresses from data collection to data analysis, we will be able to reconstruct and model entire stratigraphic layers and/or zones using the data collected from individual excavation units. This capability allows us to use true stratigraphic excavation methods within pragmatic units of any configuration.

Square-hole methods have often been perceived as necessary to be able to maintain accurate provenience and calculate density data, but because our 3D models are georeferenced, we are able to capture precise provenience data and easily calculate volume (hence artifact density) of any excavated unit layer or strat. Rather than waiting until after the field season to use unit-layer drawings and measurements to calculate volume, this can be done immediately after the 3D models are created and DEMs are exported. We use the Cut-Fill tool in ArcGIS to calculate the volume and then are able to compare the calculated volume in GIS to the volume of sediment we removed as bulk matrix (Table 2). We use a TDS to record the X, Y, Z provenience of individually collected artifacts and samples,[6] and, in addition to TDS points, we often will take specific sets of SfM photographs in order to document the relationship between artifacts and/or features within a unit. Because almost everything that comes out of the excavation unit is recorded in 3D space, we are able to record slope and dip on artifacts, ecofacts, and rocks from the 3D data even if these data were not collected in the field. When compared to traditional paper-pencil methods, SfM allows archaeologists to quickly and accurately collect more data about a single excavation unit or layer, and have all this data immediately digitized for display and analysis. Because each SfM model is georeferenced and can be used in any GIS, many of the analytical tools in programs like ArcGIS can be used for conducting spatial analyses on the layers without having to digitize paper illustrations.

Profile Documentation in Eagle Cave

One of the great uses of SfM is for documenting stratigraphic profiles (e.g., Barsanti et al. 2013; De Reu et al. 2014). Many of the profiles we record with SfM (see Figure 6) could not be documented with sufficient resolution with a single photograph. By using SfM, a high-resolution 3D model and associated orthophotos and DEMs can be generated whether the profile is in the bottom of a 1-m square or a several-meter-long trench profile (e.g., Willis et al. 2016:Figure 10). Whenever we photograph profiles, these become processing priorities so that we can record the profiles in the field the next day using the data generated from the 3D models (similar to De Reu et al. 2014:261). Rather than using string, line levels, and tape measures, when we record profiles, we go back to the field armed with full-color printouts of the orthophotos generated from the 3D data in Photoscan. Thus we are able to annotate directly on the images, noting subtle stratigraphic interfaces, sample locations, and various other data. Like a Munsell™ book or small geologic sieve for in-field particle size analysis, these SfM printouts become a valuable tool for in-field stratigraphic descriptions. The annotated orthophotos are then digitized using a drawing tablet (Figure 10a). Because the profiles are georeferenced to the same coordinate system as all the TDS points, we are also able to overlay the locations of samples and artifacts collected from the profile (Figure 10b). However, it is not just the TDS-plotted artifacts and samples we can overlay onto the profiles. Using the 3D models generated from each of the excavation layers, we are able to project exactly where we excavated back onto the profiles in GIS (Figure 10c). This is very useful for assigning stratigraphic provenience to artifacts and samples collected prior to stratigraphic documentation, but can also be used to check our excavated layers against the stratigraphic layers defined in profile.

DISCUSSION

We realize that our application of ground-based SfM as a primary tool for documenting excavations may seem tailored for rockshelters with definable stratigraphy, but we believe that these same methods can be applied to open-air archaeological sites. Even at sites lacking clearly defined stratigraphy, SfM can accurately maintain vertical and horizontal provenience and allow archaeologists to target specific areas regardless of their location or orientation to the grid. Furthermore, by using this approach, archaeologists are not tethered to square holes, arbitrary levels, and a fixed-grid orientation. As we believe, and hope the figures in this article show, SfM allows archaeologists to collect more and higher-quality data than by using traditional methods alone.

We acknowledge that this documentation method is more time consuming on the front end. It may take longer to collect a series of SfM photographs and process the models for a single excavation unit layer than to create a simple measured drawing.

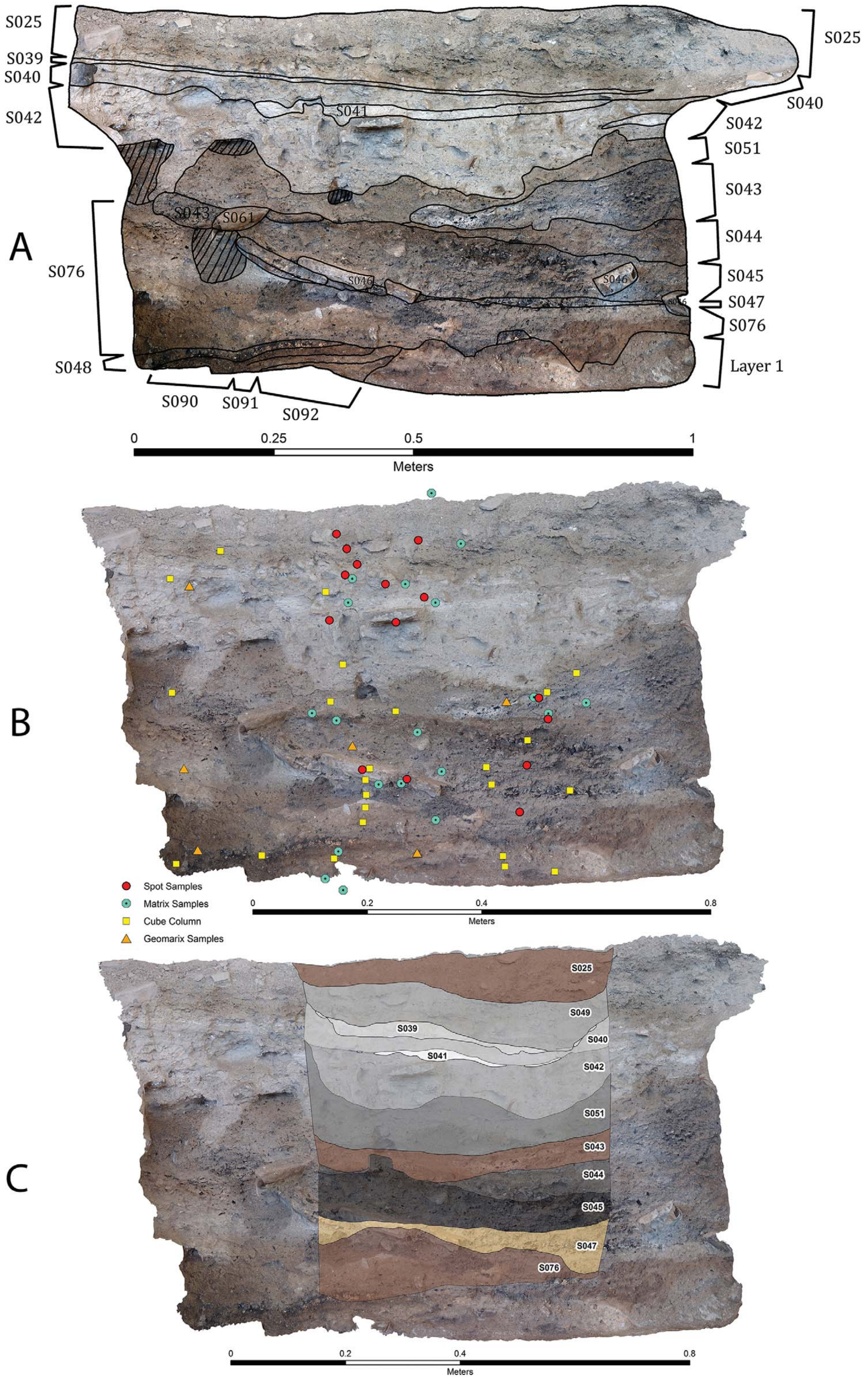

FIGURE 10. Profile Section 3 from Eagle Cave: (a) after a hand-annotated version of the profile was created in the field, this digital annotation was created in the lab using a Cintiq^{TM} drawing tablet; (b) various samples collected from Profile Section 3 and shot in with a total data station overlaid onto the profile; and (c) interpolation of excavated strats from Unit 6 in Eagle Cave projected back onto Profile Section 3. The underlying orthographic photo for all three images has a pixel resolution of .5 mm and was exported from a 3D model created from 61 photographs. By georeferencing all the 3D models, we are able to combine points, polygons, orthophotos, and digital elevation models of surfaces into the same ArcGIS environment.

However, when time spent processing SfM models is compared against paper methods for the duration of the project, we believe that SfM has a clear advantage. How many projects take months or years after excavations are completed to digitize paper drawings and illustrations, let alone bring these data into a format compatible with GIS? SfM gives archaeologists the ability to view excavation data directly in GIS software once the 3D models are processed, making SfM more time efficient than paper methods on the back end of projects.

There are other considerations that archaeologists must take into account when thinking about SfM. First, we have access to a field lab with electricity and a computer capable of processing large numbers of 3D models, conveniences that do not exist for all archaeological projects. Without the ability to charge batteries and download data on a daily basis (let alone process the 3D models themselves), using this method would be much more difficult. Second, we often take thousands of photographs each field day, and we had to create a file structure and database to systematically and efficiently input and organize all of these photographs. Each of our photographs is renamed in a consistent format and saved in a database to allow researchers to quickly access their location. Without these procedures, the tens of thousands of photographs would become a data nightmare. Finally, it is important to remember that SfM represents another tool in the archaeologist's toolkit. SfM alone does not collect all the necessary data for the thorough documentation and recording of an excavation unit or profile. We are constantly combining SfM data with TDS data to collect and record X, Y, Z data on artifacts and samples. We still take conventional notes and describe what we find within a given excavation unit or profile. As impressive as the SfM data can be, the archaeologist still needs to provide the analytical framework to give the 3D data meaning. With these considerations in mind, and with modifications to the strategy and new ways of implementing the technology, we believe that archaeologists around the world should consider the benefits of using SfM as a primary excavation documentation tool.

As De Reu et al. (2014:251) point out, archaeological excavation is inherently destructive, and applying SfM methods to the daily excavation process allows archaeologists to maximize the amount of data we both collect and *preserve* for future generations. To date, we have well over 1,000 3D models of our excavations in Eagle Cave, ranging from the entire site to profiles, excavation units, stratigraphic layers, and features. Combine these 1,000 models with approximately 500 3D models from other sites within Eagle Nest Canyon, and we have an incredible digital record of these archaeological sites that will be available to future researchers long after all the units are filled.

CONCLUSION

Methodological innovations and new applications of Structure from Motion technology are continually being developed as knowledgeable archaeologists apply SfM techniques to different contexts and documentary challenges (e.g., Fulton et al. 2016; Porter et al. 2016). In our view, however, SfM should not be reserved for monumental and extraordinary archaeological discoveries, but, rather, should be applied to any archaeological site/project no matter the scale. This technology has the capacity to transform and improve many aspects of essential archaeological field and laboratory documentation and open new interpretive windows that archaeologists have only just begun to explore. Applying SfM to excavations not only allows archaeologists to record the precise provenience and context of excavations, but also allows greater flexibility in excavation strategies.

We call on all field archaeologists: start taking systematic, sequential sets of digital photographs of all critical and fleeting archaeological exposures, linked to known reference points. You may not have the time, software, hardware, or technological inclination to process the photographic data and create 3D models while in the field, but these steps can be taken months, years, or decades later if you capture and preserve the essential data. Cultural resource managers and researchers will increasingly employ SfM models to create compelling interpretive and public outreach graphics, to highlight preservation efforts, and to monitor and quantify resource damage assessments (e.g., Rua and Alvito 2011). Archaeological SfM models are now being used to create augmented reality views of the real-world environment, making it possible for us to walk through a previously excavated site while holding a mobile computing device and watching as excavation exposures appear on the screen just as the viewer would have seen them when the work was being done. The future of archaeological documentation, analysis, and interpretation is multidimensional and graphically vivid, and Structure from Motion provides a means to achieve that future far beyond the confines of the square hole.

Acknowledgments

The implementation of SfM to excavation would not have been possible without our dedicated field crew over the past three seasons: Tina Nielsen, Jacob Sullivan, Brooke Bonorden, Bryan Heisinger, Victoria Pagano, Matt Larsen, Emily McCuistion, Amanda Castañeda, Spencer Lodge, Stephanie Mueller, Kelton Meyer, and Justin Ayers. Funding for the ASWT project was provided by the Thomas E. Miller Estate. We are grateful for the useful comments and critiques of early versions of this article by Emma Koenig, Amanda Castañeda, C. Britt Bousman, Robert (Zac) Selden Jr., and David Kilby. Thanks to David O. Brown for providing the Spanish translation of the abstract. The final version of this manuscript greatly benefited from editor Sarah Herr and the insights of four anonymous reviewers.

Data Availability Statement

We are acutely aware that traditional hard-copy, black-and-white photographic curation standards and current file-size-based digital curation costs cannot accommodate all of the massive raw SfM data files (e.g., original images) that we generate. Archaeologists across the world have a vested interest in developing viable digital curation alternatives to accommodate the unfolding digital reality. This problem is not unique to archaeology, and the rapid evolution of cloud-based data storage suggests that digital curation challenges will be met. Supplemental materials associated with this article are currently housed at Texas State University. These data include underlying photographs, 3D OBJ files, GCP coordinates, DEMs, and Orthographic photos. We are currently working with Texas State University to curate these data in a location that will be accessible to researchers and the public.

Currently, access to these materials is available only upon request, but inquiries can be sent to ck1286@txstate.edu and sblack@txstate.edu.

REFERENCES CITED

Agisoft LLC

2014 Agisoft Photoscan User Manual: Professional Edition, Version 1.1. Electronic document, http://www.agisoft.com/downloads/user-manuals/, accessed August 8, 2015.

2015 Agisoft Photoscan Professional Edition, Version 1.1.6. Electronic document, http://www.agisoft.com/features/professional-edition/, accessed August 8, 2015.

Barsanti, S. Gonizzi, F. Remondino, and D. Visintini

2013 3D Surveying and Modeling of Archaeological Sites—Some Critial Issues. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 2:145–150.

Basham, G. Matt

2015 Subsistence Strategies and Landscape Use in the Canyon Edge Zone: Eagle Nest Canyon, Langtry, Texas. Unpublished Master's thesis, Department of Anthropology, Texas State University, San Marcos.

Bement, Leland C.

1986 *Excavation of the Late Pleistocene Deposits of Bonfire Shelter, 41VV218, Val Verde County, Texas 1983–1984*. Archeology Series 1. Texas Archeological Survey, University of Texas, Austin.

Black, Stephen L.

2013 The Archaeologists. In *Painters in Prehistory: Archaeology and Art of the Lower Pecos Canyonlands*, edited by Harry J. Shafer, pp. 139–152. Trinity University Press, San Antonio.

Black, Stephen L., and J. Phil Dering

2001 Lower Pecos Canyonlands. Electronic document, www.texasbeyondhistory.net/pecos, accessed August 8, 2015.

Boyd, Carolyn E.

2003 *Rock Art of the Lower Pecos*. Texas A&M University Press, College Station.

2016 *The White Shaman Mural: An Enduring Creation Narrative in the Rock Art of the Lower Pecos*. University of Texas Press, Austin.

Boyd, Carolyn E., Francisco Marcos Marín, Christopher Goodmaster, Angel Johnson, Amanda Castañeda, and Benjamin Dwyer

2012 Digital Documentation and the Archaeology of the Lower Pecos Canyonlands. *Virtual Archaeology Review* 3(5):98–103.

Brown, David O, Byron Camino, and Mark D. Willis

2010 Algunas Observaciones a las Fortalezas Incas del Oeste montañoso del Ecuador. Instituto Nacional de Parrimonio Cultural: INPC – *Revista del Patrimonio Cultural del Ecuador*. INPC No. 2:43–56.

Brutto, M. Lo, and Paola Meli

2012 Computer Vision Tools for 3D Modelling in Archaeology. *International Journal of Heritage in the Digital Era* 1:43–56.

Byerly, Ryan M., Judith R. Cooper, David J. Meltzer, Matthew E. Hill, and Jason M. LaBelle

2007 A Further Assessment of Paleoindian Site-Use at Bonfire Shelter. *American Antiquity* 72:373–381.

Campbell, John

2012 Modeling Burned Rock Features as Units of Subsistence Intensification. Unpublished Master's thesis, Department of Anthropology, Texas State University, San Marcos.

Castañeda, Amanda M.

2015 The Hole Story: Understanding Ground Stone Bedrock Feature Variation in the Lower Pecos Canyonlands. Unpublished Master's thesis, Department of Anthropology, Texas State University, San Marcos.

Chandler, Jim H., and J.G. Fryer

2005 Recording Aboriginal Rock Art Using Cheap Digital Cameras and Digital Photogrammetry. CIPA 2005 XX International Symposium 26. Torino, Italy.

Davenport, J. Walker

1938 *Archaeological Exploration of Eagle Cave, Langtry, Texas*. Big Bend Basket Maker Papers No. 4. Witte Memorial Museum, San Antonio, Texas.

De Reu, Jeroen, Gertjan Plets, Geert Verhoeven, Philippe De Smedt, Machteld Bats, Bart Cherretté, Wouter De Maeyer, Jasper Deconynck, Davy Herremans, Pieter Laloo, Marc Van Meirvenne, and Wim De Clercq

2013 Towards a Three-Dimensional Cost-Effective Registration of the Archaeological Heritage. *Journal of Archaeological Science* 40:1108–1121.

De Reu, Jeroen, Philippe De Smedt, Davy Herremans, Marc Van Meirvenne, Pieter Laloo, and Wim De Clercq

2014 On Introducing an Image-Based 3D Reconstruction Method in Archaeological Excavation Practice. *Journal of Archaeological Science* 41:251–262.

Dering, J. Phil

2002 *Amistad National Recreation Area: Archeological Survey and Cultural Resource Inventory*. Intermountain Cultural Resources Management Anthropology Projects Professional Paper No. 68. Center for Ecological Archaeology, Texas A&M University, College Station, Texas.

Dibble, David S., and Dessamae Lorrain

1968 *Bonfire Shelter: A Stratified Bison Kill Site, Val Verde County, Texas*. Miscellaneous Papers 1. Texas Memorial Museum Publications, University of Texas, Austin.

Drap, Pierre

2012 Underwater Photogrammetry for Archaeology. In *Special Applications of Photogrammetry*, edited by Daniel Carneiro da Silva, pp. 111–136. InTech, DOI: 10.5772/33999. Electronic document, http://www.intechopen.com/books/special-applications-of-photogrammetry/underwater-photogrammetry-for-archaeology, accessed August 8, 2015.

Douglass, Matthew, Sam Lin, and Michael Chodoronek

2015 The Application of 3D Photogrammetry for In-Field Documentation of Archaeological Features. *Advances in Archaeological Practice* 3(2):136–152.

Farrand, William R.

2001 Sediments and Stratigraphy in Rockshelters and Caves: A Personal Perspective on Principles and Pragmatics. *Geoarchaeology: An International Journal* 16(5):537–557.

Fulton, Carrie, Andrew Viduka, Andrew Hutchinson, Joshua Hollick, Andrew Woods, David Sewell, and Sturt Manning

2016 Use of Photogrammetry for Non-Disturbance Underwater Survey: An Analysis of In Situ Stone Anchors. *Advances in Archaeological Practice* 4(1):17–30.

Furukawa, Yasutaka, and Jean Ponce

2007 Accurate, Dense, and Robust Multi-View Stereopsis. In *Proceedings/CVPR, IEEE Computer Society Conference on Computer Vision and Pattern Recognition*. Minneapolis, Minnesota.

Goldberg, Paul, and Richard I. Macphail

2006 *Practical and Theoretical Geoarchaeology*. Blackwell Publishing. Malden, Massachusetts.

Graves, Tim, Juan Arias, and Mark Willis

2013 Guadalupe Village (LA 143472), A Burned Rock Midden Site in Southeastern New Mexico and the Use of Innovative and Inexpensive Mapping Techniques. In *Advances in Jornada Mogollon Archaeology: Papers from the 17th Jornada Mogollon Conference*, edited by Todd L. VanPool, Elizabeth M. McCarthy, and Christine S. Van Pool, pp. 17–40. El Paso Museum of Archaeology, El Paso, Texas.

Green, Susie, Andrew Bavan, and Michael Shapland

2014 A Comparative Assessment of Structure from Motion Methods for Archaeological Research. *Journal of Archaeological Science* 46(2014):173–181.

Harris, Edward C.

1989 *Principles of Archaeological Stratigraphy*. 2nd ed. Academic Press, London.

Houk, Brett A. (editor)

2013 *The 2013 Season of the Chan Chich Archaeological Project*. Papers of the Chan Chich Archaeological Project, Number 7. Department of Sociology, Anthropology, and Social Work. Texas Tech University, Lubbock.

Howland, Matthew D., Falko Kuester, and Thomas E. Levy
2014 Photogrammetry in the Field: Documenting, Recording, and Presenting Archaeology. *Mediterranean Archaeology and Archaeometry* 14(4):101–108.
Kelly, Robert L., and David Hurst Thomas
2013 *Archaeology*. 6th ed. Wadsworth, Belmont, California.
Kenmotsu, Nancy A., Leonard Kemp, and Lawrence L. Loendorf
2012 *Jornada Rockshelters as Special Places: Investigations of 13 Sites along the Otero Mesa Escarpment, Fort Bliss Military Reservation, Otero County, New Mexico*. Historic and Natural Resources Reports Nos. 11–12 and 11–26, Environmental Division, Fort Bliss Garrison Command, Fort Bliss, Texas.
Kersten, Thomas P., and Maren Linstaedt
2012 Image-Based Low-Cost Systems for Automatic 3D Recording and Modelling of Archaeological Finds and Objects. In *EuroMed 2012, LNCS 7616*, edited by M. Ioannidis et al., pp. 1–10. Springer-Verlag, Berlin/Heidelberg, Germany.
Kim, Jinsoo, Seongkyu Lee, Hoyong Ahn, Dongju Seo, Soyoung Park, and Chuluong Choi
2013 Feasibility of Employing a Smartphone as the Payload in a Photogrammetric UAV System. *ISPRS Journal of Photogrammetry and Remote Sensing* 79:1–18.
Kjellman, Erik
2012 From 2D to 3D—A Photogrammetric Revolution in Archaeology? Unpublished Master's thesis, Department of Archaeology and Social Anthropology, University of Tromsø, Tromsø, Norway.
Koenig, Charles W.
2012 Burned Rock Middens, Settlement Patterns, and Bias in the Lower Pecos Canyonlands of Texas. Unpublished Master's thesis, Department of Anthropology, Texas State University, San Marcos.
Liebmann, Matt, Chester Walker, and Jennie Sturm
2013 Mapping Archaeological Sites Using an Unmanned Aerial Vehicle. *NewsMAC* 2013-1:8–10.
Lin, Albert Yu-Min, Alexandre Novo, Shay Har-Noy, Nathan D. Ricklin, and Kostas Stamatiou
2011 Combining GeoEye-1 Satellite Remote Sensing, UAV Aerial Imaging, and Geophysical Surveys in Anomaly Detection Applied to Archaeology. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 4(4):870–876.
Lowe, David G.
1999 Object Recognition from Local Scale-Invariant Features. *Proceedings of the International Conference on Computer Vision* 2:1150–1157.
McCarthy, John
2014 Multi-Image Photogrammetry as a Practical Tool for Cultural Heritage Survey and Community Engagement. *Journal of Archaeological Science* 43:175–185.
Manaugh, Geoff
2013 36-Gigapixel Image Captures Ancient Petroglyphs in Texas. *Gizmodo*. Electronic document, http://gizmodo.com/36-gigapixel-image-captures-ancient-petroglyphs-in-texa-1410698528, accessed August 8, 2015.
Miller, Myles R., Lawrence L. Loendorf, and Leonard Kemp
2012 *Picture Cave and Other Rock Art Sites on Fort Bliss*. Historic and Natural Resources Report No. 13-36, Environmental Division, Fort Bliss Garrison Command, Fort Bliss, Texas.
Miller, Myles R., and Tim B. Graves
2009 *Madera Quemada Pueblo: Archaeological Investigations at a 14th Century Jornada Mogollon Pueblo*. Historic and Natural Resources Report No. 03-12, Environmental Division, Fort Bliss Garrison Command, Fort Bliss, Texas.
Pollefeys, Marc, and Luc van Gool
2002 Visual Modelling: From Images to Images. *Journal of Visualization and Computer Animation* 13:199–209.
Pollefeys, Marc, Reinhard Koch, Maarten Vergauwen, and Luc van Gool
1998 Virtualizing Archaeological Sites. In *Proceedings of the 4th International Conference on Virtual Systems and Multimedia (VSMM)* 98:600–605.
Pollefeys, Marc, Luc van Gool, Maarten Vergauwen, Kurt Cornelis, Frank Verbiest, and Jan Tops
2001 Image-Based 3D Acquisition of Archaeological Heritage and Applications. In *Proceedings of the 2001 Conference on Virtual Reality, Archaeology, and Cultural Heritage*, pp. 255–262.
Porter, Samantha Thi, Morgan Roussel, and Marie Soressi
2016 A Simple Photogrammetry Rig for the Reliable Creation of 3D Artifact Models in the Field: Lithic Examples from the Early Upper Paleolithic Sequence of Les Cottés. *Advances in Archaeological Practice* 4(1):71–86.
Prewitt, Elton R.
2007 To Jump or to Drag: Reflections on Bonfire Shelter. *Bulletin of the Texas Archeological Society* 78:149–158.
Reinhard, Jochen
2012 Things on Strings and Complex Computer Algorithms: Kite Aerial Photography and Structure from Motion Photogrammetry at the Tulul adh-Dhahab, Jordan. *AARGnews: The Newsletter of the Aerial Archaeology Research Group* 45:37–41.
Roberts, Tim, and Luis Alvarado
2011 *Terminal Archaic/Late Prehistoric Cooking Technology in the Lower Pecos: Excavation of the Lost Midden Site (41VV1991), Seminole Canyon State Park and Historic Site, Val Verde County, Texas*. Texas Antiquities Permit No. 4868. Texas Parks and Wildlife Department Cultural Resources Program, Austin, Texas.
Rodriguez, Daniel P.
2015 Patterns in the Use of the Rockshelters of Eagle Nest Canyon, Langtry, Texas. Unpublished Master's thesis, Department of Anthropology, Texas State University, San Marcos.
Ross, Richard E.
1965 *The Archaeology of Eagle Cave*. Papers of the Texas Archeological Salvage Project No. 7. University of Texas, Austin.
Rua, Helena, and Pedro Alvito
2011 Living the Past: 3D Models, Virtual Reality and Game Engines as Tools for Supporting Archaeology and the Reconstruction of Cultural Heritage—The Case Study of the Roman *Villa* of Casal de Freiria. *Journal of Archaeological Science* 38:3296–3308.
Sayles, E. B.
1935 *An Archaeological Survey of Texas*. Gila Pueblo. Globe, Arizona.
Shafer, Harry J. (editor)
1986 *Ancient Texans*. Texas Monthly Press, Austin.
2013 *Painters in Prehistory: Archaeology and Art of the Lower Pecos Canyonlands*. Trinity University Press, San Antonio, Texas.
Turpin, Solveig A.
1991 Time Out of Mind: The Radiocarbon Chronology of the Lower Pecos River Region. In *Papers on Lower Pecos Prehistory*, edited by Solveig A. Turpin, pp. 1–49. Studies in Archeology 8, Texas Archeological Research Laboratory, University of Texas, Austin.
1995 The Lower Pecos River Region of Texas and Northern Mexico. *Bulletin of the Texas Archeological Society* 66:541–560.
2004 The Lower Pecos River Region of Texas and Northern Mexico. In *The Prehistory of Texas*, edited by Timothy K. Perttula, pp. 266–280. Texas A&M University Press, College Station.
Verhoeven, Geert
2009 Providing an Archaeological Bird's-Eye View—An Overall Picture of Ground-based Means to Execute Low-Altitude Aerial Photography (LAAP) in Archaeology. *Archaeological Prospection* 16:233–249.
2011 Software Review: Taking Computer Vision Aloft—Archaeological Three-dimensional Reconstructions from Aerial Photographs with PhotoScan. *Archaeological Prospection* 18:67–73.
Verhoeven, G., M. Doneus, Ch. Briese, and F. Vermeulen
2012 Mapping by Matching: A Computer Vision-Based Approach to Fast and Accurate Georeferencing of Archaeological Aerial Photographs. *Journal of Archaeological Science* 39:2060–2070.
Willis, Mark D.
2010 How to Create a Digital Elevation Model from Photosynth Point Clouds. *Markaeology*. Electronic document, http://palentier.blogspot.com/2010/12/how-to-create-digital-elevation-model.html, accessed August 8, 2015.

2013 Drone Mapping the Pyramids of Zuleta. *Markeology*. Electronic document, http://palentier.blogspot.com/2013/10/drone-mapping-pyramids-of-zuleta.html, accessed August 8, 2015.
Willis, Mark D., and Andrea Jalandoni
2011 The Pictographs of the Rock Islands of Koror, Palau: Advanced Enhancement and 3D Modeling at Five Sites for UNESCO. Unpublished report submitted to Ministry of Community & Cultural Affairs of Palau.
Willis, Mark D., Charles W. Koenig, Amanda M. Castañeda, and Stephen L. Black
2016 Archaeological 3D Mapping: The Structure from Motion Revolution. *Journal of Texas Archeology and History* 3:1–36.

NOTES

1. There are other software packages available, but our project uses only Agisoft Photoscan. For reviews and comparisons between Agisoft Photoscan and other 3D modelling programs, see Green et al. (2014), Kersten and Lindstaedt (2012), and Kjellman (2012).
2. There are cameras available with built-in GPS units, but most do not have the accuracy to georeference 3D models to the scale of an excavation unit or profile.
3. Cultural Heritage Imaging (culturalheritageimaging.org) produces calibrated photogrammetric scale bars that can also be used to georeference SfM models.
4. Radiocarbon dates obtained by the University of Texas in the 1960s indicate that the site was intermittently occupied from at least 8700 B.P. to 3400 B.P. (Ross 1965; Turpin 1991). New, as-yet-unpublished radiocarbon dates demonstrate occupation as recent as 600 B.P. and dates from deep, pre-8700 B.P. are forthcoming.
5. Although not included in this study, as part of the ASWT work in Eagle Cave, all of the X, Y, Z data from the 1963 work in Eagle Cave have been digitized and added to the GIS for Eagle Cave. The 1963 data have been georeferenced to the same spatial system as ASWT is currently using, and all of these data can be viewed in the same GIS.
6. Because the TDS points and the 3D models are georeferenced to the same spatial system, TDS points, orthophotos, and DEMs exported from Photoscan can be viewed in the same spatial system in ArcGIS (see also Figures 4, 5, and 10b).

AUTHORS INFORMATION

Charles W. Koenig ■ Department of Anthropology, Texas State University, 601 University Drive San Marcos, Texas 78666 (ck1286@txstate.edu)

Mark D. Willis ■ Sacred Sites Research, Inc. 6220 Mojave Street NW, Albuquerque, New Mexico 87120

Stephen L. Black ■ Department of Anthropology, Texas State University, 601 University Drive San Marcos, Texas 78666 (sblack@txstate.edu)