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RESEARCH ARTICLE

Terrestrial laser scanning and photogrammetry techniques for documenting fossil-bearing palaeokarst with an example from the Drimolen Palaeocave System, South Africa

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Abstract

This paper presents the results of a recent three-dimensional (3D) survey at the Drimolen Makondo palaeontological deposits in the Hominid Sites of South Africa UNESCO World Heritage site. The Drimolen Makondo is a palaeokarstic feature that consists of a heavily eroded 2.6-2.0 Ma fossil-bearing palaeocave remnant. With photogrammetry and a laser scan survey, two 3D site models were created, georectified, and imported into geographical information system software. This paper outlines both of these survey techniques and provides an assessment of the relevant merits of each method and their applicability for detailed recording and archival documentation of palaeokarstic palaeontological and archaeological sites. Given the complex depositional context of many of the fossil-bearing South African cave systems and their importance for understanding our evolutionary history, new methods are critical to visualising and analysing 3D spatial data. The utility of 3D models lies in their ability to integrate with total station survey techniques to accurately record and control excavations and provide a means of visualising stratigraphic, sedimentary, and spatial contexts in various geographical information system platforms. The use of low-cost and time-efficient digital photographic surveys to create accurate 3D models, if completed accurately, can provide researchers with a means of contextualising excavation data without the need for expensive and highly specialised equipment. The development of this method combined with differential global positioning systems provides a solution in more remote locations to recording highly accurate fossil and 3D site contexts with increasing ease. It also allows the sites to be recorded as part of an evolving landscape rather than as single isolated localities. This technique should be a standard technique implemented when working on irreplaceable UNESCO World Heritage sites such as the hominin-bearing caves of South Africa.

KEYWORDS

3D models, cradle of humankind, Drimolen, palaeontology, photogrammetry, terrestrial laser scanning

1 | INTRODUCTION

The early fossil discoveries in South Africa occurred by chance during mining extraction activities (Broom, 1936; Dart, 1925), with many other historically collected hominin fossil finds having little to no provenience (Bae, 2010; Kuhn et al., 2016) and many fossil finds published with little to no precise spatial context beyond assignment to a deposit or Member (e.g., Berger & Lacruz, 2003; DeSilva, Steininger, & Patel, 2013; Thackeray & Watson, 1994). In some cases, where fossils are close to the contact between two different units, this has caused unnecessary mixing of fossils of different ages that has in turn caused major confusions over the age of deposits (Herries & Shaw, 2011). Better levels of accuracy and precision are needed to record fossil sites in three dimensions as new extraction, and dating techniques can provide higher resolution dating and localised palaeo-environmental information. With the advent of the total station theodolite (TST) in the 1970s and further automatic and computer-based additions, levels of millimetre accuracy can be achieved for recording samples and fossils in situ. The decreasing cost of total stations now means that no excavation should be undertaken without mapping using such a device. Archaeological and palaeontological excavations are destructive, and thus we have ethical obligations to record fossil and artefact locations, and assess their provenience as accurately as possible.

The use of total stations has been augmented by the development of new technologies in the form of terrestrial laser scanners and digital photography over the last decade. There is an increasingly large body of literature devoted to laser scanning (Barber & Mills, 2011; Grussenmeyer, Landes, Doneus, & Lerma, 2016; Mohammed Oludare & Pradhan, 2016) and photogrammetry (Grussenmeyer, Hanke, & Streilein, 2002; Remondino & Campana, 2014; Stylianidis, Georgopoulos, & Remondino, 2016). These examples highlight methods, applications, and the wide range of different uses of these technologies. There are now many projects utilising these methods for three dimensional (3D) documentation of built heritage and archaeological sites (Haddad, 2011; Dellepiane, Dell′Unto, Callieri, Lindgren, & Scopigno, 2013; Fiorillo, Fernández-Palacios, Remondino, & Barba, 2013; Remondino, 2011), and there are some examples of where these techniques have been specifically applied to palaeontological sites (see Bates et al., 2010; Breithaupt, Matthews, & Noble, 2004; Falkingham, Bates, & Farlow, 2014), but their use is more common in the geotechnical and geological industry (Abellán, Vilaplana, & Martínez, 2006; Armesto, Ordóñez, Alejano, & Arias, 2009; Sturzenegger & Stead, 2009; Vanneschi, Salvini, Massa, Riccucci, & Borsani, 2014). Their limited application at palaeontological sites thus far is due to the need for specialist operators and the expense of laser scanning equipment. It is rapidly becoming apparent that 3D documentation of in situ fossils and their associated geological contexts is critical for assigning the fossils to particular temporal periods of deposition, rather than to broader classically defined Members that may have formed over hundreds of thousands of years (Herries & Adams, 2013; Herries & Shaw, 2011). The further disconnect that often exists between fossils in museums and their provenience means that fossils from multiple different deposits, or even sites, are sometimes grouped together as if they are from one temporally distinct assemblage, causing major misinterpretations of the record. In South Africa, fossil studies often refer to fossils as coming from "Makapansgat," or "Taung" (e.g., Gilbert, Takahashi, & Delson, 2016; Williams & Patterson, 2010), and yet these localities are large areas that contain multiple sites spanning millions of years of deposition. Thus although it is important to collect detailed location data of fossils and artefacts from sites, these data also need to be published and logged with the specimens.

Currently, many researchers have employed both 3D scanning and photogrammetry successfully, implementing a combined approach to data collection (Guidi et al., 2002; Guidi et al., 2009; Lambers et al., 2007; Yastikli, 2007). The dual approach generally utilises the spatial accuracy of laser scanning in combination with photogrammetry to provide high-resolution colour corrected imagery. Highly accurate photographic imagery can be rendered as 3D surface textures or alternatively used for image analysis techniques (Fisher et al., 2015). The implementation of sophisticated photogrammetry methods is greatly determined by project specific aims, and in the case of laser scanning, access to funds and specialised technicians. The ability to conduct photogrammetry is largely determined by the lighting context of the site under investigation, with low light or changeable conditions making this method difficult to apply.

Cave systems are often challenging environments to work in, as they can be difficult to access, with limited space and little to no natural lighting. However, they often contain a vast array of ecological, archaeological, and palaeontological information, and therefore accurate mapping is pivotal to understanding them. Three-dimensional surveys of cave sites are increasingly employed throughout Europe (Brown, Chalmers, Saigol, Green, & D′errico, 2001; Lerma, Navarro, Cabrelles, & Villaverde, 2010; Grussenmeyer, Alby, et al., 2012; Núñez, Buill, & Edo, 2013; Tyree, McCoy, Frey, & Stamos, 2014). Three-dimensional projects have been undertaken in South Africa at sites such as Gladysvale (Häusler, Isler, Schmid, & Berger, 2004), Swartkrans (Nigro, Ungar, de Ruiter, & Berger, 2003), Wonderwerk Cave (Birkenfeld, Avery, & Horwitz, 2015; Rüther et al., 2009), and Pinnacle Point (Herries & Fisher, 2010) and the scanning of the Stw573 "littlefoot" fossil at Sterkfontein (Subsol et al., 2015). However, many of these early studies were undertaken using a standard total station, which is time-consuming and results in limited 3D outputs. Access to expensive 3D laser scanners has been prohibitive for African researchers, with many palaeontological and archaeological projects unable to employ them. Moreover, few of these projects have been integrated with other data and used to further understand the context and geology of the fossils, but rather presented as static scans of the caves. In the case of palaeokarst and palaeocaves such as the hominin-bearing sites of South Africa, the cave systems have undergone many phases of cave formation, erosion, and infill; and thus it is necessary to be able to model and pull apart these complex sequences as well as later phases of erosion.

Palaeontological sites offer a unique challenge within a range of environmental contexts, from open eroded sites to deep cave systems. Many have been significantly affected by mining activities and are currently under threat from a range of anthropogenic processes. This highlights the need for digital site models that can be used for the purposes of research, education, and archiving. Determining the appropriate strategy to document these sites in 3D is critical not only for their management but also for enabling researchers to integrate legacy and future data into a 3D environment. The issue is one of generating 3D models of sites that are fit for a number of purposes including site management, archival use, tracking excavation progress, and integration into a geographical information system (GIS). In addition, these models have to be robust enough to be used with emerging technologies such as immersive virtual reality systems.

One area of uncertainty surrounding these approaches is the level of spatial accuracy that is required for a given task. For example, in civil engineering projects such as the building of bridges, roads, and other infrastructure, the minimum spatial accuracy required is usually in the millimetre range. In the case of documenting palaeontological material recovered from naturally accumulated cave fills, the aim would be to record as accurately as possible given the constraints of georeferencing and terrain. The protocol used throughout this study was to record fossils with a TST that is ~10 mm in size. The maximum initialisation error tolerated for TST set-ups was 5 mm (across *XYZ*). In this situation, an outcome that produces a model that is spatially accurate to within 10 mm would be ideal. Ultimately, for the palaeontologist, the issue is one of choice: Which 3D method is the most appropriate given conditions, resources, and aims? In this paper, we compare laser scanning using a ~$AUD 74,000 Leica Multi-Station with low-cost photogrammetry of the newly discovered Drimolen Makondo fossil site in South Africa (Rovinsky, Herries, Menter, & Adams, 2015).

2 | THE DRIMOLEN MAKONDO SITE

The Drimolen Palaeocave System is located in the Hominid Sites of South Africa UNESCO World Heritage Site (Figure 1). The fossil-bearing deposits within the Drimolen Main Quarry (DMQ) part of the site, were first discovered in the early 1990s, and systematic excavations over the past two decades have revealed a large number of *Paranthropus robustus* remains, including the most complete specimen of this species to date, the nearly complete skull DNH 7 (Keyser, 2000). The deposits at this site are dated to somewhere between 2.0 and 1.4 Ma (Adams, Rovinsky, Herries & Menter, 2016; Herries et al., 2017) and contain the fossil remains of our own genus, *Homo*, as well as stone and bone tools (Backwell & d'Errico, 2008; Moggi-Cecchi, Menter, Boccone, & Keyser, 2010).

Exploratory excavations to the west of DMQ had identified other fossil-bearing palaeocaves deposits throughout the 1990s and 2000s (Keyser, Menter, Moggi-Cecchi, Pickering, & Berger, 2000); however, they had never been fully explored, or their extent determined or mapped. One such feature, a "makondo" (solution pockets formed around a tree root; Brink & Partridge, 1980; Partridge & Brink, 1967) that formed into deposits 55 m west of DMQ was sampled in 2013 and then excavated extensively in 2014–2016 to reveal the full lateral extent of the preserved palaeocaves deposit. Ground-penetrating radar was used to help establish the extent of the buried palaeocave, which was named the Drimolen Makondo (DMK). Preliminary dating suggest that the deposits formed somewhere between ~2.6 and ~2.0 Ma (Herries et al., 2017; Rovinsky et al., 2015). To date, these deposits have not produced hominins but have produced important specimens of *Dinofelis*, *Chasmaporthetes*, *Cercopithecoides*, *Eurygnathohippus*, and *Metridiochoerus* (Rovinsky et al., 2015).

Controlled excavations were undertaken with dating, micromorphology and sediment samples, in situ and ex situ bone fragments, and breccia blocks recorded in three dimensions using a TST. This approach is seldom undertaken during palaeontological excavation, despite the significance of these sites and the complicated nature of the depositional environments common to these fossil-bearing sites. A rigorous approach to data collection as well as the application of multidimensional visualisation techniques is proving necessary to avoid

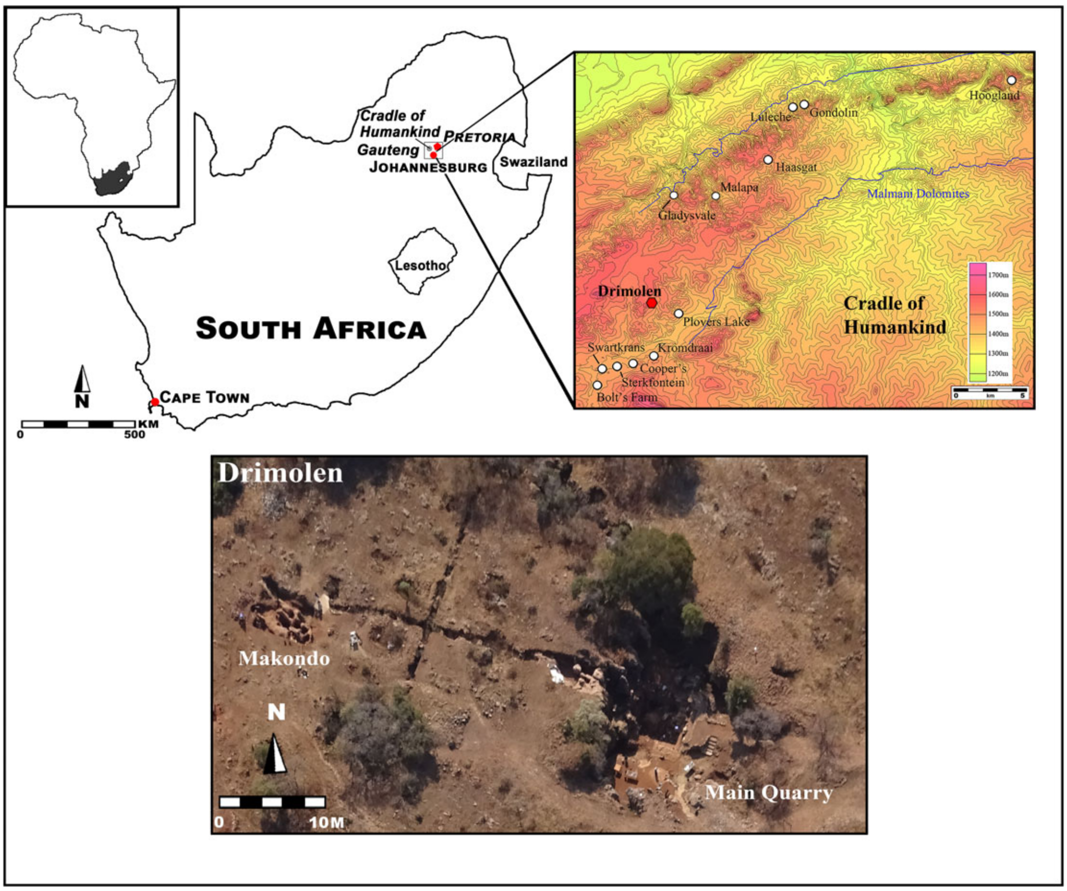


FIGURE 1 Drimolen and Makondo site location: Hominid Sites of South Africa UNESCO World Heritage Site [Colour figure can be viewed at wileyonlinelibrary.com]

the misidentification and misinterpretation of different aged deposits. This is due to the complex relationships that exist in such sites between the stratigraphy of the original palaeocaves deposits and the different phases of secondary erosion, karstification, and sediment infill.

The early Pleistocene age for DMK has meant that much of the original cave deposit, which consists of calcified breccia, siltstone, and sandstone deposits as well as speleothem, has been eroded away and covered by hillside colluvium. Secondary processes have formed a makondo-karren (Herries & Shaw, 2011) beneath the colluvium due to groundwater flow and solution processes around tree roots. The formation of the makondo-karren has in some cases decalcified the original palaeocave deposits, whereas in other cases, this decalcified material has been washed away through small karstic conduits and the makondo features have refilled with colluvium. This creates a complex sequencing of formation, deposition, erosion, and reworking that requires careful documentation during excavation. The destructive process of excavation removes much of this contextual information and may preclude later reinterpretation and reanalysis, given only a traditional record of the site. Sites such as Sterkfontein and Swartkrans present an example of the challenges faced where contextual environments are complicated and research has been conducted over many generations (Herries & Adams, 2013; Reynolds, Bailey, & King, 2011). Furthermore, the ability to accurately date these sites is often hindered by the complexities of site formation (Blackwell, 1994; Herries et al., 2013). The collection of high-resolution spatial data in three dimensions provides researchers with a means to assess the integrity of excavated materials and investigate site formation processes after primary data collection and fieldwork has been undertaken.

To create an archive of our excavations at DMK, facilitate volumetric and spatial analysis, and provide a multidimensional framework to accompany the TST data, a 3D model of the site was required. Two methods were implemented in order to assess and compare the use of a laser scanner (active sensor system) and a low-cost photogrammetric survey (passive sensor system).

3 | METHODS AND DATA COLLECTION

A Leica Nova MS50 MultiStation was selected due to its dual functionality (total station and laser scanner, with the ability to be upgraded to include a differential global positioning system [DGPS]) to test the utility of laser-based active sensor systems. The Leica MS50 is capable of capturing up to 3,000 data points per second at distances of up to 300 m and produces a point cloud that is automatically georegistered. In addition, an on-board camera can be used to create panoramic images for use as a textured surface or point cloud colouration. For comparison, a digital photography survey using a standard Nikon DSLR camera and the photogrammetry software Agisoft PhotoScan (ver. 1.1.6) was conducted. This approach has the potential to be undertaken without artificial lighting and therefore uses less energy to operate and can be significantly cheaper to acquire. Key aims were to assess the user friendliness of both of the methods in order to obtain a workable and accurate model useful for 3D spatial analysis and to create a cultural heritage archive for use within a GIS platform.

3.1 | Leica MS50 laser scanner

3.1.1 | Field data collection

Prior to the commencement of field seasons in 2015 and 2016, laser scan surveys were conducted at the DMK. The MS50 was set up using site control points and a resection to triangulate its location. The control points were established in and around the site by Dr Andre Keyser and Dr Colin G Menter (pers. comm.) using a compass orientation and TST measurements in the late 1990s. Subsequent DGPS surveys have georectified the site grid onto the South African coordinate system (Hartebeesthoek 94, Lo 27, SA Geoid 2010). To maintain consistency with previously collected site data, all recording is conducted using the site grid and batch converted in ArcGIS using an affine transformation.

For the 2015 site scan, five different resection set-ups (occupy points) were required to record the Makondo. Unlike other laser scanning systems, the total station capability of the MS50 eliminates the need to place control targets within the captured scene. The set-up and scan operations were conducted within a 2-hr time frame. The five set-ups were positioned at ranges of between 6 and 8 m from the site, and optimum scan resolutions were set to 5 mm. A discreet zone around the excavation was defined using the inbuilt software to capture data, so as not to record extraneous areas of the site. The set-ups were positioned in order to capture the site extent and to generate an overlapping dense point cloud.

3.1.2 | Post-processing

The laser scan data were uploaded to a field computer on site using the Leica Infinity software and exported in a point cloud format (*.e57, *.las). 3DReshaper (ver. 10,1,9,21754) was used to build a meshed surface model of the site from the point cloud. This model was automatically georegistered using the local coordinate system embedded within the laser scan set-ups, with very little post-processing required. Decimation of the meshed surface was necessary to import the model into ArcScene. A colourised version of this model can be created using the inbuilt camera system of the MS50 and exporting as landXML files; however, this feature lacks manual exposure and ISO settings and therefore was not flexible enough to be useful in this environment. The full laser scanner workflow is outlined in Figure 2.

3.2 | Photogrammetry survey

3.2.1 | Field data collection

In addition to the laser scanning, digital photo surveys were undertaken in 2015 and 2016, using the methodology outlined in the Agisoft PhotoScan user manual (Agisoft, 2013). This method requires that each photo overlaps with the preceding and succeeding photos in order for PhotoScan to align them during processing. The more overlap achieved (at least 60% of side overlap and 80% of forward overlap is preferable), the more successful later photo alignment will be. A systematic approach is necessary, and it was found that walking

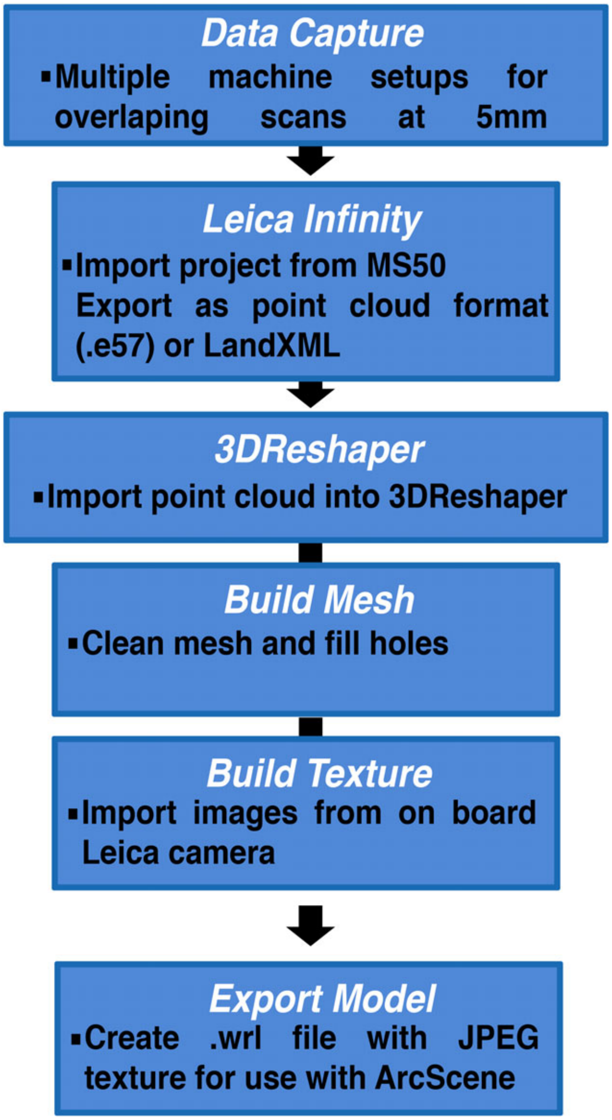


FIGURE 2 Flow chart of laser scan data collection and processing [Colour figure can be viewed at wileyonlinelibrary.com]

in transects across and around the site was the most effective approach for capturing the DMK from multiple directions and locations (Figure 3a). Manual alignments can be performed later in the software; however, this can be time-consuming, and a systematic approach at the data collection stage is more efficient and less problematic. In 2015, all photos were captured with a Nikon D80, AF-S DX Nikkor 35 mm f/1.8G fixed lens (Nikon Corp., Japan). A total of 615 photos were taken in native Nikon *.NEF format at ISO 100/200. The timing of the photo survey was limited to an hour around midday to minimise the effects of shadow on the site, although deeper areas around the narrow Main Makondo area were shadowed. After completing the laser scan and photo surveys, the field season commenced. A TST was used to piece provenance fossil finds, geological samples, and changes in strata to be integrated into the site GIS.

3.2.2 | Post-processing

Data processing was conducted on a 6-core Intel i7 CPU with a Nvidia GTX 780 GPU and 48 GB of RAM. Processing time is heavily dependent on hardware, and dual CPU and GPU set-ups with 64 GB or more of RAM are ideal for surveys larger than 500 photos. The 2015 survey was processed in 31 hr 37 min using this set-up, although this can be shortened if less accurate photo alignments and lower levels of point cloud accuracy are acceptable. PhotoScan conducts a number of phases during model creation. These phases can be individually initiated, or the entire process can be run as a batch if the parameters and output of the model required are known in advance. For this survey, photos in *.NEF format were converted to *.TIFF using Nikon software and imported into PhotoScan. Workflow process and parameters for this model are outlined in Figure 3b with further details available in the PhotoScan Reports (Supporting Information).

Varying levels of alignment accuracy and a variety of textures can be applied. Selection of these settings is dependent on the proposed function of the finished model and will have a significant impact on processing time. High-resolution textured models are suitable for more intensive visualisation purposes such as a virtual reality site walk-through; however, they are often data heavy and have limited functionality if imported into GIS Software (in this case ESRI's ArcScene ver. 10.3). Georectification of the 2015 model was conducted with data points obtained from the total station survey on easily recognisable ground features. These points were entered into the reference window of PhotoScan.

Although high-resolution models are available as direct exports from 3DReshaper or PhotoScan, the surface and texture resolution of the models must be reduced to be successfully integrated into ArcScene. In theory, the higher resolution models can be imported; however, they require greater computing and rendering power than are available for the majority of PC users. We found that a maximum file size of 200 MB was most suitable for importing our models in ArcScene. Depending on the dimensions of the model, this should be adequate to visualise important morphological attributes of a site such as variations in strata (Figure 3c). When used in conjunction with excavation site data, this provides a platform for spatial and visual analysis. Both the models were imported into ArcScene using the Import 3D Files tool within the 3D Analyst Tools in the ArcToolbox.

4 | RESULTS

Direct visual overlay comparison of the models can be achieved in ArcScene with the use of the measuring tool. With this approach, it was found that the majority of meshed surfaces of both models were within 15 mm of each other. Quantifying the degree of correspondence between the two models created using the different data capture methods proved to be difficult due to qualitative differences in the abilities of each technique. For example, the photo survey was able to capture the lowest and most confined areas of the excavation better than the laser scanner due to the limited angle of operation of the MS50. A direct point-to-point or surface-to-surface comparison is problematic because of the fundamentally different data collection capabilities. A second issue arises with regard to the different algorithms used to create meshed surfaces in PhotoScan and 3DReshaper, as these were likely to give differing results depending on the settings

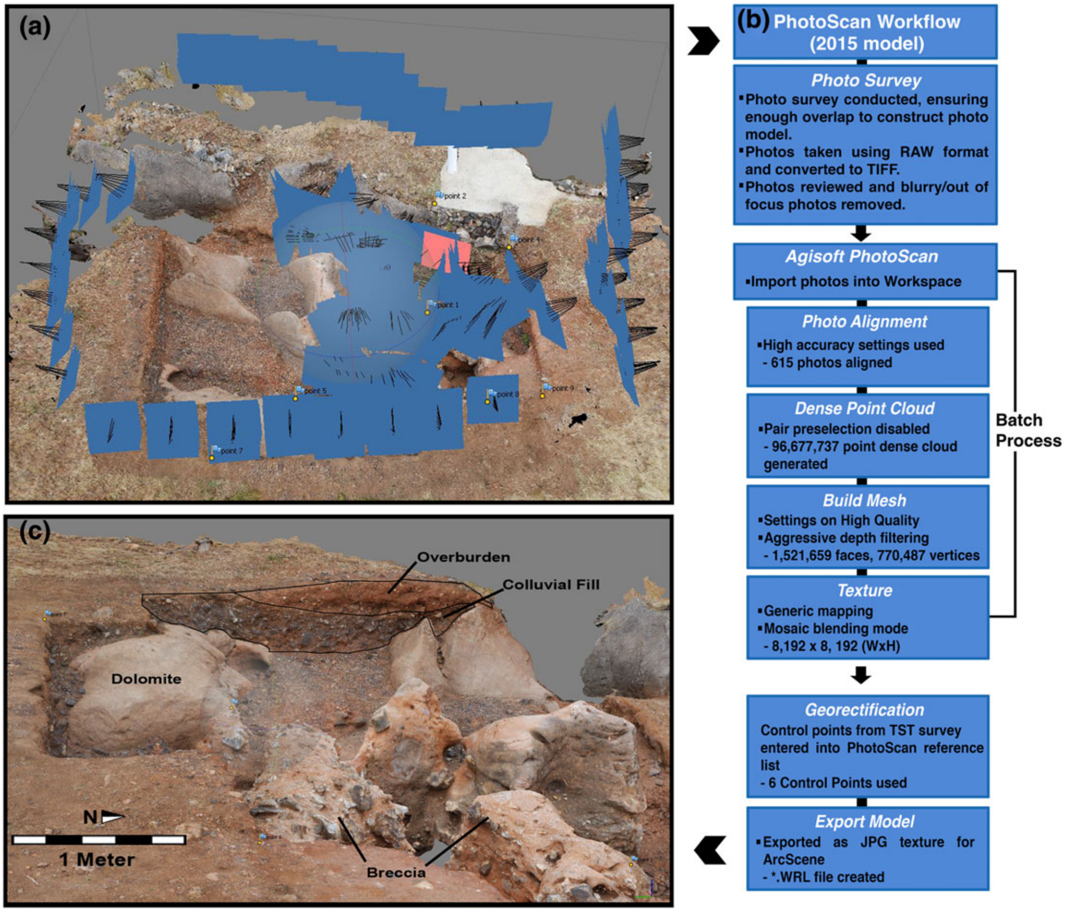


FIGURE 3 (a) Locations of camera survey points. (b) Agisoft PhotoScan work flow. (c) Rendered 3D model showing changes in geology and stratigraphy [Colour figure can be viewed at wileyonlinelibrary.com]

employed. Finally, different control points were used for the two different surveys, tending to have a strong influence on the result.

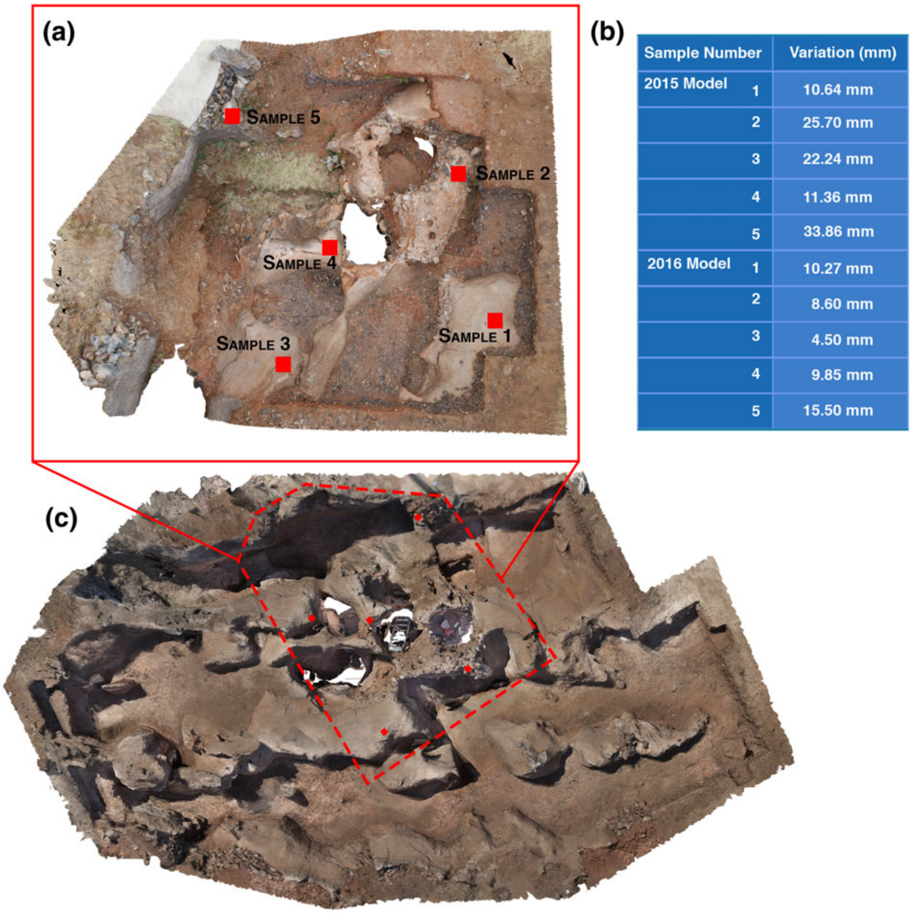
Given these constraints on a quantitative assessment of the difference between these models, a sampling approach was adopted on points that appear in both data sets. A number of assessments were conducted using Cloud Compare (ver. 2.8) and Meshlab (ver. 2016.12) open source software:

- assessment of the influence of Agisoft ground control markers by comparing the 2015 model to a new one generated in 2016;
- assessment of the variability between point clouds generated between laser scanning and PhotoScan survey; and
- assessment of meshed surface variability caused by two different software packages.

Analysis of point cloud data was conducted using Cloud Compare to determine the statistical variation between different point clouds. The laser scanner data and the photogrammetry point clouds were cropped (on the *X* and *Y* axes) and loaded into the software. Five sample points were taken across all the point clouds. These points were visible in all of the 2015 and 2016 data sets (Figure 4a). With the compute Cloud–Cloud Distance tool, the variation between the laser scan data and the points derived from PhotoScan was compared (Figure 4b). The results indicate a greater level of correspondence in the 2016 model than in the 2015 models. This is due to the more rigorous control methods implemented in the 2016 season, although when the complete point clouds are assessed independently, the 2015 laser scan shows greater correspondence with the PhotoScan point cloud than does the same assessment on the 2016 model. This is due to the 2016 model being of a larger area and a deeper excavation zone than the laser scanner was able to capture, whereas the photo survey could capture data in this zone.

To assess different surfaces in Meshlab (using Hausdorff distance sampling), models were cropped to the same size (on the *X* and *Y* axes) and meshed in 3DReshaper using the same settings (regular sampling of 0.002 m between points and hole detection and filling at 0.15 m). Laser scan models formed the base data for comparison with the PhotoScan models. The analysis was conducted with (a) a meshed PhotoScan model as a *.wrl file and (b) a *.las point cloud exported from PhotoScan and meshed in 3DReshaper. A summary of the results is presented in Figures 5 and 6. Results from Meshlab indicate that the different algorithms used by PhotoScan and 3DReshaper to mesh the models have minimal impact on the variability of the surface (on average between 1 and 3 mm across the site).

It should be noted that the MS50 is accurate to within 2 mm (Leica Geosystems AG, 2014); however, this accuracy refers to the instrument optics and not its set-up. The outcome of the scan will also be dependent on the quality of the control points used for this purpose (at Drimolen, they were set up in 1997 and may have errors of over



Sample Number		Variation (mm)
2015 Model	1	10.64 mm
	2	25.70 mm
	3	22.24 mm
	4	11.36 mm
	5	33.86 mm
2016 Model	1	10.27 mm
	2	8.60 mm
	3	4.50 mm
	4	9.85 mm
	5	15.50 mm

FIGURE 4 (a–c) Documentation of excavation progress 2015–2016; sampled point cloud variation in Cloud Compare [Colour figure can be viewed at wileyonlinelibrary.com]

5 mm). It should be noted that site data collected with the onsite TST will often have errors within the range of 1–5 mm or more, due to TST set-up, instrument accuracy, and method of point acquisition (using a reflector vs. a prism). Given that many of the fossils recorded with a TST are greater than 20 mm in size, the overall accuracy of the models generated with PhotoScan is acceptable and improves greatly with user experience and the use of well-spaced ground markers and well-planned survey data acquisition.

PhotoScan offers a range of colour texture resolutions, suitable to see clear differentiation between strata when visualised within the GIS (Figures 3c and 7). In the final phase, models can be exported as 3D PDFs (see Supporting Information), which become useful in comparing static photos of the completed 2016 excavation (Figure 8a) with composite imagery generated from the 3D model seen here at the same viewpoint (Figure 8b). In addition to tracking excavation progress, a 3D volumetric analysis was conducted on the models between the start and end of the 2015 season. Results indicate that during the field season, a total of 6.07-m^3 deposit was removed. In total, 7.57 m^3 has been removed in 2014 and 2015.

Few 3D methods have been employed at these type sites in South Africa, and as such, it represents a new approach to examining these palaeocaves. The resulting models provide a fit-for-purpose output for site documentation, visualisation purposes, and archival material, but the use of a GIS and TST data collection is necessary for continued spatial analysis of site data.

5 | DISCUSSION

Laser scanning and photogrammetry have been increasingly used in archaeological and heritage projects; with the notable exception of the recently discovered Rising Star Cave System (Kruger, Randolph-Quinney, & Elliott, 2016), few palaeontological sites in South Africa have been documented using these methods. Early attempts were made to create a 3D GIS at two sites within the UNESCO World Heritage Site (Häusler et al., 2004; Nigro et al., 2003), but at the time, the technology was not available to place these data effectively within a realistic 3D environment. The development of new technologies has resulted in the opportunities for these to be tested in these environments and to assess their suitability, as well as the advantages and disadvantages of each (for a summary, refer to Table 1).

In terms of the Leica MS50, it produces an automatically georectified point cloud without the need to place markers in the scene. Although point cloud acquisition rate is slower than a dedicated scanner (3,000 points per second compared to 1 million points per second; e.g., Leica models P30/P40, Leica Geosystems AG, 2016), post-processing time is reduced. Leica Infinity software has the ability to recalculate the MS50 occupy points, allowing for conversion of the model from a local grid to a projected coordinate system. This enables site data to be integrated into regional and global scales of analysis. The inbuilt camera can capture the surveyed scene for the generation of coloured surface textures; however, manual control over the camera

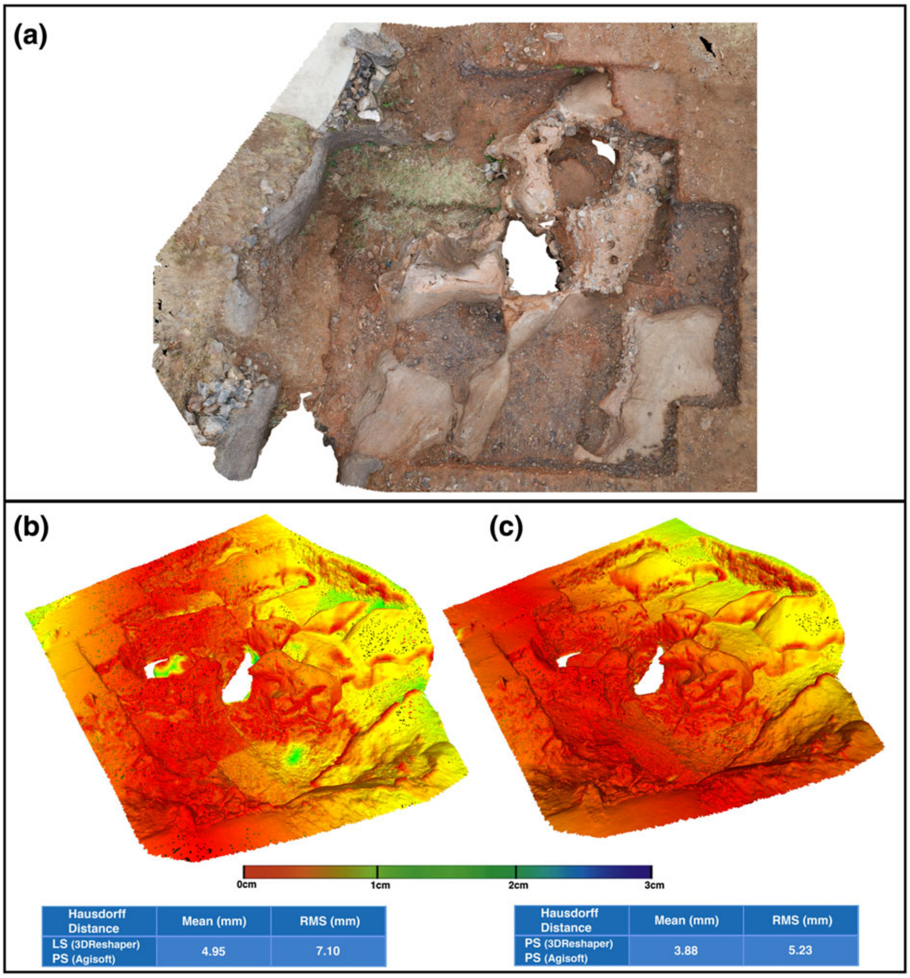


FIGURE 5 A 2015 photo model of the Makondo and Hausdorff distance analysis using Meshlab software, showing (a) the model rendered in Agisoft PhotoScan, (b) Meshlab geometry comparison of the laser scan (LS) meshed in 3DReshaper and photo model (PS) meshed in PhotoScan, and (c) comparison of the photo model meshed in 3DReshaper and the same model meshed in PhotoScan [Colour figure can be viewed at wileyonlinelibrary.com]

settings (e.g., aperture and ISO) does not presently exist, and the camera is currently only 5 MP. This limits its usefulness in cloudy, dark, or high-glare field conditions in comparison to a DSLR.

The speed of data collection using both methods is worth noting, with the surveys completed in less than 2 hr. The photo survey was somewhat faster than the laser scan, with one systematic survey of 615 photos sufficient to build the 2015 3D model. The laser scan required multiple set-ups in order to capture the entire site, thus using more operator time. The time taken to complete both approaches will vary considerably depending on the size of the site to be surveyed, and good planning is key to reducing in-field time costs. For the photogrammetry method, consideration of the survey route and overlap strategy of the photos is crucial to the success of the alignment phase and helps reduce post-processing time.

One advantage of the laser scan approach is that the results can be viewed instantly, whereas the photogrammetry method required a number of hours of processing time. In both cases, additional surveys can be conducted to fix errors and holes in the meshed models; however, for the photogrammetry method, lighting conditions must be taken into account. The MS50 does not have the ability to record features closer than 1.5 m and has a limited angle of view downwards (19.4°). As a consequence, capturing the base of scenes that are narrow and deep is difficult, resulting in area holes in the mesh (e.g., the Main Makondo solution pocket, Figure 7).

In contrast, the photogrammetry method can be used to target areas that the MS50 is unable to reach, although with poor lighting, this becomes increasingly problematic. This may be overcome by using a more sophisticated approach such as that conducted at the site of Pinnacle Points 5–6 (Fisher et al., 2015). By controlling the lighting conditions and focal distance of each photo, this method produces highly accurate high-resolution imagery. This has proven to be a powerful tool for conducting complex colour analysis and assessment of archaeological strata. Given the low light conditions of many South African cave systems, an approach such as that used by Fisher et al. (2015) could be useful for creating highly accurate 3D models using PhotoScan where artificial lighting is necessary. However, the in-field costs in terms of time and resources for implementing these standards may preclude their wider use on palaeontological sites, as was the case for this project. Furthermore, controlling lighting conditions on open sites is difficult given the variability of shade and weather. Moreover, palaeokarst sites such as the Drimolen Makondo would be almost impossible to document

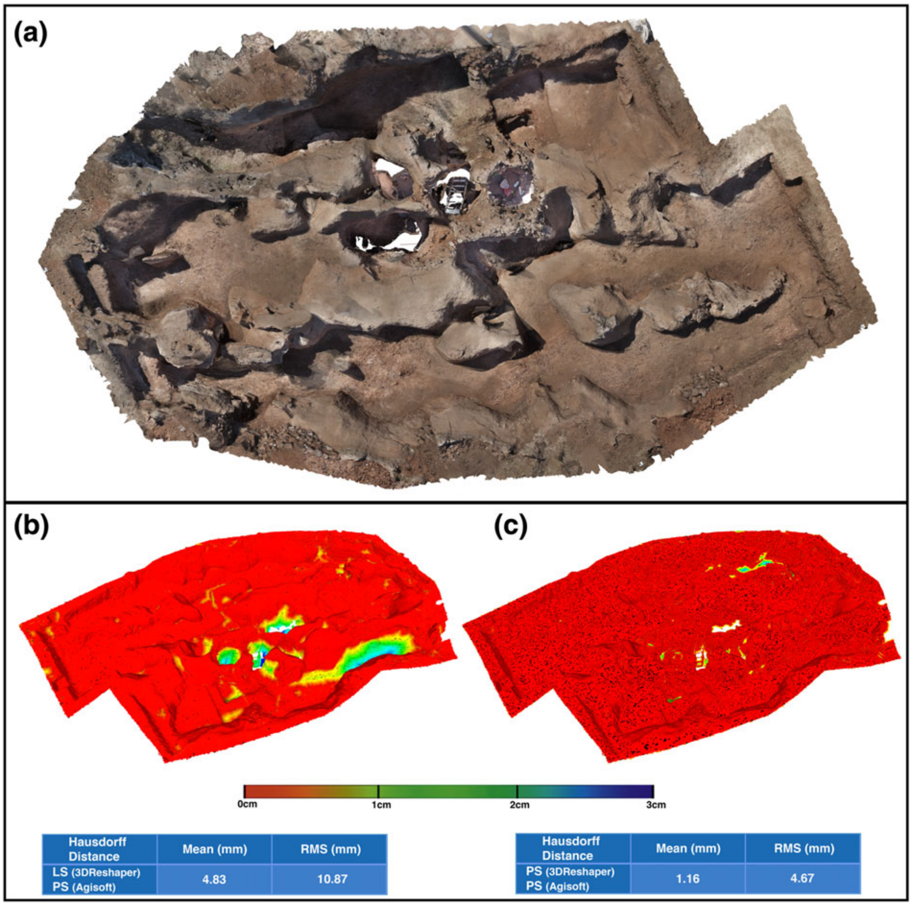


FIGURE 6 A 2016 photo model of the Makondo and Hausdorff distance analysis using Meshlab software, showing (a) the model rendered in Agisoft PhotoScan, (b) Meshlab geometry comparison of the laser scan (LS) meshed in 3DReshaper and photo model (PS) meshed in PhotoScan, and (c) comparison of the photo model meshed in 3DReshaper and the same model meshed in PhotoScan [Colour figure can be viewed at wileyonlinelibrary.com]

with the method of Fisher et al. (2015) due to their constricted nature and curved breccia outcrops. Although the use of a handheld scanner such as the Artec Spider (Adams, Olah, McCurry, & Potze, 2015) can be used to infill these difficult areas. As such, a combined approach would be needed for the majority of South African fossil-bearing palaeocaves sites.

In addition to the costs of initial field-based data collection, the post-processing phase for various types of 3D models may require

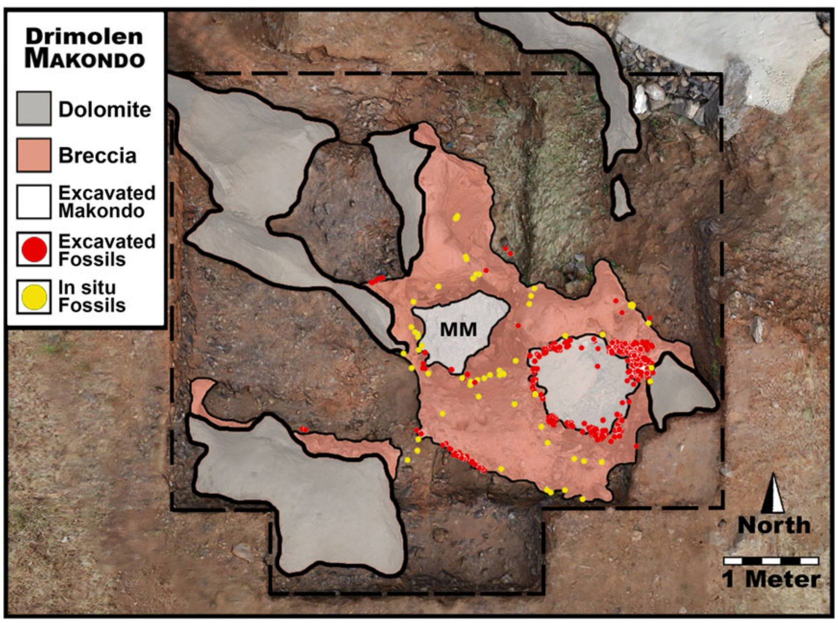


FIGURE 7 Site plan and model integration with collected site TS data. MM = Main Makondo [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 8 (a) Makondo at completion of excavation 2016. (b) Completed PhotoScan model 2016. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Advantages and disadvantages of the two methods

MS50 MultiStation	Photogrammetry
Automatically georectified point cloud	To georectify photo model a total station or ground control points required
High cost	Low cost
Technology is currently expensive	Can be implemented with most digital cameras (point and shoot and DSLR)
Can be processed and assessed in field	Can be processed and assessed in field but requires sufficient computer power
Moderately fast data acquisition, requires multiple set-ups of instrument	Fast data acquisition when photo surveys are carefully planned
Active sensor	Passive sensor
Functions in all light conditions	Requires natural or artificial lighting
Less post-processing required	Post-processing is time-consuming
Experience needed in instrument operation and post-processing software	Experience in photo survey and post-processing is useful to produce accurate models
Laser scans are highly accurate (±2 mm)	Accuracy achieved through georectification
Requires highly accurate instrument initialisations (resections/known points)	Requires accurate and well-placed ground control points
Confined areas difficult to scan due to limited angle of operation and minimum distance of 1.5 m from instrument	Can target smaller areas that are unreachable with a laser scanner
Point clouds produced by laser scanner have limited applications and are usually in greyscale	High-resolution colour photos can be used for further analysis and archival documentation of sites

significant computing resources. There are options available within both 3DReshaper and PhotoScan to complete larger models by reducing alignment accuracy or utilising smaller point cloud densities. For example, when processing a large number of photos in PhotoScan, it may be necessary for the photos to be separated into smaller groups or "Chunks." This is due to processing time being more dependent on the total number of photos rather than on the quality, resolution, or file size. The workflow menus in PhotoScan offer a number of custom options for more advanced users that allow greater control over processing time and the final size of the models. We found that for surveys of 600 photos or less, high-resolution settings can be used to generate functional models, but larger surveys of between 1,000 and 6,000 photos required different settings typically utilising less point clouds, smaller face mesh settings, and texture sizes no bigger than 8,192 × 8,192. Models with large texture files will not function or render well within ArcScene, and 3D PDFs will not open on the average user's computer.

Likewise, the laser scan data can be processed in 3DReshaper to produce different resolutions of meshed models. This can be achieved relatively quickly on most hardware systems. The usability and workflow proved to be more difficult with 3DReshaper, requiring a greater level of manual processing to produce colourised textured models than with PhotoScan.

When rendering laser scan and photogrammetry data, model size outputs and their intended functions are important for determining processing strategies. In this case, models suitable for spatial analysis in a GIS were generated; however, experimental work is already being conducted on larger walk-through environments using virtual reality technology. As yet, these remain unpublished, although examples are available online (James, 2015). Three-dimensional immersion technologies such as the Oculus Rift (https://www.oculus.com/en-us/rift/) or HTC Vive (http://www.htcvr.com/) and Google Cardboard (https://www.google.com/get/cardboard/) are still in development but are likely to become widely used in the near future. As a proof of concept, using the Unity Game engine, a walk-through model was developed of the site, utilising the high-resolution outputs from PhotoScan. Although processor heavy, the raw data generated from these surveys can be adapted to create virtual reality environments and used as communication and educational tools. Using these interactive systems to experience a place in virtual reality is also a fun, exciting, and novel way in which people can engage with research.

Surface analysis indicated the maximum variation occurs on the *Z* axis (as expected due to the different methods employed), and the variability on the *X* or *Y* axis is within tolerances expected for the majority of surfaces. After applying PhotoScan ground control markers in the 2016 model, this variability is reduced. Nevertheless, both methods have the capacity to produce fit-for-use spatially accurate 3D models for palaeontological sites. However, given the technical specifications of the Leica MS50 (2 mm), it will reliably outperform photogrammetry methods in terms of spatial accuracy.

The Leica MS50 and associated software are considerably more expensive to acquire (~$AUD74,000) and operate than the use of a commonplace DSLR and the PhotoScan software. The somewhat limited budgets of many palaeontological projects have to be considered; in most cases, the ability to purchase a laser scanner is simply not possible. On open and well-lit sites, the photogrammetry method offers a viable alternative to using a laser scanner, although the use of a TST is still required for georectification. Many of the sites in the UNESCO World Heritage Site, although technically designated as caves, are heavily eroded and could be considered open sites. Table 2 presents a list of known sites that could be accurately documented using the photogrammetry method without the use of artificial lighting systems.

TABLE 2 Applicability on South African palaeontological sites

South African palaeokarst sites	Applicable method	Completed methods
Drimolen Main Quarry	Photogrammetry	Combined
Drimolen Makondo	Photogrammetry	Combined
Wonder Cave	Laser scan	Laser scan
Plovers Lake	Combined	
Haasgat	Laser scan	Laser scan
Malapa	Photogrammetry	
Gondolin	Photogrammetry	
Sterkfontein	Combined	
Swartkrans	Photogrammetry	
Cooper's D	Photogrammetry	
Kromdraai	Photogrammetry	
Motsetse	Photogrammetry	
Hoogland	Combined	
Rising Star	Combined	Combined
Taung	Combined	
Gladysvale	Combined	
Goldsmith's	Photogrammetry	
Makapansgat	Combined	
Bolts Farm:		
Main cave	Laser scan	Laser scan
Aves Cave	Laser scan	Laser scan
Elephant Cave	Laser scan	Laser scan
Cobra Cave	Laser scan	Laser scan
W160	Photogrammetry	Photogrammetry
Brad Pit	Photogrammetry	Photogrammetry
Milo	Photogrammetry	Photogrammetry

The key advantage of the photogrammetry method is its cost-effectiveness and the ease with which photorealistic textured models can be generated. In closed cave systems, however, the use of the laser scanner may be the only option available unless significant time and resources are invested in a temporary lighting system. The data acquisition and post-processing stages of the photogrammetry method are more user-friendly and offer a greater variety of texture rendering choices than do a laser scan survey. It is possible for the images acquired during the photo survey to be integrated with the laser scan model, by using either 3DReshaper or open source software such as MeshLab or Cloud Compare to combine or georectify point clouds together. This combination will provide the best possible accuracy and surface textures; however, manual processing time increases dramatically.

A combined approach to the collection of data for South African sites within the UNESCO World Heritage Site is possible given that many of these systems are open settings. We estimate that between 12 and 18 of the known Plio-Pleistocene sites could be accurately mapped in 3D using the lower cost photogrammetry method (Table 2). although for these to be accurately georegistered on the South African grid, the use of an RTK DGPS system would be necessary. Some of these sites are currently being excavated, and the low-cost photo surveys could be undertaken at the start and end of field seasons, building a continuous 3D record of these sites over many years. This approach has been applied at Drimolen and is proving to be a useful tool for post-excavation data analysis and volumetric assessments of materials and strata removed.

An additional benefit of the photogrammetry method is the large archival record of photos that is generated during the photo survey. Within the PhotoScan software, it is possible to isolate and view individual photos on any point of the model. Having this record may be crucial for proving the veracity of claims regarding the context of fossils and for the interpretation of uranium–lead, palaeomagnetic, electron spin resonance, or cosmogenic dating samples. In the past, attempts to revisit, visualise, and comprehensively understand important fossils within their context have proven to be challenging (Herries & Shaw, 2011). Nevertheless, the capabilities now exist for researchers and stakeholders to record these sites for future generations.

There may be potential for these models to be used for the analysis of legacy data at sites excavated over many decades of research. The visualisation of these sites in three dimensions can be useful for interpreting complex spatial associations between different geological and geomorphological elements of cave systems. Having a colourised and textured model of a site representing different excavation phases offers the potential to clarify many of the issues surrounding interpretation of site formation and fossil assemblages. Additionally, the use of image analysis software has the potential to provide a clearer picture of geomorphological and stratigraphic variability in 3D. Large data sets of newly collected photos could be transferred and processed with relative ease, and the outputs and models could be provided to communities and museums as a digital or 3D printed resource for educational and engagement purposes. This form of documentation is of critical importance given the continued impact of developments in the UNESCO World Heritage Site and the significance of these sites in the story of the evolution of humankind.

6 | CONCLUSION

The two methods discussed are capable of producing fit-for-purpose accurate 3D models that can be integrated with many forms of digital data through the use of GIS and visualisation software. Ultimately, having access to equipment to be able to utilise the two methods would be the preferred solution for all environments, but cost is usually the most important factor in determining an appropriate strategy. Given that the photogrammetry method is currently more affordable, it is likely that this will prove to be the most popular. Software options now exist to provide a combined approach in certain environments, by merging high-resolution colour point clouds generated from photogrammetry with more accurate laser scan data (Grussenmeyer, Burens, et al., 2012; Moussa, Abdel-Wahab, & Fritsch, 2012). More automated cloud matching and the possibilities of using legacy photography in projects open up future areas of research.

Application of these methods will prove to be useful not only in terms of visualising excavation progress but also as a means of producing a comprehensive photo archive of the site. Limitations on this approach include the ongoing costs of data management and storage as well as the computer processing power required to generate these models. Over time, the costs associated with these methods are likely to decrease as hardware capabilities increase.

Ongoing work at the site of the Drimolen Makondo will attempt to integrate a number of technologies including ground penetrating radar, geotechnical borehole testing, aerial imagery, geological mapping, and ongoing analysis of excavation data. Three-dimensional modelling of surface and subsurface characteristics will represent the next phase of research at the site. Ultimately, the fossil finds have to be placed within their landscape and environmental context, and given the complex infill and erosion patterns in the majority of these caves, both methods provide a powerful tool to assist in their interpretation. This method also has incredible potential to enable immersive experiences through the use of wearable headsets, and to help inspire the general public to engage with and learn about these unique places.

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SUPPORTING INFORMATION

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