2020

The Digital Revolution to Come: Photogrammetry in Archaeological Practice

Matthew Magnani

Matthew Douglass

Whittaker Schroder

Jonathan Reeves

David R. Braun

The Digital Revolution to Come: Photogrammetry in Archaeological Practice

Matthew Magnani, Matthew Douglass, Whittaker Schroder, Jonathan Reeves, and David R. Braun

---

The three-dimensional (3D) revolution promised to transform archaeological practice. Of the technologies that contribute to the proliferation of 3D data, photogrammetry facilitates the rapid and inexpensive digitization of complex subjects in both field and lab settings. It finds additional use as a tool for public outreach, where it engages audiences ranging from source communities to artifact collectors. But what has photogrammetry's function been in advancing archaeological analysis? Drawing on our previous work, we review recent applications to understand the role of photogrammetry for contemporary archaeologists. Although photogrammetry is widely used as a visual aid, its analytical potential remains underdeveloped. Considering various scales of inquiry—graduating from objects to landscapes—we address how the technology fits within and expands existing documentation and data visualization routines, while evaluating the opportunity it presents for addressing archaeological questions and problems in innovative ways. We advance an agenda advocating that archaeologists move from proof-of-concept papers toward greater integration of photogrammetry with research.

Keywords: photogrammetry, three-dimensional modeling, digital cultural heritage, object photogrammetry, terrestrial photogrammetry, aerial photogrammetry, Agisoft PhotoScan (Metashape)

La revolución tridimensional (3D) prometió transformar la práctica arqueológica. De las tecnologías que han contribuido a la proliferación de datos en 3D, la fotogrametría facilita la digitalización rápida y económica de sujetos complejos tanto en el laboratorio como en el campo. Además, hay utilidad en aplicar la fotogrametría como una técnica de alcance comunitario, donde involucra a audiencias diversas desde comunidades de origen hasta coleccionistas de artefactos. Pero ¿para qué ha servido la fotogrametría en avanzar el análisis arqueológico? Aprovechando estudios anteriores publicados por los autores, revisamos aplicaciones recientes para entender el papel de la fotogrametría para arqueólogos contemporáneos. Aunque ampliamente empleado como ayuda visual, su potencial analítico permanece poco desarollado. Considerando varias escalas de investigación—pasando desde objetos hasta paisajes—examinamos cómo la tecnología encaja dentro y expande métodos existentes de documentación y visualización de datos, mientras evaluamos la oportunidad que presenta en abordar preguntas y problemas arqueológicos en formas innovadoras. Avanzamos una agenda que apoya a que arqueólogos avancen de trabajos de prueba de concepto a una mayor integración con la investigación.

Palabras clave: fotogrametría, modelado tridimensional, patrimonio cultural digital, fotogrametría de objetos, fotogrametría terrestrial, fotogrametría aérea, Agisoft PhotoScan (Metashape)

The computational revolution has shaped diverse domains of scholarship from the humanities to the sciences. Archaeologists, cultural heritage professionals, and the populations they seek to engage benefit greatly from these developments, particularly

---

Matthew Magnani (matthewmagnani@g.harvard.edu, corresponding author) ■ Department of Anthropology, Harvard University, 11 Divinity Avenue, Cambridge, MA 02138, USA
Matthew Douglass ■ College of Agricultural Sciences and Natural Resources, and Agricultural Research Division, University of Nebraska-Lincoln, Lincoln, NE 68583, USA
Whittaker Schroder ■ Department of Anthropology, University of Pennsylvania, Penn Museum, 3260 South Street, Philadelphia, PA 19104, USA
Jonathan Reeves ■ Center for the Advanced Study of Human Paleobiology, George Washington University, 800 22nd St NW, Washington, DC 20052, USA
David R. Braun ■ Center for the Advanced Study of Human Paleobiology, George Washington University; and Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology, Deutscher Platz 6, 04103 Leipzig, Germany

American Antiquity 85(4), 2020, pp. 737–760

doi:10.1017/aaq.2020.59

the growing ease of three-dimensional (3D) model production, sharing, and manipulation. A number of technologies—ranging from computed tomography and laser scanning to photogrammetry—facilitate the visualization and analysis of 3D data and may be incorporated into museum exhibits or viewed remotely. Inexpensive hardware and software, combined with a simplicity of practice, have fueled an explosion of interest in creating 3D representations of anthropological subjects.

Of these tools, photogrammetry has emerged to play an important role for communities of researchers and the public alike. Defined broadly, photogrammetry involves the measurement of distances from still photographs (Bolles et al. 1987; see also Magnani and Douglass 2018). The rapid development and declining cost of computer hardware ensure that a tool once reserved for national governments that had access to specialized equipment is now available to individual researchers with modest budgets. This rapid growth in the use of photogrammetry has recently led to a proliferation of publications detailing photogrammetric protocols and proofs of concept. Using the data scraper *Publish or Perish*, we were able to demonstrate the expansion of photogrammetry's use from 2009 to 2018 across 10 major archaeological publications: 27 manuscripts mentioned photogrammetry in 2009 versus 92 publications in 2018, attesting to a threefold increase within the decade (Figure 1).

Although photogrammetry may be used to create and analyze datasets to answer new questions about the past, the majority of scholarly papers remain focused on the technology and the creation of visual representations at the expense of photogrammetry's application and analysis. As Shott suggests about digital applications more generally, "Certainly, the burgeoning literature on digital methods in archaeology has its share of 'See what I did because I could do it' contributions. There is nothing wrong with such papers when they serve as proof-of-concept, but they do not always contribute directly to the accumulation of archaeological knowledge" (2014:2). In another review on digital archaeology, Zubrow offers a similar reflection: "There is a tendency to use digital technological solutions simply because one has the 'toys' available" (2016:22).

In recent commentaries on the computational revolution in archaeology, scholars have considered both the promise and unreached potentials of applying new technologies—ranging from 3D imaging to large-scale database analysis—to address innovative research questions and expand archaeological knowledge (Grosman 2016; Howland 2018; Shott 2014). Grosman suggests, "We should target issues that cannot be resolved using traditional approaches and benefit from data that are accessible only by applying digital methodologies," but she questions whether these benefits of new technology have been realized (2016:140).

Does photogrammetry have greater interpretive potential than previously employed archaeological methods? Or is it best suited as a new medium for community outreach and visualization? In either case, is its practice addressing the needs of archaeologists and the communities we work with, or are we preoccupied with demonstrating the merits of the latest software and workflows?

Photogrammetry in Perspective

It has only been in the last decade, and even more so in the last five years, that there has been an exponential increase in the number of published papers integrating photogrammetry. This increase was brought about by the declining costs of and improvements in computer technology, including both hardware and software advances, coupled with similar changes in digital photography. Compared to earlier technologies that required heavy and expensive equipment paired with specialists for data processing and interpretation (Anderson 1982; Fussell 1982; Turpin et al. 1979), contemporary photogrammetry simply requires a digital camera matched with generally inexpensive or open-source software. Because of this ease of accessibility, photogrammetry compares favorably to other 3D digitization methods used today, such as laser and white-light scanners that are often bulkier, are expensive, and may require specialized operators.

The development of a range of options for processing and manipulating data has further

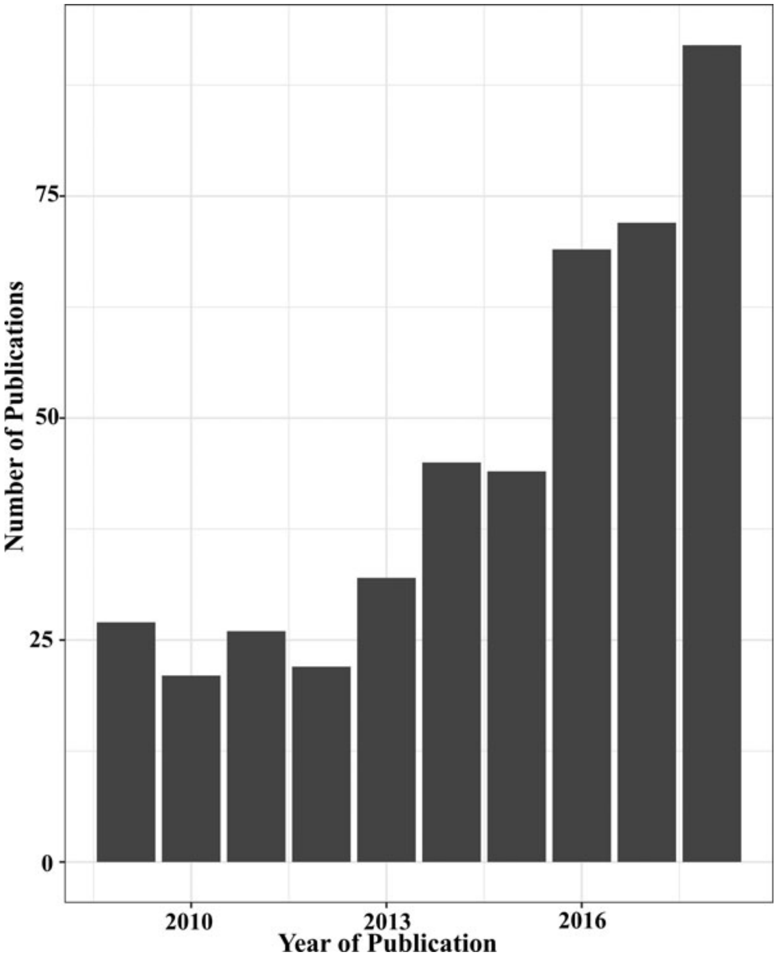

Figure 1. Bar graph showing an increase in publications mentioning photogrammetry from 2009 to 2018, derived from the data scraper *Publish or Perish*. Analysis was limited to high-ranking publications in archaeology and heritage studies that have been existence for the last 10 years: *Archaeological and Anthropological Sciences, Antiquity, Current Anthropology, Heritage Science, International Journal of Heritage Studies, Journal of Archaeological Science, Journal of Archaeological Method and Theory, Journal of Cultural Heritage, Journal of Field Archaeology,* and *World Archaeology*.

encouraged the widespread adoption of photogrammetry. Several software packages are available to process models; they range in price from free to those with monthly or yearly subscriptions. Although some programs are conducive to object-based modeling (e.g., AutoDesk ReCap, PhotoModeler Scanner, RealityCapture), others are frequently used or intended for aerial applications (e.g., Altizure, AutoPilot, Pix4D). Because of its straightforward interface and relatively low cost, Agisoft PhotoScan (re-released as Agisoft Metashape) has emerged as the preferred software for archaeologists, especially those with access to an educational license (De Reu et al. 2013; Douglass et al. 2015; Fassi et al. 2013; Olson et al. 2013; Roosevelt et al. 2015). However, in other cases—for instance, when using historic imagery with low overlap between photographs—alternate algorithms (e.g., Automatic Terrain Extraction) and software (e.g., SocetGXP) may be desirable (Papworth et al. 2016).

In the following discussion of recent studies on photogrammetry, we focus on one of its most frequently used forms—modeling using structure-from-motion (SfM)—which entails the production of 3D data from a series of overlapping photographs. We categorize previously conducted research based on the scale of inquiry, beginning with photogrammetric modeling as practiced at its smallest, sub-centimeter scale, to ground-based photogrammetry, and finally to landscape-scale projects that often rely on photographs collected by unmanned aerial vehicles (UAVs). We scaffold a discussion of the general trends, advances, and shortcomings of each of these scales of inquiry on examples drawn from our own recent applications. We consider why photogrammetry has been used at each scale and whether its use has permitted the approach of archaeological and anthropological data from new angles. Our role is as archaeological and anthropological practitioners, not programmers or computer-vision specialists. Despite this, we hope to initiate discussion on the limitations of current mainstream applications—which usually fall into the category of "proof of concept"—and suggest ways we may challenge this trend.

Object-Based Photogrammetry

Uses in Archaeological and Cultural Heritage Research

Artifact analysis is a central component of archaeological inquiry. We define object-based photogrammetry as the production of models on the scale of sub-centimeter artifacts to larger movable objects. At this scale, photogrammetry has been applied to essentially all classes of archaeological remains, including stone, ceramics, and human and animal bone. When applied to individual pieces or assemblages, photogrammetry may be used to extract traditional information in novel ways (e.g., to quantify the length of a stone tool, but from behind a computer screen) or to gather and analyze datasets that were less accessible before the advent of 3D modeling (e.g., artifact cross-sectional profiles or geometric morphometric landmarks). Yet, the analytical potential of the technology at this scale has yet to be realized. With few exceptions, scholars have merely affirmed the accuracy of specific workflows, cultivating best practices in the absence of implementation.

Considering the ubiquity of the technology, photogrammetry has rarely been used to analyze archaeological material. However, some object-based studies analyze both skeletal and lithic remains. In these cases, photogrammetric data often replace that acquired by more expensive and specialized equipment. In studies observing cut marks, researchers combined microphotogrammetric models with morphometric analysis, observing cross-sectional cut mark profiles at regular intervals. The resulting models allow the evaluation of marks on bones and promise to help identify lithic raw materials used in butchery practices (Arriaza et al. 2017; Maté-González et al. 2019; Thompson et al. 2017; Yravedra et al. 2017). Photogrammetry thus provides an inexpensive replacement for similar work previously undertaken with costly and immobile equipment, including scanning electron microscopes (González et al. 2015).

An emerging body of scholarship analyzing stone tools has also applied photogrammetry. Here, the technology replaces measurements made with devices ranging from calipers to microscribes. In a study analyzing Levallois technology, Ranhorn and colleagues (2019) calculated core volumes and flake scar angles, though they note the same data could have been derived from other methods, including comparatively low-technology cross-beam calipers (Lycett et al. 2006). Analyzing cores from experimental and archaeological assemblages, Ranhorn and coauthors established geometric measures drawing on preexisting analytical frameworks in lithics. Porter and colleagues (2019) measured core attributes with greater precision than achieved with traditional methodologies using notoriously clumsy and imprecise instruments like goniometers. Finally, other scholars integrated morphometrics to analyze ethnographic stone tool use among the Hadza. Benito-Calvo and colleagues (2018) quantified patterns of use wear from baobab pounding, with implications for studying other ethnographic and archaeological collections.

Additional work has explored photogrammetry as a tool to observe edge damage on metalwork (Molloy et al. 2016) and to explain stone artifact reduction sequences on rapidly acquired digital representations of artifacts left in the field (Bleed et al. 2017). Researchers extracted landmarks from models of crania to inform research on animal domestication (Evin et al. 2016) and hominin evolution (Hassett and Lewis-Bale 2016). Others used photogrammetric models of crania from archaeological assemblages to differentiate among populations based on temporal morphologies (Timbrell and Plomp 2019). The technique was also proposed as an inexpensive replacement for archaeological illustration (Magnani 2014), and its output was compared to the production of models made with laser (Koutsoudis et al. 2007) or structured-light scanners (Evin et al. 2016). Photogrammetry is thus most often touted as a replacement for preexisting methodologies—from archaeological illustration to morphometrics: it is seen as useful not because of the new analyses the technology facilitates, but because of the lower cost and improved accessibility of 3D model generation.

Other proof-of-concept papers have demonstrated photogrammetry's potential in reading degraded or destroyed artifact surfaces. Using 3D models, scholars improved legibility of epigraphic Roman texts through manipulation of artificial lighting parameters (Carrero-Pazos and Espinosa-Espinosa 2018). In a similar case study, Andreu and Serrano (2019) showed how photogrammetry of stellae and the virtual manipulation of model attributes—including the generation of height maps—can improve readability of weathered or damaged inscriptions. Integrating virtual reconstruction of pottery and designs with other techniques like D-stretch on pottery (González et al. 2019) and reflectance transformation imaging with basketry (Kotoula et al. 2019), archaeologists developed techniques to visualize designs that had degraded. Other studies matched 3D models derived from photogrammetry with principal component analysis, allowing the complete estimated reconstruction of ceramic vessels (Zvietcovich et al. 2016).

In addition to proof-of-concept papers detailing analytical possibilities, object-based modeling has quickly become a medium for sharing digital representations and engaging with broader publics. Such projects emphasized 3D models as tools for data visualization and sharing with diverse stakeholders. Magnani and colleagues (2018) coupled ethnographic interviews with photogrammetry to improve museum access for Indigenous artisans. In another study by Douglass and coauthors (2017), photogrammetric data were collected during "artifact roadshows" that fostered public engagement through the digitization of private collections. The project promises to improve regional archaeological knowledge and relationships with artifact collectors.

Although applications in this area are generally lacking, a robust literature testing photogrammetric workflows has developed. Previous research emphasizes that working with smaller subjects permits tight control to be exerted over data collection parameters. To stabilize the camera and regularize photography routines, objects may be placed on turntables against a matte background to simplify processing (facilitating a step known as masking, or background removal) while the camera is mounted on a tripod. Greater control over camera settings (e.g., low ISO, slow shutter speed, and a high f-stop to increase the depth of field) and lighting (e.g., even, shadowless illumination) similarly influenced model quality positively (see, for example, Gallo et al. 2014). The equipment for these routines is generally affordable and portable, and different variants were suggested as a best practice to meet different circumstances (Magnani et al. 2016a; Porter et al. 2016; Sapirstein 2018).

Researchers have emphasized the flexibility of the technology and the need to employ methodologies suited to the research context at hand. For instance, with field-based applications where time is the primary limiting factor, it is often sufficient to use a more expedient, less tightly controlled setup to generate models (e.g., Bleed et al. 2017). In other cases, conditions may allow, and research questions may warrant, a workflow using a turntable and controlled lighting. Practitioners must strike a balance between the precision and detail needed for the specific 3D research application and the time, budget, and scope of the modeling that has to be completed. Work comparing two approaches—one expedient and one refined—demonstrated that they differ qualitatively but not significantly quantitatively: both approaches produced models with accuracy within the tolerance of caliper measurements (Magnani et al. 2016a, 2016b). Nonetheless, qualitative differences influencing model visualization indicate the benefit of more controlled protocols.

A Case Study in Object-Based Research

A recent report on Early Stone Age bifaces exposed by erosion in the Doring River Valley in western South Africa shows how object-based photogrammetric models facilitate detailed, post-fieldwork analysis (Bleed et al. 2017). We also include this example as an illustration of how digital models support remote study.

Drought and overgrazing along the Doring River increase erosion of terrace sediments, exposing discrete archaeological surfaces. A survey of the broader area revealed a particular abundance of scatters dating to the Middle Stone Age (MSA) and post-MSA time periods (Lin et al. 2016; Shaw et al. 2019). The area of Uitspankraal 1 (UPK1) reflects one such exposure, with multiple archaeological components mostly dating to the MSA. UPK1 rests on an undated calcrete; U/Th dating was unsuccessful due to high levels of debris in the sediment. However, the same geological component at nearby UPK9 returned dates of approximately 220,000 years ago (Mackay et al. 2014). While conducting a reconnaissance survey at UPK1 in 2014, 21 Early Stone Age (ESA) bifaces were discovered along a pronounced ridge. This unique find presented a commonly encountered archaeological dilemma: time in the area was limited, the research permit did not authorize artifact collection, and the authors would not be able to return to the location for additional analysis any time soon.

To facilitate detailed research of the newly discovered artifacts, a series of overlapping digital photographs were taken of each biface. The bifaces were placed on an improvised stand, consisting of a block of wood with a nail driven partially through, which was mounted on a survey tripod. Photographs (approximately 100 per biface) were taken at multiple angles by moving around the artifact and stand (Figure 2). Automatic camera settings and natural lighting were used. The approach provided a seamless representation in one step, without the need for merging separate chunks, and it generated serviceable and quantitatively accurate models under field conditions (Magnani et al. 2016a). On return to the United States, each biface was processed using Agisoft Photoscan.

Three observers then conducted a virtual analysis of the collection. Each lithicist digitally examined textured and untextured biface models to determine the number, orientation, placement, and sequence of flake scars. This information was recorded in sketches that depicted biface outlines and provided a template for organizing information about the reduction of each artifact.

Combined, the models and inferred reduction sequences provided a basis for examining each artifact's history and spoke to broader behavioral patterns underlying production and discard at UPK1. Results demonstrated considerable variation in the initial blank/cobble shape, reduction intensity, and biface outline, but regularity in the placement, sequencing, and procedural organization of blows. These findings, as well as the comparison to bifaces documented in other contexts in the study region, will support further understanding about the unique life histories of ESA bifacial tools, as well as the cognitive and social processes of those who made, used, and discarded the objects.

Our initial approach represented a conventional analysis undertaken in a virtual setting. However, a distinct benefit of photogrammetric modeling is the ability to retain and share models for future work. Volumetric and morphometric landmark-based analysis (e.g., Iovita and McPherron 2011; Ranhorn et al. 2019) is possible using the reported biface models. At the same time, growing collections of ESA/MSA bifaces housed in digital archives (e.g., Sketchfab) will facilitate expanded comparison of the Doring sample to materials from other archaeological contexts in South Africa and beyond. Although widespread digital analysis lags behind the production of 3D data, the preservation of these Doring models provides an accessible record for future study.

In sum, virtual examination of an assemblage of ESA bifaces supported detailed post-fieldwork analysis and established a foundation for additional research. As stand-ins for physical

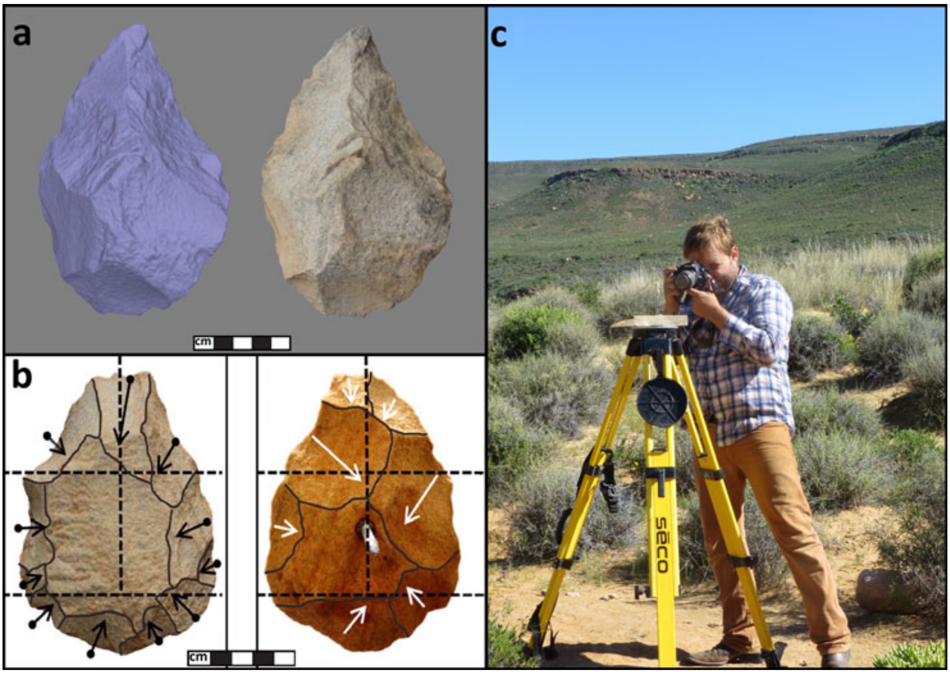

Figure 2. UPK1 Bifaces. (a) Representative 3D model; (b) flake scar organization recorded through virtual analysis of model orthophotos; and (c) Matthew Douglass using an expedient photogrammetry setup. (Color online)

artifacts, the volumetric qualities and photorealistic textures of the biface models provided an analytical experience comparable to hands-on laboratory analysis and exceeded the potential of illustrations or photographs. Photogrammetry thus has potential as a tool not only for remote, post-field analysis and broader collaboration (via model sharing) but also in contexts where artifacts must be left in the field.

A Future Agenda for Object-Based Photogrammetry

Research conducted to date, with few exceptions, highlights the development of the method. These studies hint at what photogrammetry may allow in the future, yet generally lack application to substantial research questions or archaeological datasets. It has been clearly established that the technology is suitable for replacing data acquired using more expensive techniques. Yet, even though complex datasets may be extracted from 3D models, few publications (including our own presented earlier) reported using 3D morphometric landmarks taken from photogrammetric data. Nor has the digitization of artifacts using photogrammetry led to widespread remote analyses that should be technologically possible. In fact, even complex morphometric analyses may be achievable with simple and dependable technology (see Lycett et al. 2006). Still, in the field or in other contexts where specimens cannot be revisited, 3D models provide the opportunity to return and extract additional data. Therefore, applications may increase with time as researchers become more aware of these potentials and more comfortable with and trusting of photogrammetric workflows.

Despite its unrealized potential, we expect that object-based photogrammetry will retain and expand its utility in some cases (e.g., under specific field conditions or contexts where budgets are limited or a faithful photographic texture is important) and contract in others. In particular, its cost effectiveness may be overshadowed by structured-light and laser scanners, technologies that will continue to decrease in price and improve in speed, accuracy, and precision. Though most accessible, photogrammetry lags behind comparable technologies in application. Structured-light and laser scanners were adopted earlier and remain better established analytical tools. For example, publications drawing on non-photogrammetric scan data have furthered the study of lithic reduction, from the measurement of flake mass (Clarkson and Hiscock 2011) and cortex (Lin et al. 2010) to post-depositional transformation (Grosman et al. 2011). To become more seriously considered as a research tool, studies using photogrammetry must move beyond proof of concept and parallel analyses undertaken with 3D datasets derived using other methodologies.

As with digital applications more generally, photogrammetric modeling can help preserve and share cultural heritage still in use, left in the context of its discovery, or held privately. Digitization can enable remote access to objects independent of distance or the abilities of museums to display those objects publicly (e.g., Hirst et al. 2018; Hollinger et al. 2013; Katyal 2017; Kwan and Kwan 2017). Through model viewing platforms, file sharing, and the use of 3D printing, a range of communities may be offered new opportunities to interact, touch, and even possess representations of objects in ways that break through the "glass-case paradigm" of more conventional displays (Wilson et al. 2017). When we break this barrier in the near future, we will likely see the benefits of matching photogrammetry with techniques of additive manufacture and milling, whereby 3D replicas of artifacts may be used in museum and other public environments (Kaufman et al. 2015).

Ground-Based Photogrammetry

Ground-based photogrammetry, as defined here, refers to the production of models of immovable objects and features documented from ground height. Images are taken as the photographer moves around the subject being recorded, and the camera is either handheld or mounted to a portable tripod. In practice, ground-based photogrammetry is often merged with aerial photogrammetry (see the next section), particularly when top views of tall features are obtained using cameras mounted to poles. The use of photogrammetry for ground-based applications has moved past discussions of workflows to regular utilization. In practice, most archaeologists use the technology either to gather data comparable to those obtained with existing methods or to remotely visualize data. Digital facsimiles may stand in for inaccessible features, unreachable because of their remote or obscured locations or those lost through excavation or otherwise degraded. Photogrammetric data preserve the ability for post-field analysis, capturing details not easily recorded with pen and paper or photography alone (e.g., profile and sketch maps).

Photogrammetry has been incorporated into excavation routines (Doneus et al. 2011; Elvis Badillo et al. 2020; Garstki et al. 2018; Koenig et al. 2017; Meredith-Williams et al. 2014; Peng et al. 2017) in which it is used as an alternative to standard recording protocols, including measurements with total stations and documentation using photographs or pen and paper. Since excavation is destructive and image acquisition is potentially rapid, researchers emphasize photogrammetry's ability to retain visual representations of sediment characteristics and object associations that would otherwise be lost. The same benefits exist for the documentation and preservation of threatened or degrading subjects (e.g., Fujii et al. 2009), including more ubiquitous heritage like street pavement (Martínez et al. 2015) or features destroyed by natural disasters, such as buildings that caught fire (Lancaster 2018) or architecture damaged by earthquakes (Forlin et al. 2018).

Similarly, models provide a basis for post-hoc study after fieldwork. Douglass and colleagues (2015) incorporated photogrammetry with a pedestrian survey, augmenting standard field measurements and facilitating remote analysis. Applications in cave settings (Grussenmeyer et al. 2010; Strasser et al. 2018) and inaccessible spaces such as tombs (Pérez-García et al. 2019) presented similar cases where digital stand-ins supported visualization and analysis for contexts that were otherwise inaccessible to archaeological examination.

Revisiting archival sources, archaeologists are beginning to demonstrate the value of old excavation photographs for contextualizing contemporary excavations in 3D. From case studies in Greece, Wallace (2017) demonstrated how using photographs from as far back as the 1970s to generate models provides a useful baseline for conducting archaeological work today. The use of old photographs was also productive for Paleolithic excavations, which often revisit the same sites and benefit from improved spatial context derived from archival photographs (Discamps et al. 2016). In other exceptional cases, photogrammetry permitted the reconstruction of heritage lost through conflict or natural disaster using publicly shared images (Grün et al. 2004).

Increasing application is also witnessed in rock art studies, where SfM has proven to be an inexpensive and accurate methodology for generating representations of rock art (Jalandoni et al. 2018); in some cases it was used explicitly to document and reinterpret previously studied sites (Salazar et al. 2019). The technique is sufficiently accessible that it may be used by nonspecialized field crews during rock art survey and documentation, as well as by avocational archaeologists participating in site monitoring schemes (Davis et al. 2017; Johnson and Solis 2016; Lynch et al. 2017). Building on the difficulty of visualizing wall modifications like engravings, 3D models derived from photogrammetry allowed a manipulation of shading that improves readings of rock art panels (Carrero-Pazos and Espinosa-Espinosa 2018). Height maps generated using Agisoft permitted other rock art researchers to distinguish between prehistoric and historic engravings (López et al. 2019). Finally, photogrammetric models were even used to estimate the sex of individuals who produced hand sprays in rock art, comparing archaeological and experimental data (Mackie 2015).

Underwater applications (Henderson et al. 2013; McCarthy and Benjamin 2014; Yamafune et al. 2017) provide a similar opportunity to support detailed mapping and post-hoc metric analysis, facilitating the visualization of inaccessible contexts. Photogrammetric techniques have democratized in parallel with diving technologies, increasing public accessibility and potential risk to underwater heritage. As a result, scholars have argued for the importance of creating photogrammetric repositories of submerged heritage to aid in its preservation (Aragón et al. 2018). Further work established underwater photogrammetry as a useful analytical tool in diverse research contexts. For example, researchers verified the accuracy of the methodology for measuring stone anchors, highlighting photogrammetry's benefits as a nondisruptive survey technique after verifying its accuracy through land-based examples (Fulton et al. 2016). Other projects integrating the footage from GoPro cameras demonstrated the viability and flexibility of modeling even under low-visibility conditions (Pacheco-Ruiz et al. 2018).

Applied ground-based studies often facilitate the digital reconstruction of archaeological subjects. These projects may integrate different techniques, including laser scanning or other photogrammetric protocols with SfM (e.g., multi-image spherical photogrammetry). Robinson and colleagues (2019) used a combination of photogrammetry and LiDAR data to hypothesize about the roof structures of Neolithic temples in Malta, which lack any material traces. In a similar case study, Pierdicca (2018) integrated spherical photogrammetry with Agisoft to re-create monumental archaeological sites in Peru. In another applied case, reconstructions of cisterns using photogrammetry matched with computer simulations improved understandings of volume and fill time required for a UNESCO-registered site in Spain (Ortiz-Cordero and Fernández 2017).

Although ground-based photogrammetry supports analysis comparable to standard field measurements and visualization in new formats, the technology infrequently enables new analyses like the abovementioned reconstructions. Instead, models may enable fast and increasingly accurate measurement of features. Photogrammetry was used to estimate the volume of archaeological earthworks (Magnani and Schroder 2015), monitor the erosional rates of preserved hominin footprints (Zimmer et al. 2018), and evaluate building costs and enable basic measurements of architectural features (Polo et al. 2017; Štuhec et al. 2019). Digital analysis of model geometry likewise supported the quantitative measurement of shapes and the documentation of details otherwise invisible to the naked eye. Hixon and colleagues (2017) presented a case in which model curvature analysis elucidated previously unrecorded etching in scoria bodies from the island of Rapa Nui. The authors reported a number of petroglyphs, imperceptible due to color and light conditions in the field, that had previously escaped detection.

Because ground-based photogrammetry entails the documentation of immovable subjects in field contexts, it typically does not offer the level of control over environmental variables seen in lab-based object photogrammetry. Efforts must be made to prepare a scene by removing obscuring vegetation, mitigating human traffic, cleaning excavation units, and placing ground controls for scale and georeferencing. Photography routines vary based on the subject at hand and the circumstances of the project. On one end of the spectrum, photogrammetric survey can be added as part and parcel of regular field recording (Douglass et al. 2015; Haukaas and Hodgetts 2016). Similarly, the technology represents a valuable tool to record sites that are at risk of destruction (Magnani and Schroder 2015) or that have already disappeared (Grün et al. 2004). It may be applied in contexts where archaeologists must collect detailed spatial data quickly or even after the fact; for example, where a salvage site is at imminent risk of erosion, where survey budgets are limited, or where heritage has been destroyed but a sufficient quantity of photographs of the subject exist (Bryan and Chandler 2008; Dhonju et al. 2017; Edwards et al. 2016; Haukaas and Hodgetts 2016; New Palmyra 2019; Project Mosul 2019; Vincent et al. 2015). In these circumstances emphasis is placed on the ease of use and the benefit that models can add to more traditional forms of documentation. Photographs are taken rapidly using field-grade cameras and are often shot without the aid of tripods. Camera settings are less often controlled, and scale is determined during postprocessing from objects of known size.

In other situations where higher degrees of accuracy and precision are desired, photogrammetry has been used to document specific features with more advanced planning (Koenig et al. 2017; Peng et al. 2017; Sapirstein 2016). In those cases documentation was done by specialists using more exacting routines. The role of photogrammetric modeling in these cases is comparable to that of terrestrial laser scanning. Printed ground control points tied into a coordinate system (as determined by total station or DGPS) are placed around the subject. In these applications, greater care is taken to produce optimal lighting, tighter controls are placed on camera settings, larger numbers of images are taken from more angles, and tripods are used to stabilize often higher-quality cameras. These controls yield more accurate, precise, and qualitatively superior models.

A Case Study in Ground-Based Photogrammetry of Archaeological Features

To illustrate how photogrammetry facilitates archaeological field research and improves traditional recording techniques, Magnani and Schroder (2015) developed models of earthen mounds at Hopewell Culture National Historic Park and the Newark Earthworks in central Ohio, which were associated with the Hopewell culture of the Middle Woodland period (200 BC–AD 500; Romain 1996). Researchers have experimented with numerous mathematical formulas to estimate the volumes of such features (Bernardini 2004; Jeter 1984). However, these methods necessitate the assumption of simplified shapes to calculate approximations based on “conoidal” or “trapezoidal prism” formulas, for example, and these estimates tend to overestimate the true volume. Other methods, including the use of gridding, contours, and computer simulations, are costly and typically underestimate the true volume (Lacquement 2010; Sorant and Shenkel 1984).

Ground-based photogrammetry was chosen as an affordable and efficient method to calculate volume and potentially track rates of erosion of the mounds. The researchers used DSLR cameras, an educational license of Agisoft PhotoScan, and an optional photo pole for larger features. They selected the Mound City Group and Newark Earthworks areas, because they are landscaped areas free of vegetation, which facilitates the photography of features (Figure 3a). Up to 200 photographs of single features were taken from various heights and angles. Images were collected at regular intervals around the mounds, creating a circle of inward-facing pictures.

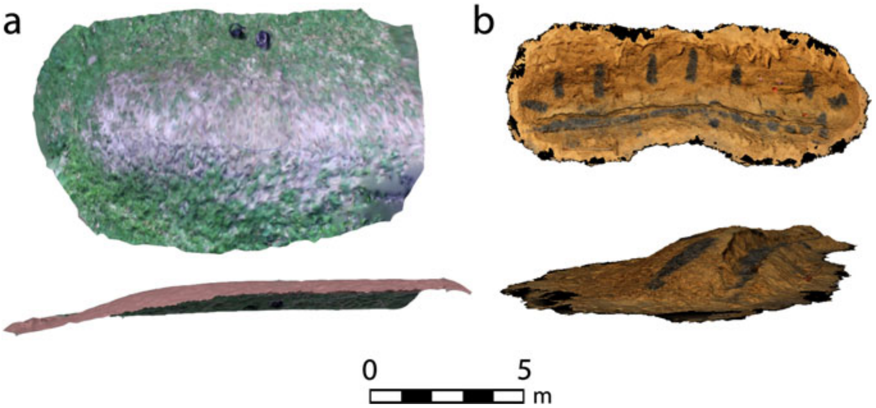

Figure 3. (a) Overhead and profile views of a linear feature from Newark Earthworks, Ohio, used in cross-sectional analysis; (b) overhead and oblique views of an artificial mound used to test photogrammetry's sensitivity to volumetric change. The darker sections represent intentionally placed gravel to highlight modification to the feature. (Color online)

After the models were processed using Agisoft PhotoScan, the researchers determined the limits of features at points of inflection with the ground. Then, watertight models were generated by closing the large hole at the base of the mounds using free software, such as MeshLab (version 1.3.2, developed by the Visual Computing Lab ISTI-CNR). Final analyses and volume calculations were conducted by exporting models to the computer-aided design (CAD) application Rhinoceros 3D (version 5, developed by Robert McNeel & Associates).

Precision was tested by generating up to five separate models of a single feature with different batches of photos. A comparison of volume estimates of these trials demonstrated that results derived from photogrammetry were far more precise than other traditional volume estimates calculated using geometric formulas. Finally, to verify photogrammetry's accuracy in this scenario, Magnani and Schroder (2015) tested the methodology on "mock" mounds that were constructed out of a known volume of sand and altered in controlled ways (Figure 3b). These mounds were photographed in the same manner as those in central Ohio and were additionally mapped with a total station. The results demonstrated that photogrammetry produced accurate and precise models, especially in relation to total station contours. The point clouds generated using triangulated, integrated networks from a series of individual total station points proved far less accurate.

This case study demonstrates that photogrammetry can be used to model features in uncontrolled environments. More importantly, the method was shown to be precise in detecting subtle changes in volume, outperforming measuring instruments like total stations. Finally, the affordability and simplicity of the methodology suggest that photogrammetry may be used in both academic research contexts and in cultural resource management to record and monitor changes in archaeological features particularly susceptible to erosion, either from public use or environmental threat.

The Future of Ground-Based Photogrammetry

Two features of ground-based photogrammetry make it a likely staple among archaeologists. The relative affordability of data capture using cameras and of subsequent processing using inexpensive software makes it an easily accessible resource. Despite its increasing acceptance in the field, it appears to be used most frequently as a recording tool to document features and excavation progress or as a replacement for photographs and maps in conference and seminar presentations.

As with object-based applications, there are competing technologies that threaten to overtake photogrammetry. As terrestrial scanners become more inexpensive and portable, they may eventually surpass photogrammetry in ease of use. Photogrammetry is inherently more subjective because of the variability in the routines described earlier, but its low cost and image-textured skins still make it the best choice for many applications (Davis et al. 2017).

Although proof-of-concept papers suggest that photogrammetry is suitable for the study of ground-based features, 3D data captured using other technologies are more regularly incorporated into archaeological analyses. As an example related to our case study, terrestrial laser scanning (or ground-based lidar) is already being used to study mound variability. In a case from Queensland, Larsen and colleagues (2017) studied 51 shell mounds, integrating radiocarbon dates and studies of shape, to inform the broader understanding of site taphonomy. Moving forward, archaeologists using photogrammetry should first seek to match the body of preexisting work framed by comparable technologies. Regardless, some combination of techniques may represent the best possible solution going forward. For instance, there are now routines that merge data from terrestrial scanners and photogrammetry, where scanning provides metric precision and methodological reliability and photogrammetry provides superior photo realistic texturing (Pepe et al. 2016).

The development of such approaches will be an essential first step to move photogrammetry beyond its proof stage. We must seek not only to generate new publications *on* the technology but also contribute more tangibly *to* bodies of archaeological knowledge, as we seek major changes through the pursuit of "grand challenges" (Huggett 2015). If we are to move beyond implementing photogrammetry as a "digital toy" and as a theoretical rather than just methodological contribution (sensu Zubrow 2006), we must critically assess and expand how the technologies are deployed.

Such broader considerations must inform the way we use photogrammetric models to generate visual representations of our subjects; we must also increase our awareness of how decisions about digitization affect interpretation. As a case in point, Thompson (2017) critically analyzed the choices made in photogrammetric salvage efforts to reclaim sites lost to conflict in Iraq and Syria. In those efforts, Roman and other pre-Islamic heritage were disproportionately represented in digital reconstructions, even though more recent shrines, mosques, and churches comprised the majority of damaged sites. In other cases, the act of framing can impose a false sense of boundaries for features and other archaeological subjects. For instance, in the example from our presented work, the limits of the mounds were assigned during processing and analysis, potentially affecting an understanding of the broader site or mound context.

Aerial Photogrammetry

At its largest scale, photogrammetry has been combined with aerial photography to reconstruct large archaeological features, sites, and landscapes. This has increased the accessibility of and potential for conservation of archaeological sites in new media and has elaborated gains made using less accessible aerial platforms (e.g., Nikolakopoulos et al. 2017; Peinado Checa et al. 2014).

The expansion of aerial photogrammetric modeling in archaeology is directly tied to changing technologies in other sectors. The commercial development of lightweight rotary wing UAVs, including quadcopters, hexacopters, and octocopters, drives cost reductions and performance improvements (Remondino et al. 2011). Improvements include growing payload capacities for camera equipment and GPS-inertial equipment ideal for accurate georeferencing (Eisenbeiss and Sauerbier 2011; Nex and Remondino 2014; Saleri et al. 2013; Themistocleous et al. 2014, 2015; Vallet 2007). Modern lightweight drones use simple interfaces that allow manual flying with basic training, as well as automatic flying and image acquisition with the use of a tablet or smartphone.

The simultaneous development of high-quality and low-cost video equipment, available to practicing archaeologists and members of the public, expands the possibilities of deriving photogrammetric models from aerial footage. Pérez-Alvárez and colleagues (2019) demonstrated how aerial videos could be used to extract photogrammetric models of landscapes for archaeological analysis. Themistocleous (2017) showed how sites could be modeled using videos posted on social media, vastly expanding potential sources of archaeological data.

For analysis and conservation, models made from aerial photographs come with a smaller price tag than those made by laser-scanning systems and provide photographic textures as well. Aerial photogrammetry permits the analysis and observation of sites—for instance, high or dangerous-to-reach rock art panels—that are typically inaccessible to pedestrian survey or the public (Berquist et al. 2018). However, photogrammetry lacks the ability to map ground surfaces accurately in contexts with significant ground vegetation. In addition to these limitations of the technology, in many cases there are legal considerations associated with aerial photogrammetry. As drones have become accessible to the general public, many countries have restricted their use. Governmental permits, as well as local permissions, are often required before UAVs can be used.

To avoid these potential barriers, it may be desirable to collect data from aerial vantage points using photo poles or mast systems, which not only circumvent flight restrictions but also the steep learning curves associated with drones. Photo poles or booms allow cameras to be rigged up to 20 m off the ground (Verhoeven 2009), though shorter masts at heights of up to 6 m are reported as more manageable. Masts are used in conjunction with a camera remote and, in some cases, are connected to Wi-Fi to refine camera views from the ground. Increasing mast height results in greater site coverage but sacrifices the mobility of camera systems. At the same time, although these setups may provide similar results to photogrammetric systems integrated with UAVs at low altitude, they often require an increased investment of time and higher quantities of photographs to achieve optimal results (Pérez-García et al. 2018).

Despite these considerations, and because of advances in UAV technology, photogrammetric models made using drones have rapidly become essential tools for archaeologists (Jo and Kim 2017; Lonneville et al. 2014; Olson and Rouse 2018; Rinaudo et al. 2012; Ruiz Sabina et al. 2015). When integrated with photogrammetry, UAVs have the potential to quickly produce accurate site maps and architectural plans. In particular, UAVs have excelled at documenting intricate features that benefit from high-resolution results, including agrarian landscapes, rock features and geoglyphs, and threatened sites (Casana et al. 2014; Harrison-Buck et al. 2016; Mark and Billo 2016; Parcero-Oubiña et al. 2016; Wernke et al. 2014). When combined with geospatial analyses, these high-resolution models have major implications for expanding the scale and scope of archaeological analysis. The most innovative proofs incorporated machine learning with data derived from photogrammetry. For instance, Orenga and Garcia-Molsosa (2019) demonstrated how drones can automatically identify sherd scatter density.

Aerial photogrammetry is increasingly being used in the creation of digital elevation models (DEMs) that are tasked with site identification, spatial analysis, and conservation. DEMs derived from aerial photographs have been produced from the scale of landscapes to smaller features. For instance, Grund and colleagues (2016) matched photogrammetry with GIS modeling to analyze bison jump sites. Using this method, they predicted that bison jumps would be expected in areas with low cliff visibility. Howland and colleagues (2018) created DEMs to model erosion, predicting processes of site formation and degradation. Similar workflows, integrating analysis of satellite imagery and DEMs, were used to understand damage caused by off-road vehicles on features as famous as the Nasca lines (Hesse 2015). On a smaller scale, Kreij and others (2018) studied Australian fish traps, modeling their filling patterns to determine their antiquity.

Although the production of accurate maps is essential to the field, some archaeologists have pointed out that, while photogrammetric data and models are being produced frequently, they have been analyzed less often (Megarry et al. 2018). In the same study, Megarry and colleagues used models constructed from aerial photographs to evaluate Neolithic-era quarries. Analyzing models to determine quarry characteristics, they identified differences in raw materials, with a focus on identifying the tool stone, felsite, and debitage size. Another recent study in Ireland used photogrammetry to visualize and record stone forts on the Tentative List of World Heritage Sites for UNESCO (O'Driscoll 2019). After producing the models, the researchers used GIS analysis to consider least cost paths (LCP) and viewsheds from the features.

A Case Study in Aerial Photogrammetry

A recent study of taphonomic effects on surface assemblages in the Koobi Fora Formation of Marasbit District, northern Kenya, provides an illustration of the increased analytical potential of detailed landscape models. This study showed that landscape-scale surface deposits have the potential to inform interpretations of early hominin mobility and foraging behavior. However, before behavioral inferences can be drawn, an assessment of post-depositional disturbance must be made (Fanning and Holdaway 2001). Water flow is the primary process eroding in situ sediments, and this process has the potential to transport artifacts from their primary locations, creating fluvial lag deposits (Ozán 2017; Petraglia and Potts 1994; Rick 1976; Schick 1986).

Investigating the effect of topography on the surface record requires high-resolution elevation data (<0.5 m/pixel), which are largely commercially inaccessible, prohibitively expensive, and not easily generated with traditional tools (e.g., total stations or other survey equipment; see also Howland et al. 2018). To provide these data in this case study, photogrammetric models were developed with UAVs (DJI Mavic, DJI Phantom), using the free tablet software Pix4D Capture to enable systematic, preplanned autonomous flight paths. The UAV was flown on a series of transects covering the extent of each region of interest. The spacing of each transect was automatically determined by Pix4D Capture to ensure at least 80% overlap between images. During flight, captured images were geotagged with GPS coordinates by the UAV (see Phillips et al. 2018).

Agisoft Photoscan Professional was used to generate 3D models. Image geotags and ground control points georectified models to an accuracy of 0.3 m or higher. Models were exported in DEM format, which may then be analyzed using GIS software. The statistical software R—specifically raster and rsaga packages—were used to generate slope, topographic wetness, and stream power models. These surface features allow for the quantification of the effect of flowing water on the modern surface. Whereas slope (Figure 4a) quantifies change in elevation, topographic wetness (Figure 4b) indicates the potential for water to collect in a location, and stream power (Figure 4c) characterizes the erosional potential of any given area. If modern erosional processes were the main impetus for the movement and subsequent redeposition of artifacts on these surfaces, then we would expect the locations of artifacts to be correlated with areas of active water erosion and pooling. In instances where the spatial distribution of specimens does not correspond to these topographical features, it can be assumed that artifact distribution is related to patterns of hominin behavior. These results provide a basis for determining which areas of the surface record can be suitably interpreted to explain ancient land use. They demonstrate the potential of UAV-assisted photogrammetry as a tool for supporting archaeological research on the scale of landscapes (Reeves et al. 2018).

Future Prospects in Aerial Photogrammetry

As technology continues to improve, archaeologists can expect further breakthroughs in capturing aerial imagery. The payload of lightweight drones is likely to increase, while the weight of devices like cameras and GPS/INS will drop. Such developments will allow archaeologists to attach other instruments capable of photographing bands outside the visible spectrum that can detect nuances in vegetation and soil types suggesting the presence of past activity areas (Hill et al. 2014). Advances in solid-state or focal-plane array lidar, currently being adapted for self-driving cars, may significantly decrease the size of lidar sensors, allowing them to be attached to lightweight UAVs (see also Risbøl and Gustavsen 2018). Aerial photogrammetry, however, is likely to remain an essential mapping tool, because under some conditions it currently offers higher-resolution data than lidar and creates realistic textures based on imagery. Significantly, photogrammetric data of landscapes can be captured with greater frequency and at lower cost than competing technologies, potentially

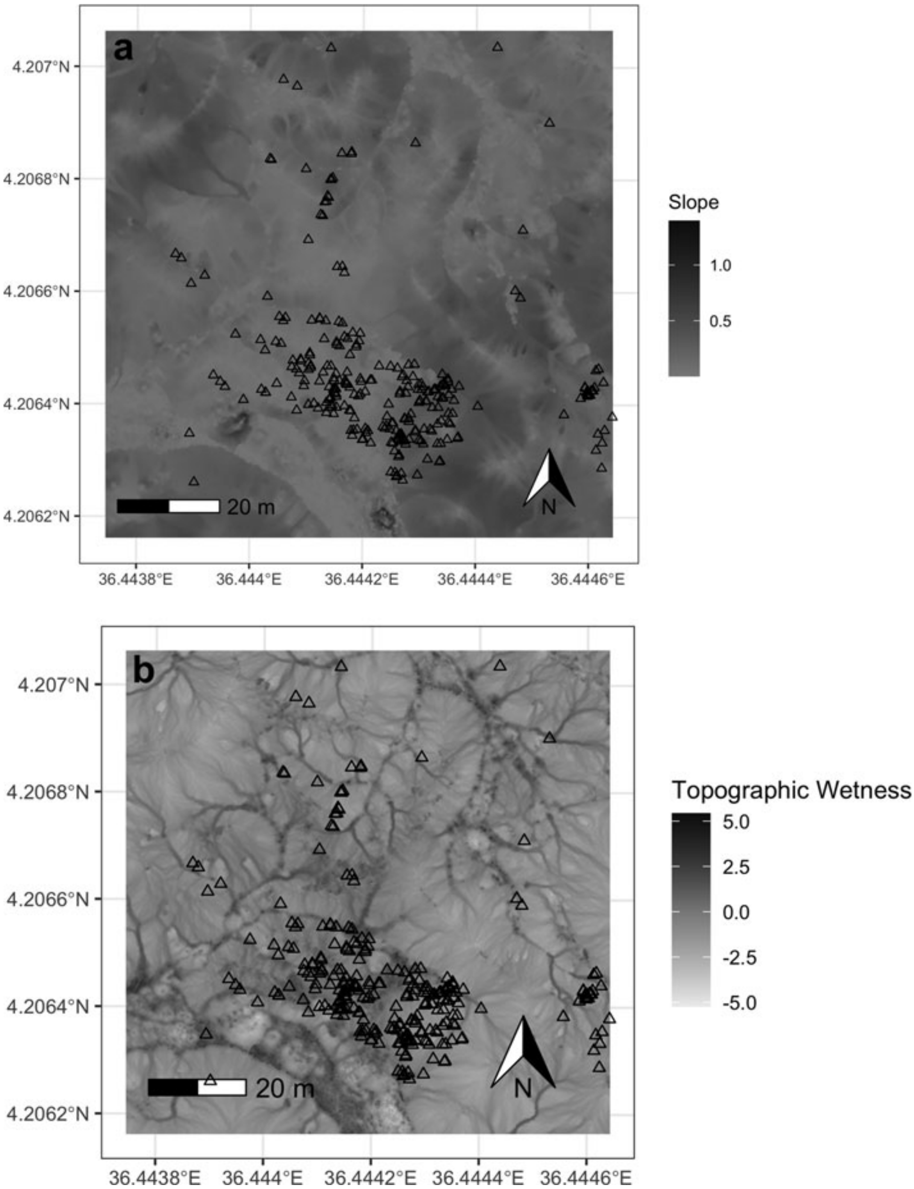

Figure 4. (a–c) Photogrammetric models from Koobi Fora, Kenya. Locations of artifacts compared with their associated landscape topography as characterized by the (a) slope, (b) topographic wetness, and (c) stream power.

allowing transformation of ground surfaces to be documented at more regular intervals.

Finally, as photogrammetry is increasingly combined with data derived from other technologies, we expect productive intersections with laser scanning systems. Researchers already have shown the possibilities of incorporating aerial photogrammetric data with laser scanning to map urban spaces, including clusters of historical buildings (Balsa-Barreiro and Fritsch 2018).

As with the other scales of study discussed in this article, archaeologists have been slower to deploy photogrammetry to answer research questions than with lidar, which has been used extensively for landscape survey and the study of regional settlement histories (Canuto et al. 2018; Chase et al. 2010; Inomata et al.

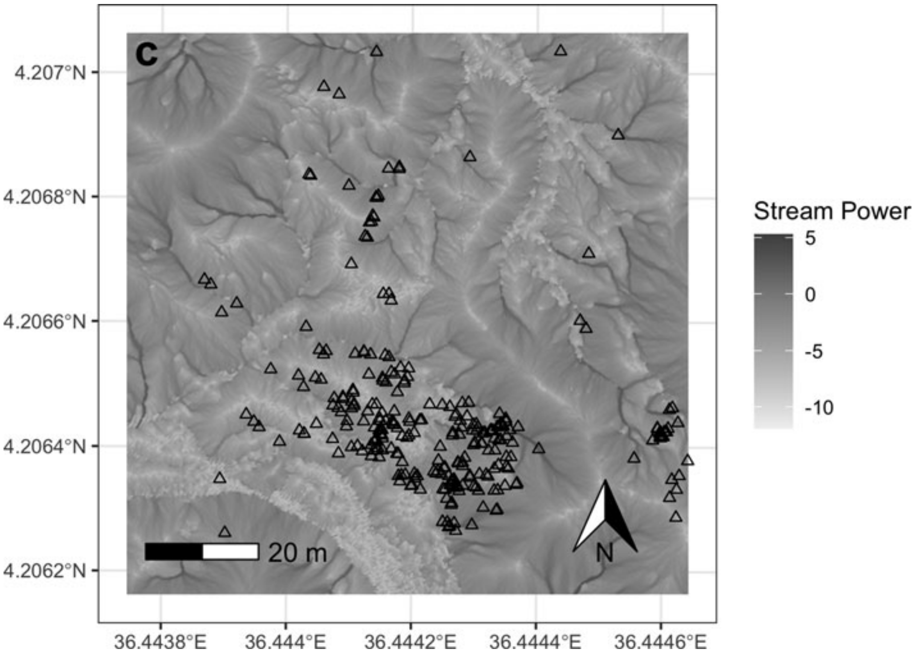

Figure 4. Continued.

2018; Murtha et al. 2019). Though such areas are unlikely to be modeled using digital cameras and drones, archaeologists may look to lidar studies to begin to imagine research questions that may be addressed with photogrammetry. Landscape-scale datasets are vital to interpreting the archaeological record, and thus, the affordability of aerial photogrammetry offers opportunities for archaeological sampling unattainable by other means.

Conclusion: The Present and Future of Photogrammetry

In its relatively short life as a user-friendly tool, photogrammetry has democratized the production of complex, 3D datasets. Its availability has improved access to lines of inquiry that were previously reserved for archaeologists with the largest budgets. Data whose collection recently required specialists and expensive equipment—ranging from laser scanners, to lidar, and to total stations— can now be gathered and processed with an inexpensive digital camera, open-source software, and a short period of training.

Bolstering access to complex datasets is a significant development in its own right, one that is central to creating an equitable archaeology. Still, the digital revolution should be transformative for archaeological *analysis*. The 3D models derived from photogrammetry, however, have made few substantive moves toward realizing this goal. In effect, the benefits of 3D data are not so much that they are revolutionary but that they further ease and facilitate the completion of routine archaeological tasks, including field documentation and sharing representations of our work in a tangible way with diverse publics.

In our synthesis we stress that a majority of studies focus on proofs of concept or recommendations for best practice. Stopping short of revolutionizing archaeology, the most practical advances have been made through the incorporation of photogrammetry in field documentation routines—although we also recognize that the technology has begun to show its potential in cultural heritage applications and community outreach. Moving forward, we hope the ability of 3D models to provide new insights into archaeological data—whether large-scale spatial or small-scale geometric morphometric data—will improve. More and more, these analyses will occur remotely.

Even as innovative applications of this technology are somewhat slow to materialize and are fraught with novel considerations, photogrammetry's future in anthropology and cultural heritage is bright. In addition to improving access and decreasing the cost of traditional analyses, its accuracy will improve as complementing technologies mature in parallel. Virtual reality platforms will continue to decrease in production cost, and 3D data will be integrated with game engines and web viewers to facilitate visualization and analysis (see, for example, Bassier et al. 2018). The incorporation of individual objects with larger landscapes and archaeological sites will create new ways to provide immersive experiences. Advances in 3D printing hold equal potential when paired with photogrammetry. Finally, its utility in education and other training spheres is becoming evident (Means 2015).

We close this article by challenging archaeologists and other heritage professionals employing digital photogrammetry—including ourselves, whose work is critically reviewed here—to broaden their analytical creativity using the technology. What constitutes a digital revolution in archaeology, and how will photogrammetry contribute to it in the future? Returning to Grosman's (2016) reflections on the computational revolution, scholars must work beyond using the technology for visualization and move toward analysis.

Photogrammetry and other 3D tools have the potential to revolutionize archaeological practice, but progress has been slow. The most significant analytical advances offered by the technology to date are to augment or perhaps refine existing techniques or to enable post-hoc evaluation of digital facsimiles. Likewise, the ability to communicate archaeological findings to the various publics who use and support our work has been further bolstered by 3D visualization. It may be through interaction with diverse stakeholders that new interpretive and analytical paths will be realized.

Photogrammetry is a well-vetted technique, and further testing in the absence of application is of limited benefit to the field. Instead, anthropologists and cultural heritage specialists must now adapt and develop the questions they are asking of 3D datasets. Perhaps rather than leading to a revolution in analysis, embracing the democratic aspects of the technology and its broad adoption hold the most promise. Still, we remain hopeful that addressing the proposed challenge will lead to a reimagining of the analytical potentials of 3D datasets—and not just those derived from photogrammetry—to integrate broader community perspectives and move beyond the refining and expediting of tested archaeological practices.

Acknowledgments. We would like to thank Simon Holdaway for providing critical feedback on a draft of this article, in addition to the anonymous reviewers who provided commentary. For the research reported in this study, Matthew Magnani was supported by the National Science Foundation Graduate Research Fellowship Program (DGE1144152). Matthew Douglass was supported by the Maude Hammond Fling Faculty Research Fellowship and the Graduate Research Council Grant in Aid of the University of Nebraska, Lincoln. Jonathan Reeves thanks the Leakey Foundation, Wenner-Gren Foundation, and National Science Foundation (DDRIG, Grant Number 1747943) for supporting this research.

Data Availability Statement. The object and ground-based portions of this article are based on previously published data. Inquiries regarding data from the aerial case study may be directed to Jonathan Reeves.

References Cited

Anderson, Richard C.
1982 Photogrammetry: The Pros and Cons for Archaeology. *World Archaeology* 14:200–205.
Andreu, Javier, and Pablo Serrano
2019 Contributions of the Digital Photogrammetry and 3D Modelling of Roman Inscriptions to the Reading of Damaged Tituli: An Example from the Hispania Tarraconensis (Castiliscar, Saragossa). *Digital Applications in Archaeology and Cultural Heritage* 12:e00091.
Aragón, Enrique, Sebastia Munar, Javier Rodríguez, and Kotaro Yamafune
2018 Underwater Photogrammetric Monitoring Techniques for Mid-Depth Shipwrecks. *Journal of Cultural Heritage* 34:255–260.
Arriaza, Mari Carmen, José Yravedra, Manuel Domínguez-Rodrigo, Miguel Ángel Mate-González, Elena García Vargas, Juan Francisco Palomeque-González, Julia Aramendi, Diego González-Aguilera, and Enrique Baquedano
2017 On Applications of Micro-Photogrammetry and Geometric Morphometrics to Studies of Tooth Mark Morphology: The Modern Olduvai Carnivore Site (Tanzania). *Palaeogeography, Palaeoclimatology, Palaeoecology* 488:103–112.

Elvis Badillo, Alex, Joshua A. Myers, and Ryan J. Peterson
2020 SfM Photogrammetric Field Methods for Historic Burial Excavations: The Case of Bethel Cemetery. *Advances in Archaeological Practice* 8:151–161.

Balsa-Barreiro, José, and Dieter Fritsch
2018 Generation of Visually Aesthetic and Detailed 3D Models of Historical Cities by Using Laser Scanning and Digital Photogrammetry. *Digital Applications in Archaeology and Cultural Heritage* 8:57–64.

Bassier, Maarten, Stan Vincke, Roberto Lima Hernandez, and Maarten Vergauwen
2018 An Overview of Innovative Heritage Deliverables Based on Remote Sensing Techniques. *Remote Sensing* 10(10):1607.

Benito-Calvo, Alfonso, Alyssa N. Crittenden, Sarah V. Livengood, Laura Sánchez-Romero, Adrián Martinez-Fernandez, Ignacio de la Torre, and Michael Pante
2018 3D 360° Surface Morphometric Analysis of Pounding Stone Tools Used by Hadza Foragers of Tanzania: A New Methodological Approach for Studying Percussive Stone Artefacts. *Journal of Archaeological Science: Reports* 20:611–621.

Bernardini, Wesley
2004 Hopewell Geometric Earthworks: A Case Study in the Referential and Experiential Meaning of Monuments. *Journal of Anthropological Archaeology* 23:331–356.

Berquist, Stephen, Giles Spence-Morrow, Felipe Gonzalez-Macqueen, Branden Rizzuto, Wiley Yépez Álvarez, Stefanie Bautista, and Justin Jennings
2018 A New Aerial Photogrammetric Survey Method for Recording Inaccessible Rock Art. *Digital Applications in Archaeology and Cultural Heritage* 8:46–56.

Bleed, Peter, Matthew Douglass, Alexandra Sumner, Maia Behrendt, and Alex Mackay
2017 Photogrammetrical Assessment of Procedural Patterns and Sequential Structure in "Handaxe" Manufacture: A Case Study along the Doring River of South Africa. *Lithic Technology* 42:3–12.

Bolles, Robert C., Harlyn Baker, and David H. Marimont
1987 Epipolar-Plane Image Analysis: An Approach to Determining Structure from Motion. *International Journal of Computer Vision* 1:7–55.

Bryan, Paul, and Jim Chandler
2008 Cost-Effective Rock-Art Recording within a Non-Specialist Environment. *International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences* 37:259–264.

Canuto, Marcello, Francisco Estrada-Belli, Thomas G. Garrison, Stephen D. Houston, Mary Jane Acuña, Milan Kováč, Damien Marken, Philippe Nondédéo, Luke Auld-Thomas, Cyril Castanet, David Chatelain, Carlow R. Chiriboga, Tomáš Drápela, Tibor Lieskovský, Alexandre Tokovinine, Antolín Velasquez, Juan C. Fernández-Díaz, and Ramesh Shrestha
2018 Ancient Lowland Maya Complexity as Revealed by Airborne Laser Scanning of Northern Guatemala. *Science* 361(6409):eaau0137.

Carrero-Pazos, Miguel, and David Espinosa-Espinosa
2018 Tailoring 3D Modelling Techniques for Epigraphic Texts Restitution: Case Studies in Deteriorated Roman Inscriptions. *Digital Applications in Archaeology and Cultural Heritage* 10:e00079.

Casana, Jesse, John Kanter, Adam Wiewel, and Jackson Cothren
2014 Archaeological Aerial Thermography: A Case Study at the Chaco-Era Blue J Community, New Mexico. *Journal of Archaeological Science* 45:207–219.

Chase, Arlen F., Diane Z. Chase, John F. Weishampel, John F. Drake, Ramesh Shrestha, K. Clint Slatten, Jaime J. Awe, and William E. Carter
2010 Airborne LiDAR, Archaeology, and the Ancient Maya Landscape at Caracol, Belize. *Journal of Archaeological Science* 38:387–398.

Clarkson, Chris, and Peter Hiscock
2011 Estimating Original Flake Mass from 3D Scans of Platform Area. *Journal of Archaeological Science* 38:1062–1068.

Davis, Annabelle, David Belton, Petra Helmholz, Paul Bourke, and Jo McDonald
2017 Pilbara Rock Art: Laser Scanning, Photogrammetry and 3D Photographic Reconstruction as Heritage Management Tools. *Heritage Science* 5:article 25.

De Reu, Jeroen, Gertjan Plets, Geert Verhoeven, Philippe De Smedt, Machteld Bats, Bart Cherretté, Wouter De Maeyer, 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.

Dhonju, Hari Krishna, Wen Xiao, Bandana Shakya, Jon P. Mills, and Vasilis Sarhosis
2017 Documentation of Heritage Structures through Geo-Crowdsourcing and Web-Mapping. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 42:17–21.

Discamps, Emmanuel, Xavier Muth, Brad Gravina, Fancois Lacrampe-Cuyaubère, Jean-Pierre Chadelle, Jean-Philippe Faivre, and Bruno Maureille
2016 Photogrammetry as a Tool for Integrating Archival Data in Archaeological Fieldwork: Examples from the Middle Palaeolithic Sites of Combe–Grenal, Le Moustier, and Regourdou. *Journal of Archaeological Science: Reports* 8:268–276.

Doneus, Michael, Geert Verhoeven, Martin Fera, Christian Briese, Matthias Kucera, and Wolfgang Neubauer
2011 From Deposit to Point Cloud—A Study of Low-Cost Computer Vision Approaches for the Straightforward Documentation of Archaeological Excavations. *Geoinformatics FCE CTU* 6:81–88.

Douglass, Matthew, Dennis Kuhnel, Matthew Magnani, Luke Hittner, Michael Chodoronek, and Samantha T. Porter
2017 Community Outreach, Digital Heritage and Private Collections: A Case Study from the North American Great Plains. *World Archaeology* 49:623–638.

Douglass, Matthew, Sam C. Lin, and Michael Chodoronek
2015 The Application of 3D Photogrammetry for In-Field Documentation of Archaeological Features. *Advances in Archaeological Practice* 3:136–152.

Edwards, Kevin, Nicolas Bigourdan, Ian McCann, and Darren Cooper
2016 3DMAPPR: A Community-Based Underwater Archaeological Photogammetry Program in Perth, Western Australia. *Journal of Australian Institute for Maritime Archaeology* 40:1–16.

Eisenbeiss, Henri, and Marin Sauerbier
2011 Investigation of UAV Systems and Flight Modes for Photogrammetric Applications. *Photogrammetric Record* 26:400–421.

Evin, Allowen, Thibaud Souter, Ardern Hulme-Beaman, Carly Ameen, Richard Allen, Pietro Viacava,

Greger Larson, Thomas Cucchi, and Keith Dobney
2016 The Use of Close-Range Photogrammetry in Zooarchaeology: Creating Accurate 3D Models of Wolf Crania to Study Dog Domestication. *Journal of Archaeological Science: Reports* 9:87–93.

Fanning, Patricia, and Simon Holdaway
2001 Stone Artifact Scatters in Western NSW, Australia: Geomorphic Controls on Artifact Size and Distribution. *Geoarchaeology* 16:667–686.

Fassi, Francesco, Luigi Fregonese, Sebastiano Ackermann, and Vincenzo De Troia
2013 Comparison between Laser Scanning and Automated 3D Modelling Techniques to Reconstruct Complex and Extensive Cultural Heritage Areas. *International Archives of Photogrammetry, Remote Sensing, and Spatial Information Sciences* XL-5/W1:73–80.

Forlin, Paolo, Riccardo Valenta, and Miklós Kázmér
2018 Assessing Earthquake Effects on Archaeological Sites Using Photogrammetry and 3D Model Analysis. *Digital Applications in Archaeology and Cultural Heritage* 9:e00073.

Fujii, Yukiyasu, Enrico Fodde, Kunio Wantanabe, and Kazuya Murakami
2009 Digital Photogrammetry for the Documentation of Structural Damage in Earthen Archaeological Sites: The Case of Ajina Tepa, Tajikistan. *Engineering Geology* 105:124–133.

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* 4:17–30.

Fussell, Angela
1982 Terrestrial Photogrammetry in Archaeology. *World Archaeology* 14:157–172.

Gallo, Alessandro, Maurizio Muzzupappa, and Fabio Bruno
2014 3D Reconstruction of Small Sized Objects from a Sequence of Multi-Focused Images. *Journal of Cultural Heritage* 15:173–182.

Garstki, Kevin, Marcus Schulenburg, and Robert A. Cook
2018 Practical Application of Digital Photogrammetry for Fieldwork in the American Midwest: An Example from the Middle Ohio Valley. *Midcontinental Journal of Archaeology* 43:133–150.

González, Miguel Ángel Maté, José Yravedra, Diego González-Aguilera, Juan Francisco Palomeque-González, and Manuel Domínguez-Rodrigo
2015 Micro-Photogrammetric Characterization of Cut Marks on Bones. *Journal of Archaeological Science* 62:128–142.

González, Esther Rodriguez, Sonia Carbonell Pastor, and Josep R. Casals
2019 Lost Colours: Photogrammetry, Image Analysis Using the DStretch Plugin, and 3-D Modelling of Post-Firing Painted Pottery from the South West Iberian Peninsula. *Digital Applications in Archaeology and Cultural Heritage* 13:e00093.

Grosman, Leore
2016 Reaching the Point of No Return: The Computational Revolution in Archaeology. *Annual Review of Anthropology* 45:129–145.

Grosman, Leore, Gonen Sharon, Talia Goldman-Neuman, Oded Smikt, and Uzy Smilansky
2011 Studying Post Depositional Damage on Acheulian Bifaces Using 3-D Scanning. *Journal of Human Evolution* 60:398–406.

Grün, Armin, Fabio Remondino, and Li Zhang
2004 Photogrammetric Reconstruction of the Great Buddha of Bamiyan, Afghanistan. *Photogrammetric Record* 19:177–199.

Grund, Brigid S., Spencer R. Pelton, Todd A. Surovell, Neffra A. Matthews, and Tommy A. Noble
2016 Bison Jump Location Is Primarily Predicted by Minimizing Visibility at the Wold Site, Johnson County, Wyoming. *American Antiquity* 81:752–763.

Grussenmeyer, Pierre, Tania Landes, Emmanuel Alby, and Laurent Carozza
2010 High Resolution 3D Recording and Modelling of the Bronze Age Cave "Les Fraux" in Perigord (France). *Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXVIII. Newcastle upon Tyne, UK.

Harrison-Buck, Eleanor, Mark Willis, and Chester Walker
2016 Using Drones in a Threatened Archaeological Landscape: Rapid Survey, Salvage, and Mapping of the Maya Site of Saturday Creek, Belize. *SAA Archaeological Record* 16(2):30–35.

Hassett, Breanna, and T. Lewis-Bale
2016 Comparison of 3D Landmark and 3D Dense Cloud Approaches to Hominin Mandible Morphometrics Using Structure-from-Motion. *Archaeometry* 59:191–203.

Haukaas, Colleen, and Lisa M. Hodgetts
2016 The Untapped Potential of Low-Cost Photogrammetry in Community-Based Archaeology: A Case Study from Banks Island, Arctic Canada. *Journal of Community Archaeology and Heritage* 3:40–56.

Henderson, Jon, Oscar Pizarro, Matthew Johnson-Roberson, and Ian Mahon
2013 Mapping Submerged Archaeological Sites Using Stereo-Vision Photogrammetry. *International Journal of Nautical Archaeology* 42:243–256.

Hesse, Ralf
2015 Combining Structure-from-Motion with High and Intermediate Resolution Satellite Images to Document Threats to Archaeological Heritage in Arid Environments. *Journal of Cultural Heritage* 16:192–201.

Hill, Austin C., Yorke Rowan, and Morag M. Kersel
2014 Mapping with Aerial Photographs: Recording the Past, the Present, and the Invisible at Marj Rabba, Israel. *Near Eastern Archaeology* 77:182–186.

Hirst, Cara S., Suzanna White, and Sian E. Smith
2018 Standardisation in 3D Geometric Morphometrics: Ethics, Ownership, and Methods. *Archaeologies* 14:272–298.

Hixon, Sean W., Carl P. Lipo, Terry L. Hunt, and Christopher Lee
2017 Using Structure from Motion Mapping to Record and Analyze Details of the Colossal Hats (Pukao) of Monumental Statues on Rapa Nui (Easter Island). *Advances in Archaeological Practice* 6:1–16.

Hollinger, Eric R., John Edwell Jr., Harold Jacobs, Lora Moran-Collins, Carolyn Thome, Jonathan Zastrow, Adam Metallo, Günter Waibel, and Vince Rossi
2013 Tlingit-Smithsonian Collaborations with 3D Digitization of Cultural Objects. *Museum Anthropology Review* 7 (1–2):201–253.

Howland, Matthew D.
2018 3D Recording in the Field: Style without Substance?

In *Cyber-Archaeology and Grand Narratives*, edited by Thomas E. Levy and Ian W. N. Jones, pp. 19–33. Springer, Cham, Switzerland.

Howland, Matthew D., Ian W. N. Jones, Mohammad Najjar, and Thomas E. Levy
2018 Quantifying the Effects of Erosion on Archaeological Sites with Low-Altitude Aerial Photography, Structure from Motion, and GIS: A Case Study from Southern Jordan. *Journal of Archaeological Science* 90:62–70.

Huggett, Jeremy
2015 Challenging Digital Archaoelogy. *Open Archaeology* 1:79–85.

Inomata, Takeshi, Daniela Triadan, Flory Pinzón, Melissa Burham, José Luis Ranchos, Kazuo Aoyama, and Tsuyoshi Haraguchi
2018 Archaeological Application of Airborne LiDAR to Examine Social Changes in the Ceibal Region of the Maya Lowlands. *PLoS ONE* 13(2):e0191619.

Iovita, Radu, and Shannon P. McPherron
2011 The Handaxe Reloaded: A Morphometric Reassessment of Acheulian and Middle Paleolithic Handaxes. *Journal of Human Evolution* 61:61–74.

Jalandoni, Andrea, Inés Domingo, and Paul S. C. Taçon
2018 Testing the Value of Low-Cost Structure-from-Motion (SfM) Photogrammetry for Metric and Visual Analysis of Rock Art. *Journal of Archaeological Science: Reports* 17:605–616.

Jeter, Marvin D.
1984 Mound Volumes, Energy Ratios, Exotic Materials, and Contingency Tables: Comments on Some Recent Analyses of Copena Burial Practices. *Midcontinental Journal of Archaeology* 9:91–104.

Jo, Young Hoon, and J.Y. Kim
2017 Three-Dimensional Digital Documentation of Heritage Sites Using Terrestrial Laser Scanning and Unmanned Aerial Vehicle Photogrammetry. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII–2/W5:395–398.

Johnson, Robin Ann, and Ariel Solis
2016 Using Photogrammetry to Interpret Human Action on Neolithic Monument Boulders in Ireland's Cavan Burren. *Journal of Archaeological Science: Reports* 8:90–101.

Katyal, Sonia K.
2017 Technoheritage. *California Law Review* 105(4): 1111–1172.

Kaufman, John, Morag Clement, and Allan Rennie
2015 Reverse Engineering Using Close Range Photogrammetry for Additive Manufactured Reproduction of Egyptian Artifacts and Other Objets d'Art. *Journal of Computing and Information Science in Engineering* 15(1):011006–011007.

Koenig, Charles W., Mark D. Willis, and Stephen L. Black
2017 Beyond the Square Hole: Application of Structure from Motion Photogrammetry to Archaeological Excavation. *Advances in Archaeological Practice* 5:54–70.

Kotoula, Eleni, David W. Robinson, Devlin Gandy, and Edward Jolie
2019 Computational Photography, 3-D Modeling, and Online Publication of Basketry for Cache Cave, California. *Advances in Archaeological Practice* 7:366–381.

Koutsoudis, Anestis, Fotis Arnaoutoglou, and Christodoulos Chamzas
2007 On 3D Reconstruction of the Old City of Xanthi: A Minimum Budget Approach to Virtual Touring Based on Photogrammetry. *Journal of Cultural Heritage* 8:26–31.

Kreij, Anna, Jason Scriffignano, Daniel Rosendahl, and Sean Ulm
2018 Aboriginal Stone-Walled Intertidal Fishtrap Morphology, Function and Chronology Investigated with High-Resolution Close-Range Unmanned Aerial Vehicle Photogrammetry. *Journal of Archaeological Science* 96:148–161.

Kwan, Daniel H., and Jamie M. Kwan
2017 Empowering Cultural Preservation in China through Participatory Digitization. *Journal of Archaeological Science: Reports* 12:161–164.

Lacquement, Cameron H.
2010 Recalculating Mound Volume at Moundville. *Southeastern Archaelogy* 29:341–354.

Lancaster, Jerrad
2018 Pre- and Post-Arson Three-Dimensional Reconstructions of the Lichtenwalter Schoolhouse, Green, Ohio. *Digital Applications in Archaeology and Cultural Heritage* 8:1–9.

Larsen, Bernie P., Simon J. Holdaway, Patricia C. Fanning, Tim Mackrell, and Justin I. Shiner
2017 Shape as an Outcome of Formation History: Terrestrial Laser Scanning of Shell Mounds from Far North Queensland, Australia. *Quaternary International* 427:5–12.

Lin, Sam C., Matthew Douglass, and Simon J. Holdaway
2010 The Application of 3D Laser Scanning Technology to the Assessment of Ordinal and Mechanical Cortex Quantification in Lithic Analysis. *Journal of Archaeological Science* 37:694–702.

Lin, Sam C., Matthew Douglass, and Alex Mackay
2016 Interpreting MIS3 Artefact Transport Patterns in Southern Africa Using Cortex Ratios: An Example from the Putslaagte Valley, Western Cape. *South African Archaeological Bulletin* 71(204):173–180.

Lonneville, Britt, Berdien De Roo, Cornelis Stal, Bart De Wit, Alain De Wulf, and Philippe De Maeyer
2014 Accurate and Cost-Efficient 3D Modelling Using Motorized Hexacopter, Helium Balloons and Photo Modelling: A Case Study. In *Digital Heritage: Progress in Cultural Heritage: Documentation, Preservation, and Protection*, edited by Marinos Ioannides, Nadia Magnenat-Thalmann, Ewald Fink, Roko Žarnić, Alex Yen, and Ewald Quak, pp. 410–417. EuroMed 2014. Lecture Notes in Computer Science Vol. 8740. Springer, Cham, Switzerland.

López, Juan F., Christian T. Hoyer, Annika Rebentisch, Anna Maria Roesch, Klaus Herkert, Nadine Huber, and Harald Floss
2019 Tool Mark Analyses for the Identification of Palaeolithic Art and Modern Graffiti: The Case of Grottes d'Agneux in Rully (Saône-et-Loire, France). *Digital Applications in Archaeology and Cultural Heritage* 14:e00107.

Lycett, Stephen J., Noreen von Cramon-Taubadel, and Robert A. Foley
2006 A Crossbeam Co-Ordinate Caliper for the Morphometric Analysis of Lithic Nuclei: A Description, Test and Empirical Examples of Application. *Journal of Archaeological Science* 33:847–861.

Lynch, Elizabeth M., Neffra A. Matthews, and Tommy A. Noble
2017 Unraveling the Enigma of Prehistoric Bedrock Ground Stone Features on the Chaquaqua Plateau,

Using Close-Range Photogrammetry. *Quaternary International* 439(B):50–68.

Mackay, Alex, Alex Sumner, Zenobia Jacobs, Ben Marwick, Kyla Bluff, and Matthew Shaw
2014 Putslaagte 1 (PL1), the Doring River, and the Later Middle Stone Age in Southern Africa's Winter Rainfall Zone. *Quaternary International* 350:43–58.

Mackie, Madeline E.
2015 Estimating Age and Sex: Paleodemographic Identification Using Rock Art Hand Sprays, an Application in Johnson County, Wyoming. *Journal of Archaeological Science: Reports* 3:333–341.

Magnani, Matthew
2014 Three-Dimensional Alternatives to Lithic Illustration. *Advances in Archaeological Practice* 2:285–297.

Magnani, Matthew, and Matthew Douglass
2018 Photogrammetry and Stereophotogrammetry. *SAS Encyclopedia of Archaeological Sciences*. Wiley-Blackwell, Hoboken.

Magnani, Matthew, Matthew Douglass, and Samantha T. Porter
2016a Closing the Seams: Resolving Frequently Encountered Issues in Photogrammetric Modelling. *Antiquity* 90:1654–1669.

Magnani, Matthew, Matthew Douglass, and Samantha T. Porter
2016b Three-Dimensional Models of Experimentally-Produced Lithic Artifacts Created Using Expedient and Refined Photogrammetry Protocols. Manuscript on file. Data Repository for the University of Minnesota, Minneapolis.

Magnani, Matthew, Anni Guttorm, and Natalia Magnani
2018 Three-Dimensional, Community-Based Heritage Management of Indigenous Museum Collections: Archaeological Ethnography, Revitalization and Repatriation at the Sámi Museum Siida. *Journal of Cultural Heritage* 31:162–169.

Magnani, Matthew, and Whittaker Schroder
2015 New Approaches to Modeling the Volume of Earthen Archaeological Features: A Case-Study from the Hopewell Culture Mounds. *Journal of Archaeological Science* 64:12–21.

Mark, Robert, and Evelyn Billo
2016 Low Altitude Unmanned Aerial Photography to Assist in Rock Art Studies. *SAA Archaeological Record* 16(2):14–16.

Martínez, Santiago, Juan Ortiz, and M. Luz Gil
2015 Geometric Documentation of Historical Pavements Using Automated Digital Photogrammetry and High-Density Reconstruction Algorithms. *Journal of Archaeological Science* 53:1–11.

Maté-González, Miguel Ángel, Diego González-Aguilera, Gonzalo Linares-Matás, and José Yravedra
2019 New Technologies Applied to Modelling Taphonomic Alterations. *Quaternary International* 517:4–15.

McCarthy, John, and Jonathan Benjamin
2014 Multi-Image Photogrammetry for Underwater Archaeological Site Recording: An Accessible, Diver-Based Approach. *Journal of Maritime Archaeology* 9:95–114.

Means, Bernard
2015 Promoting a More Interactive Public Archaeology: Archaeological Visualization and Reflexivity through Virtual Artifact Curation. *Advances in Archaeological Practice* 3:235–248.

Megarry, William, Conor Graham, Bernard Gilhooly, Brendan O'Neill, Rob Sands, Astrid Nyland, and Gabriel Cooney
2018 Debitage and Drones: Classifying and Characterising Neolithic Stone Tool Production in the Shetland Islands Using High Resolution Unmanned Aerial Vehicle Imagery. *Drones* 2(12):1–14.

Meredith-Williams, Matthew G., Niklas Hausmann, Geoff N. Bailey, Geoffrey C. P. King, Abdullah Alsharekh, Saud Al Ghamdi, and Robyn H. Inglis
2014 Mapping, Modelling and Predicting Prehistoric Coastal Archaeology in the Southern Red Sea Using New Applications of Digital-Imaging Techniques. *World Archaeology* 46:10–24.

Molloy, Barry, Mariusz Wiśniewski, Frank Lynam, Brendan O'Neill, Aidan O'Sullivan, and Alan Peatfield
2016 Tracing Edges: A Consideration of the Applications of 3D Modelling for Metalwork Wear Analysis on Bronze Age Bladed Artefacts. *Journal of Archaeological Science* 76:79–87.

Murtha, Timothy, M., Eben N. Broadbent, Charles Golden, Andrew Scherer, Whittaker Schroder, Ben Wilkinson, and Angelica Maria Almeyda Zambrano
2019 Drone-Mounted Lidar Survey of Maya Settlement and Landscape. *Latin American Antiquity* 30:630–636.

New Palmyra
2019 #NewPalmyra. Website, newpalmyra.org, accessed August 15, 2019.

Nex, Francesco, and Fabio Remondino
2014 UAV for 3D Mapping Applications: A Review. *Applied Geomatics* 6:1–15.

Nikolakopoulos, Konstantinos G., Konstantina Soura, Ioannis K. Koukouvelas, and Nikolaos G. Argyropoulos
2017 UAV vs. Classical Aerial Photogrammetry for Archaeological Studies. *Journal of Archaeological Science: Reports* 14:758–773.

O'Driscoll, James
2019 Picture Perfect: Using Drone Technology and Photogrammetry Techniques to Map the Western Stone Forts of Ireland. *Journal of Field Archaeology* 44:126–146.

Olson, Brandon R., Ryan A. Placchetti, Jamie Quartermaine and Anne E. Killebrew
2013 The Tel Akko Total Archaeology Project (Akko, Israel): Assessing the Suitability of Multi-Scale 3D Field Recording in Archaeology. *Journal of Field Archaeology* 38:244–262.

Olson, Kyle G., and Lynne M. Rouse
2018 A Beginner's Guide to Mesoscale Survey with Quadrotor-UAV Systems. *Advances in Archaeological Practice* 7:1–15.

Orenga, Hector A., and Arnau Garcia-Molsosa
2019 A Brave New World for Archaeological Survey: Automated Machine Learning- Based Potsherd Detection Using High-Resolution Drone Imagery. *Journal of Archaeological Science* 112:105013

Ortiz-Cordero, Rafael, and Rafael Fernández
2017 3D Photogrammetry, Capacity, Filling Time and Water Flow Simulation of Cordoba's Mosque-Cathedral Islamic Cistern. *Digital Applications in Archaeology and Cultural Heritage* 4:39–48.

Ozán, Ivana L.
2017 Gravity and the Formation of the Archaeological Record: Main Concepts and Methodological Tools. *Geoarchaeology* 32:646–661.

Pacheco-Ruiz, Rodrigo, Jonathan Adams, and Felix Pedrotti
2018 4D Modelling of Low Visibility Underwater Archaeological Excavations Using Multi-Source

Photogrammetry in the Bulgarian Black Sea. *Journal of Archaeological Science* 100:120–129.

Papworth, Heather, Andrew Ford, Kate Welham, and David Thackray
2016 Assessing 3D Metric Data of Digital Surface Models for Extracting Archaeological Data from Archive Stereo-Aerial Photographs. *Journal of Archaeological Science* 75:85–104.

Parcero-Oubiña, Cesar, Patricia Mañana-Borrazás, Alejandro Güimil-Fariña, Mariela Pino, Pastor Fábrega-Álvarez, and Cesar Borie
2016 Mapping on a Budget: A Low-Cost UAV Approach for the Documentation of Prehispanic Fields in Atacama (N. Chile). *SAA Archaeological Record* 16(2): 17–21.

Peinado Checa, Zaira J.P., Angélica Fernandez Morales, and Luis Agustín Hernandez
2014 Combinacion de Fotogrametria Terrestre y Aerea de Bajo Coste: El Levantamiento Tridimensional de la Iglesia de San Miguel de Agreda (Soria). *Virtual Archaeology Review* 5(10):51–58.

Peng, Fei, Sam C. Lin, Jialong Guo, Huimin Wang, and Xing Gao
2017 The Application of SfM Photogrammetry Software for Extracting Artifact Provenience from Paleolithic Excavation Surfaces. *Journal of Field Archaeology* 42:326–336.

Pepe, Massimiliano, Sebastiano Ackermann, Luigi Fregonese, and Cristiana Achille
2016 3D Point Cloud Model Color Adjustment by Combining Terrestrial Laser Scanner and Close Range Photogrammetry Datasets. *International Journal of Computer, Electrical, Automation, Control and Information Engineering* 10(11):1918–1924.

Pérez-Alvárez, Juan Antonio, Gil Rito Gonçalves, and Enrique Cerrillo-Cuenca
2019 A Protocol for Mapping Archaeological Sites through Aerial 4k Videos. *Digital Applications in Archaeology and Cultural Heritage* 13:e00101.

Pérez-García, José Luis, Antonio Tomás Mozas-Calvache, José Miguel Gómez-López, and Alejandro Jiménez-Serrano
2018 Three-Dimensional Modelling of Large Archaeological Sites Using Images Obtained from Masts: Application to Qubbet el-Hawa Site (Aswan, Egypt). *Archaeological Prospection* 26(2):1–15.

Pérez-García, José Luis, Antonio Tomás Mozas-Calvache, Barba-Colmeero Vincent, and Alejandro Jiménez-Serrano
2019 Photogrammetric Studies of Inaccessible Sites in Archaeology: Case Study of Burial Chambers in Qubbet el-Hawa (Aswan, Egypt). *Journal of Archaeological Science* 102:1–10.

Petraglia, Michael D., and Richard Potts
1994 Water Flow and the Formation of Early Pleistocene Artifact Sites in Olduvai Gorge, Tanzania. *Journal of Anthropological Archaeology* 13:228–254.

Phillips, Emily, Jonathan Reeves, Matthew Douglass, and David Braun
2018 Taphonomic Comparisons of Stone Tool Transport: Surface vs. Excavated Collection. Paper presented at the 83rd Annual Meeting of the Society for American Archaeology, Washington, DC.

Pierdicca, Roberto
2018 Mapping Chimu's Settlements for Conservation Purposes Using UAV and Close Range Photogrammetry: The Virtual Reconstruction of Palacio Tschudi, Chan Chan, Peru. *Digital Applications in Archaeology and Cultural Heritage* 8:27–34.

Polo, María-Eugenia, José M. Vaquero, and Ángel M. Felicísimo
2017 Metric Properties of Sundials Using 3-D Models from Digital Photography. *Historical Archaeology* 51:557–562.

Porter, Samantha T., 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 (France). *Advances in Archaeological Practice* 4:71–86.
2019 A Comparison of Châtelperronian and Protoaurignacian Core Technology Using Data Derived from 3D Models. *Journal of Computer Applications in Archaeology* 2:41–55.

Project Mosul
2019 Rekrei (Project Mosul). Electronic document, https://projectmosul.org/, accessed August 15, 2019.

Ranhorn, Kathryn L., David Braun, Rebecca Biermann Gürbüz, Elliot Greiner, Daniel Wawrzyniak, and Alison Brooks
2019 Evaluating Prepared Core Assemblages with Three-Dimensional Methods: A Case Study from the Middle Paleolithic at Skhūl (Israel). *Archaeological and Anthropological Sciences* 11:3225–3238.

Reeves, Jonathan, Matthew Douglass, Asrat Seminew, Melissa Miller, and David Braun
2018 Landscape Evolution, Digital Terrain Analysis, and the Integrity of Surface Assemblages: A Case Study from the Koobi Fora Formation. Paper presented at the 83rd Annual Meeting of the Society for American Archaeology, Washington, DC.

Remondino, Fabio, Luigi Barazzetti, Francesco Nex, Marco Scaioni, and Daniele Sarazzi
2011 UAV Photogrammetry for Mapping and 3D Modeling—Current Status and Future Perspectives. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 38(1):1–7.

Rick, John W.
1976 Downslope Movement and Archaeological Intrasite Spatial Analysis. *American Antiquity* 41:133–144.

Rinaudo, Fulvio, Filiberto Chiabrando, Andrea M. Lingua, and Antonia T. Spanò
2012 Archaeological Site Monitoring: UAV Photogrammetry Can Be an Answer. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 39(B5):583–588.

Risbøl, Ole, and Lars Gustavsen
2018 LiDAR from Drones Employed for Mapping Archaeology—Potential, Benefits, and Challenges. *Archaeological Prospection* 25:329–338.

Robinson, Madaline, Augustine Porter, Will Figueira, and Roland Fletcher
2019 Neolithic Temples of Malta: 3D Analysis Points to Novel Roof Reconstruction. *Digital Applications in Archaeology and Cultural Heritage* 13:e00095.

Romain, William F.
1996 Hopewellian Geometry: Forms at the Interface of Time and Eternity. In *A View from the Core: A Synthesis of Ohio Hopewell Archaeology*, edited by Paul Pachecko, pp. 194–209. Ohio Archaeological Council, Columbus.

Roosevelt, Christopher H., Peter Cobb, Emanuel Moss, Brandon R. Olson, and Sinan Ünlüsoy

2015 Excavation Is Destruction Digitization: Advances in Archaeological Practice. *Journal of Field Archaeology* 40:325–346.

Ruiz Sabina, Juan Ángel, David Gallego Valle, Cristina Peña Ruiz, Jesús Manuel Molero Garcia, and Antonio Gomez Laguna

2015 Fotogrametria aérea por drone en yacimientos con grandes estructuras: Propuesta metodológica y aplicación práctica en los castillos medievales del Campo de Montiel. *Virtual Archaeology Review* 6(13):5–19.

Salazar, Sergio, Diego Garate, Iñaki Intxaurbe, Olivia Rivero, and Javier Moreno

2019 An Unknown "Classic Cave": Re-Evaluation of El Salitre (Ajanedo, Cantabria, Spain) Rock Art with 3D Digital Recording Methodologies. *Journal of Archaeological Science: Reports* 26:101921.

Saleri, Renato, Valeria Cappellini, Nicolas Nony, Livio De Luca, Marc Pierrot-Deseilligny, Emmanuel Bardiere, and Massimiliano Campi

2013 UAV Photogrammetry for Archaeological Survey: The Theaters Area of Pompeii. *Digital Heritage International Congress* 2:497–502.

Sapirstein, Philip

2016 Accurate Measurement with Photogrammetry at Large Sites. *Journal of Archaeological Science* 66:137–145.

2018 A High-Precision Photogrammetric Recording System for Small Artifacts. *Journal of Cultural Heritage* 31:33–45.

Schick, Kathy Diane

1986 *Stone Age Sites in the Making: Experiments in the Formation and Transformation of Archaeological Occurrences*. BAR International Series 319. British Archaeological Reports, Oxford.

Shaw, Matthew, Christopher Ames, Natasha Phillips, Sherrie Chambers, Anthony Dosseto, Matthew Douglass, Ron Goble, Zenobia Jacobs, Brian Jones, Sam C. Lin, Marika A. Low, Jessica-Louise McNeil, Shezani Nasoordeen, Corey O'Driscoll, Rsaria B. Saktura, Alexandra T. Sumner, Sara Watson, and Alex Mackay

2019 The Doring River Archaeological Project: Approaching the Evolution of Human Landuse Patterns in the Western Cape, South Africa. *PaleoAnthropology* 2019:400–422.

Shott, Michael

2014 Digitizing Archaeology: A Subtle Revolution in Analysis. *World Archaeology* 49:1–9.

Sorant, Peter E., and J. Richard Shenkel

1984 The Calculation of Volumes of Middens, Mounds, and Strata Having Irregular Shapes. *American Antiquity* 49:599–603.

Strasser, Thomas F., Sarah C. Murray, Alexandra van der Geer, Christina Kolb, and Louis A. Ruprecht

2018 Palaeolithic Cave Art from Crete, Greece. *Journal of Archaeological Science: Reports* 18:100–108.

Štuhec, Seta, Geert Verhoeven, and Iztok Štuhec

2019 Modelling Building Costs from 3D Building Models: Estimating the Construction Effort from Image-Based Surface Models of Dry-Stone Shepherd Shelters (Kras, Slovenia). *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 42:691–698.

Themistocleous, Kyriacos

2017 Model Reconstruction for 3D Vizualization of Cultural Heritage Sites Using Open Data from Social Media: The Case Study of Soli, Cyprus. *Journal of Archaeological Science: Reports* 14:774–781.

Themistocleous, Kyriacos, Athos Agapiou, Helen M. King, Nigel King, and Diofantos G. Hadjimitsis

2014 More than a Flight: The Extensive Contributions of UAV Flights to Archaeological Research—The Case Study of Curium Site in Cyprus. In *Digital Heritage: Progress in Cultural Heritage: Documentation, Preservation, and Protection*, edited by Marinos Ioannides, Nadia Magnenat-Thalmann, Eleanor Fink, Roko Žarnić, Alex Yen, and Ewald Quak, pp. 396–409. EuroMed 2014. Lecture Notes in Computer Science Vol. 8740. Springer, Cham, Switzerland.

Themistocleous, Kyriacos, Vasiliki Lysandrou, Branka Cuca, Athos Agapiou, and Diofantos G. Hadjimitsis

2015 Exploring the Ancient Kourion City Site from the Air Using Unmanned Aerial Vehicles. *International Journal of Heritage in the Digital Era* 4:307–323.

Thompson, Erin L.

2017 Legal and Ethical Considerations for Digital Recreations of Cultural Heritage. *Chapman Law Review* 20:153–176.

Thompson, Jessica C., J. Tyler Faith, Naomi Cleghorn, and Jamie Hodgkins

2017 Identifying the Accumulator: Making the Most of Bone Surface Modification Data. *Journal of Archaeological Science* 85:105–113.

Timbrell, Lucy, and Kimberly A. Plomp

2019 Using the Shape of the Basicranial Portion of the Temporal Bone to Distinguish between Relatively Closely-Related Human Populations. *Journal of Archaeological Science: Reports* 26:101885.

Turpin, Solveig A., Richard P. Watson, Sarah Dennett, and Hans Muessig

1979 Stereophotogrammetric Documentation of Exposed Archaeological Features. *Journal of Field Archaeology* 6:329–337.

Vallet, Julien

2007 GPS/IMU and LiDAR Integration to Aerial Photogrammetry: Development and Practical Experiences with the Helimap System. *Vorträge Dreiländertagung* 27:1–10.

Verhoeven, Geert J.

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.

Vincent, Matthew L., Mariano Flores Gutierrez, Chance Coughenour, Victor Manuel, Lopez-Menchero Bendicho, Fabio Remondino, and Dieter Fritsch

2015 Crowd-Sourcing the 3D Digital Reconstructions of Lost Cultural Heritage. *Digital Heritage* 2015:171–172. DOI:10.1109/DigitalHeritage.2015.7413863.

Wallace, Collin A. B.

2017 Retrospective Photogrammetry in Greek Archaeology. *Studies in Digital Heritage* 1:607–626.

Wernke, Steven A., Julie A. Adams, and Eli R. Hooten

2014 Capturing Complexity: Toward an Integrated Low-Altitude Photogrammetry and Mobile Geographic Information System Archaeological Registration System. *Advances in Archaeological Practice* 2:147–163.

Wilson, Paul F., Janet Stott, Jason M. Warnett, Alex Attridge, Paul M. Smith, and Mark A. Williams
2017 Evaluation of Touchable 3D-Printed Replicas in Museums. *Curator: The Museum Journal* 60:445–465.

Yamafune, Kotaro, Raymond Torres, and Felipe Castro
2017 Multi-Image Photogrammetry to Record and Reconstruct Underwater Shipwreck Sites. *Journal of Archaeological Method and Theory* 24:703–725.

Yravedra, José, Miguel Ángel Maté-González, Juan Francisco Palomeque-González, Julia Aramendi, Verónica Estaca-Gómez, María San Juan Blazquez, Elena García Vargas, Elia Organista, Diego González-Aguilera, Mari Carmen Arriaza, Lucía Cobo-Sánchez, Agness Gidna, David Uribelarrea Del Val, Enrique Baquedano, Audax Mabulla, and Manuel Domínguez-Rodrigo
2017 A New Approach to Raw Material Use in the Exploitation of Animal Carcasses at BK (Upper Bed II, Olduvai Gorge, Tanzania): A Micro-Photogrammetric and Geometric Morphometric Analysis of Fossil Cut Marks. *Boreas* 46:860–873.

Zimmer, Brian, Cynthia Liutkus-Pierce, Scott T. Marshall, Kevin Hatala, Adam Metallo, and Vincent Rossi
2018 Using Differential Structure-from-Motion Photogrammetry to Quantify Erosion at the Engare Sero Footprint Site, Tanzania. *Quaternary Science Reviews* 198:226–241.

Zubrow, Ezra B.W.
2006 Digital Archaeology: A Historical Context. In *Digital Archaeology: Bridging Method and Theory*, edited by Thomas L. Evans and Patrick Daly, pp. 10–31. Routledge, London.

Zvietcovich, Fernando, Luis Navarro, Julio Saldana, Luis Jaime Castillo, and Benjamin Casaneda
2016 A Novel Method for Estimating the Complete 3D Shape of Pottery with Axial Symmetry from Single Potsherds Based on Principal Component Analysis. *Digital Applications in Archaeology and Cultural Heritage* 3:42–54.

Submitted August 23, 2019; Revised May 4, 2020; Accepted June 4, 2020