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Laser scanning for conservation and research of African cultural heritage sites: the case study of Wonderwerk Cave, South Africa

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ABSTRACT

The 'African Cultural Heritage and Landscape Database' project, initiated and directed by the senior author and administered by *Aluka* (www.aluka.org), is aimed at the creation of a digital library of spatial and non-spatial materials relating to cultural heritage sites in Africa. The archaeological site of Wonderwerk Cave (South Africa) is one of the 19 sites documented to date using laser scanning, conventional survey, digital photogrammetry and 3D modelling. To date, it is one of the few archaeological caves worldwide to be fully scanned. This paper explores the different uses to which the spatial data derived from this cave have been, or will be, put – for historical and educational purposes, scientific research and site conservation and development.

> "Objects of the past legitimize and inform the present; they provide a visible, durable cultural map of transient human affairs" Fekri Hassan (1999: 398)

1. Introduction

The 'African Cultural Heritage Sites and Landscape Database' project was established by the senior author in order to develop visual, spatial and research documentation of cultural heritage sites on this continent. Its goals are promoting awareness of, and stimulating interest in, African cultural heritage sites as well as preserving them as a permanent record for current and future conservation, research and educational purposes (Rüther, 1998, 2007a,b; Rajan and Rüther, 2007). Thus it provides information for:

- heritage-oriented education and research
- conservation and restoration
- site and tourism management
- increasing awareness of Africa's heritage in Africa and internationally
- providing a digital reference and record for future generations.

Although the status of cultural heritage sites is excellent in some African countries, in others these sites are endangered, facing damage or destruction (e.g. Mabulla, 1996; articles in Schmidt and McIntosh, 1996; Pwiti and Ndoro, 1999; Kankpeyeng and DeCorse, 2004). Consequently, a database of this kind may, in certain countries, be of use in combating the erosion of a valuable legacy, while in others, it will play a more pedagogic and conservation-orientated role.

The 'African Cultural Heritage and Landscape Database' was conceptualised as an integrated database combining a 'spatial approach' to heritage preservation, namely the metrically accurate documentation of spatial as-is data i.e. what is physically present, together with non-spatial contextual data. Given the rapid development of technologies for the acquisition, processing and visualizing of high precision 3D spatial data, the integration of the spatial documentation of heritage sites with their contextual information has become viable, bringing together the geomatician and the archaeologist, historian, anthropologist, heritage conservator and educator. Today it is one of three web content areas administered by *Aluka*, a collaborative international programme aimed at creating an online digital library of resources about and from Africa (http://www.aluka.org).

The non-spatial data, such as books, reports, scientific papers and expert descriptions of sites, are archived by *Aluka* in digital form. The spatial data are presented in the form of

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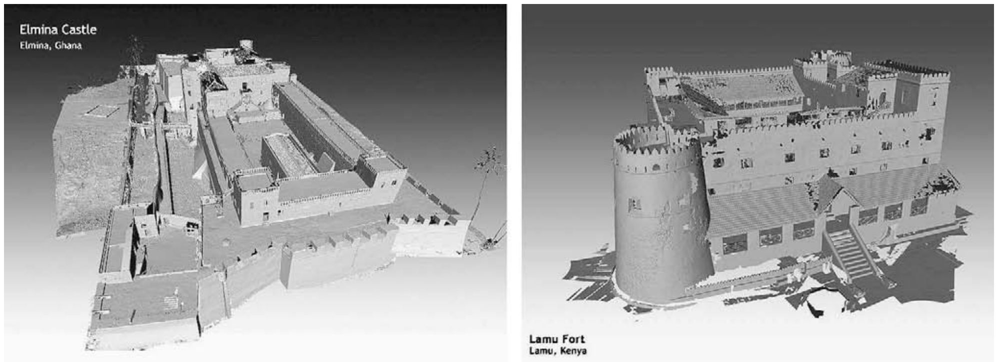

Fig. 1. Complete 3D models of two African cultural heritage sites. Left – Elmina Castle, Elmina, Ghana-trading post and important station on the Atlantic Slave Trade, erected by the Portugese in 1482. Right – Lamu Fort, Lamu, Kenya – served as a garrison and then a prison, erected between 1813 and 1821.

Geographic/Spatial Information Systems (GIS/SIS) datasets for each site, 3D laser scan models of built structures (Figs. 1 and 2), elevation views of these structures as well as of the surrounding landscape (Fig. 3), ground plans (Fig. 4), sections, photogrammetric images of the most important components of the site, videos, photographic panoramas and general images as well as a 3D landscape model combining satellite images with 3D terrain models. These were acquired using technologies such as aerial and close range digital photogrammetry, laser scanning, remote sensing and image processing, conventional surveying, GIS, CAD, 3D visualisation sand database design (Rüther, n.d., 2002; Rüther et al., 2001, 2003; Mngumi and Ruther, 2004). All spatial data are associated with extensive metadata, such as camera calibration parameters, position of cameras and laser scanner and other information about the scan and survey details. The philosophy adopted for data acquisition and preservation by the project was to collect a maximum of data and store one set of all acquired information in raw format without any processing. This is to allow for possible future processing and use based on new, presently unavailable, methods and technologies. The data once acquired are made available on the *Aluka* web page.

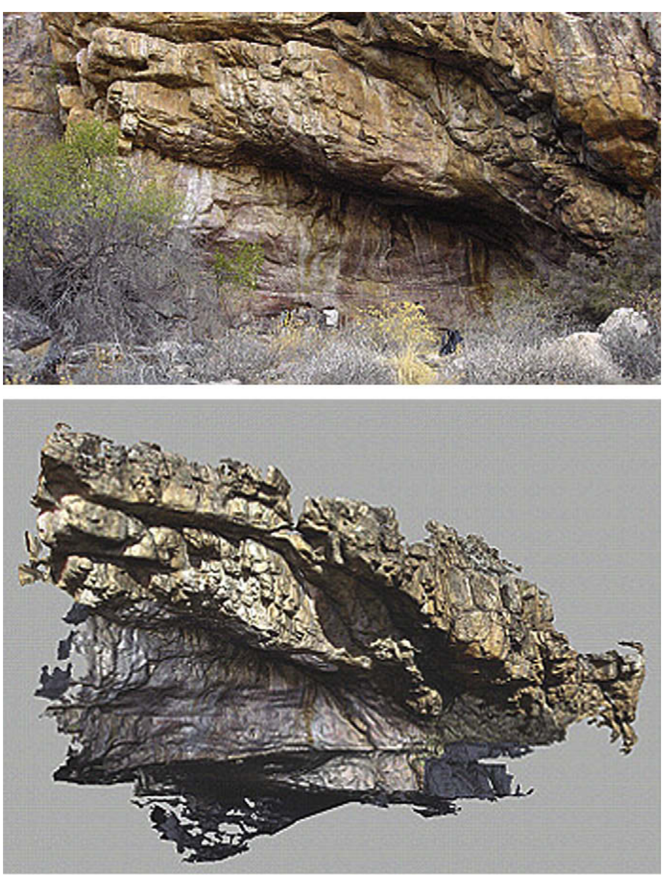

Fig. 2. Maidens Pool rock shelter in the Cederberg, South Africa containing Late Stone Age rock art. Top – photograph of the rock shelter; Bottom – 3D model of the rock shelter with texturing.

The nineteen sites documented since the implementation of this project in 2004 using geomatics technology and methods are shown in Table 1. In documenting 19 sites, the UCT team has completed more than 3000 scans and more are planned in future. Most of the scanned sites are built heritage sites, while one of the most recently documented is a cave, the archaeological site of Wonderwerk Cave located in the Northern Cape Province, South Africa. The scan was undertaken as an integral part of an ongoing research project at the site (directed by M.C. and L.K.H.). In this paper we present the use of a high precision automated 3D laser survey combined with conventional survey, photogrammetry and 3D modelling to document this cave site and its immediate environment. We will explore how this scan and the resulting model have advanced both research and heritage development at this site and will serve as an educational tool in the future.

2. The site

Wonderwerk Cave (27°50′46″S; 23°33′19″E) is an extremely large dolomite solution cavity; 140 m long, and ranging in width from 11 m to 24 m, and in height (from surface to roof) ca. >3 m to 10 m. The cavity extends into a conical hill on the eastern flank of the Kuruman Hills (Northern Cape Province, South Africa), and is the largest known cave in the Kuruman Hills–Asbestos Mountains region (Fig. 5). The hillside in which Wonderwerk Cave sites consist of dolomitic limestone overlain by banded ironstones of the Griqualand West sequence dating to ca. 2.3–2.6 Gyr (MacRae, 1999).

The cave has a single north facing entrance ca. 15 m wide and 5 m high. It is not clear when the size and form of this entrance stabilised, but speleothems which formed outside the cave mouth suggest that the cave overhang probably extended further forward in the past. Some 19 m in from the cave entrance there is a single stalagmite which stands more than 5 m above the current floor. The interior of the cave comprises a single large chamber ca. 2400 m^2 in extent which extends due south into the hillside for ca. 90 m, at which point it turns slightly to the east and continues for another

Fig. 3. Bet Giorgis Church, Lalibela, Ethiopia – 12th century AD rock-hewn Coptic church. Left – photograph of the church facade; Right – west facade view of the church derived from laser scan demonstrating this extremely useful by-product of scanning.

ca. 50 m (Fig. 6a). The cave roof is slightly arched in form, while the walls are roughly vertical and almost parallel. Late Stone Age rock paintings adorn both cave walls from the entrance inwards for ca. 40 m. The floor of the chamber comprises archaeologically rich sediments and roof spall.

Archaeological excavations in the cave commenced in the 1940s (Malan and Cooke, 1941; Malan and Wells, 1943) following finds of stone tools and fossil fauna recovered during removal of much of the organic-rich upper sediment which was fraudulently sold as guano for fertiliser. This left the surface topography of the cave uneven and pitted with deep ‘robbery pits’. Between 1974 and 1977, a study of the sediments and extant stratigraphy was undertaken by Butzer (Butzer et al., 1978). The most extensive excavations in the cave were subsequently conducted by P.B. Beaumont under the auspices of the McGregor Museum, Kimberley from 1978 to 1996, during which time 7 separate excavation areas were sampled within the cave (Beaumont, 1982, 1990, 2004; Beaumont and Vogel, 2006). Beaumont was joined for one season in 1979 by A.I. and J.F. Thackeray who studied the Holocene deposits near the cave entrance (Thackeray et al., 1981; Humphreys and Thackeray, 1983; Thackeray, 1984).

Wonderwerk Cave is distinguished by having yielded one of the longest and richest archaeological sequences in southern Africa, spanning the Late Stone Age (LSA), Middle Stone Age (MSA) and Early Stone Age (ESA) (Thackeray et al., 1981; Humphreys and Thackeray, 1983; Thackeray, 1984; Beaumont and Vogel, 2006). Recent dates place the base of this sequence in the front-most excavation area (Excavation 1) at ~2.0 Ma (Chazan et al., 2008), while the uppermost LSA deposits span the Late Pleistocene/ Holocene 12.5–1.0 kyr ago (Beaumont and Vogel, 2006). The site has thus far produced significant archaeological finds including some of the earliest dated LSA *art mobilier* from southern Africa (Thackeray et al., 1981), possible presence of fire in the ESA, and evidence of early symbolic behaviour also dating to the ESA (Beaumont and Vogel, 2006). The unique preservation of organic remains at the site has provided a significant paleoecological record (Malan and Cooke, 1941; Humphreys and Thackeray, 1983; Klein, 1988; Scott et al., 1995; Avery, 1981, 2006; Thackeray and Brink, 2004; Llyod Roussouw pers comm., 2008). Due to its archaeological significance, Wonderwerk Cave has been placed on South Africa’s Tentative List for future World Heritage nomination. (http://whc.unesco.org/en/tentativelists/1074/)

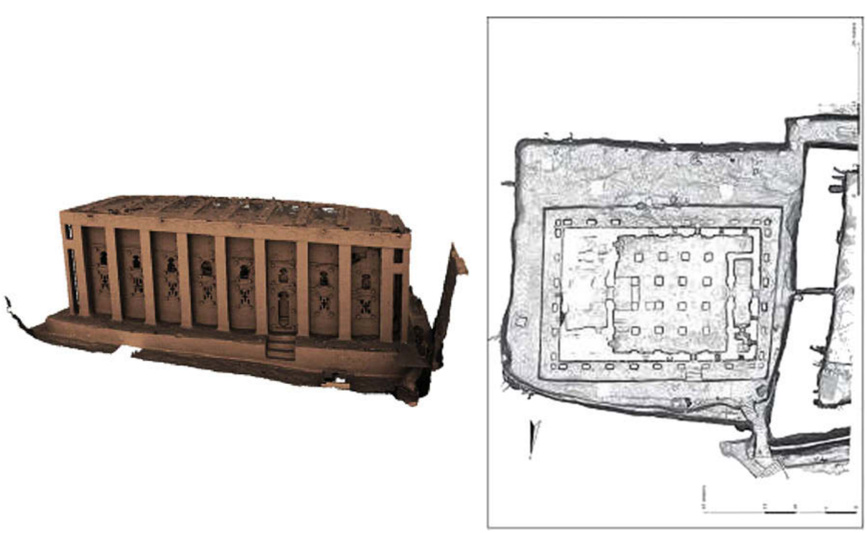

Fig. 4. Beta Medahne Alem, Lalibela, Ethiopia – 12th century AD church. Left – 3D model of the structure with texturing; Right – ground plan of structure derived from laser scan.

Table 1
List of sites documented by the 'African Cultural Heritage and Landscape Database' and managed on the Aluka website. Reconstructions can be viewed on: http://www.aluka.org.

Site	Country	Main structure
Kilwa Kisiwani	Tanzania	Fortress (Gereza and Great Mosque)
Djenne	Mali	Great Mosque
Timbuktu	Mali	Djingere Ber Mosque
Lalibela	Ethiopia	14 rock-hewn churches and intermediate terrain
Axum	Ethiopia	Stele field
Elmina	Ghana	Elmina Castle
Besease, Kumasi	Ghana	Ashanti shrine
Great Zimbabwe	Zimbabwe	Hill Complex and Great Enclosure
Stone Town	Tanzania/Zanzibar	Two Persian baths and War Memorial
Engaruka	Tanzania	Dry stone structures, enclosures and terraces
Diepkloof	South Africa	Shelter with rock art
Keerbos	South Africa	Shelter with rock art
Kriedouwkrans	South Africa	Shelter with rock art
Maidens Pool	South Africa	Shelter with rock art
Veg and Vleg	South Africa	Shelter with rock art
Lamu	Kenya	Fort, Swahili House, traditional street
Shela	Kenya	Mosque
Tassili N'Ajer	Algeria	Rock engraving of giraffes[a]
Wonderwerk	South Africa	Cave interior and Hillside

[a] This project was carried out for TARA, the Trust of African Rock Art, David Coulson, Nairobi, Kenya.

3. Geomatics

3.1. Background

The initial wave of 3D scanning applications in archaeology tended towards the recording of objects and sites as part of the development of resources to enhance public experience of archaeological and heritage resources (Addison, 2000). Among the numerous studies in this field, we list here just a few examples: the creation of virtual reconstructions of the Qin Dynasty warriors based on 3D scans (Zheng, 2000); the construction of a precise replica of the tomb of Seti I in the Valley of the Kings using a combination of laser scanning and digital photography to record the tomb and output of a replica using an industrial router (Ahmon, 2004); high resolution terrestrial laser scanning combined with photogrammetry to document the Pyramids and Sphinx at Giza (Neubauer et al., 2005), and several case studies of objects and small sites from Italy (Beraldin et al., 2004; Valzano et al., 2005): the Byzantine Crypt of Santa Cristina (Apulia), remains of Temple C of Selinunte (Sicily), the bronze sculpture Zeus of Ugento (Museum of Taranto) and a Neolithic cave painting from the Grotta dei Cervi.

More recently, extensive standing architecture and/or natural landscapes have been documented for a range of sites using terrestrial 3D laser scanning such as a historic lime-working site with a chalk pit and lime kilns (Kent, U.K.) undertaken by MoLAS (Museum of London Archaeology), in association with Plowman Craven Associates (http://www.molas.org.uk/projects). 3D laser scanning combined with aerial digital photographs, such as those taken from a model helicopter and terrestrial digital photographs, has been used to create a high precision model of the site of Pinchango Alto, Peru (Lambers et al., 2007), while in South Africa, 3D laser scanning of the Iron Age site of Thulamela (Kruger National Park) and environs has been extremely effective in building a digital terrain model of the site to which texture was added from aerial photographs (http://mcah.columbia.edu/thulamela). In eastern Austria, full-waveform airborne laser scanning was used to discover and document earthwork features obscured by forest canopy and undergrowth (Doneus et al., 2008), while Gomez-Lahoz and Gonzalez-Aguilera (2009) used airborne blimps to create 3D virtual models of extensive sections of the Roman city of Clunia and Celtic settlement of 'Las Cogotas', in Castile, Spain. Laser scanning, being a high precision and non-contact method of documentation, has also been applied to good effect in the recording of parietal art (Robson Brown et al., 2001; Díaz-Andreu et al., 2006; Freitas et al., 2007).

Archaeologists have utilised 3D imaging methods for research on a more micro-scale including for artifact analysis (Zapassky et al., 2006; Karasik and Smilanksy, 2008; Sumner and Riddle, 2008; Grosman et al., 2008), epigraphy (Meyer et al., 2006) and the collection of high precision spatial data for 3D recording of in situ finds and excavation surfaces (Losier et al., 2007; Katsianis et al., 2008; McPherron et al., 2009). To date however, few archaeological cave sites have been documented in their entirety using laser scanning. An exception is Kitley Shelter Cave in Devon, where ultrasound scanning succeeded in creating a 3D low precision map of the cave (Sellers and Chamberlain, 1998).

3.2. Scanning the interior of Wonderwerk Cave

A comprehensive laser scan of the entire interior of Wonderwerk Cave was deemed necessary as a baseline for current archaeological research at the site, as well as for historical

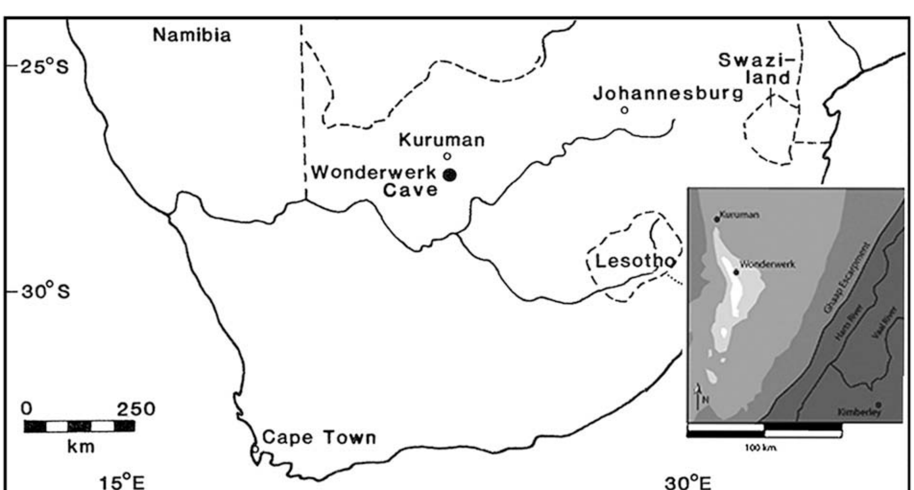

Fig. 5. Map showing location of Wonderwerk Cave, Northern Cape Province, South Africa.

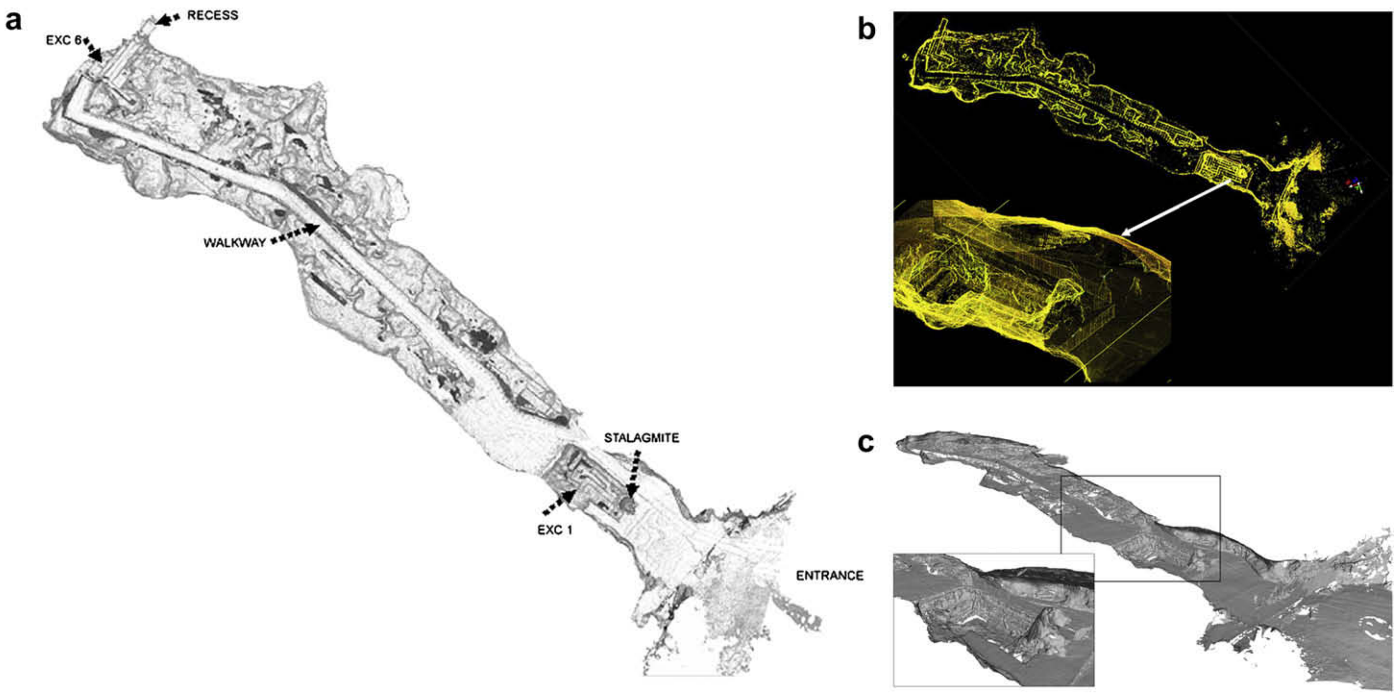

Fig. 6. 3D presentation of the interior of Wonderwerk Cave with inset showing a detail of Excavation 1. (a) ground plan (b) point cloud (c) surface model.

documentation of the cave, its rock art and the horizontal excavation grid which had been laid by the excavator (P. Beaumont) throughout the entire cave. Laser scanning was chosen over conventional survey methods and photogrammetry since it offered a rapid and high resolution method with which to map and then model this enormous and dark cavern. Conventional survey methods would require many thousands of points with which to document the natural and archaeological features within the cave (the cave wall contour, excavation grid, current pock-marked surface topography, stratigraphy of exposed sections etc.) while photogrammetry would have been far more time consuming, both in the field and during processing than the laser scan. In terms of research, the laser scan combined with solid modelling would also provide an interactive 3D grid for plotting archaeological finds post-excavation, facilitating reconstruction of lithic/faunal/botanical/geological associations. Furthermore, the scan would enable us to map existing natural/archaeological features within the cave and relate them to those outside. Finally, due to the importance of Wonderwerk Cave in the African archaeological record, it was a natural candidate for inclusion in the expanding horizons of the 'African Cultural Heritage and Landscape Database' program.

Over only three days of fieldwork, the entire interior of Wonderwerk Cave including each of the seven excavation areas, was laser scanned by two members of the geomatics team using a Leica HDS 3000 terrestrial scanner and Cyclone software operated by a laptop computer. The Leica is a 360 degree scanner with a full-dome field of view, an accuracy of approximately 6 mm and a range of 80–100 m. Depending on the reflecting qualities of the scanned surface and the angle of incidence of the laser signal, the scanner can record points at 120 m and occasionally even more.

In many ways, a natural site such as Wonderwerk Cave offers similar challenges to geomaticians as laser scanning of buildings and objects (Rüther, 2007b). These include:

- the impossibility of obtaining watertight scans due to the complexity and detail of the surface and difficulty of finding suitable vantage points to cover all missing surfaces.
- the immense amounts of time taken to register, clean, create a triangulated model, fill scan holes in the model, and texture it.
- the need to enhance software for modelling, feature extraction, texturing and presentation.
- finding software solutions for manipulation and storage of the immense volume of data that result.

The shape of a natural cave however differs in its complexity from the regular outlines and surfaces of built structures and this had to be considered when deciding on a suitable method of surveying and spatially recording Wonderwork Cave. Conventional survey methods provide the 2D or 3D positions of individual points, typically located at features of interest, such as corners, edges or changes in direction of surfaces and lines. To locate such points on regular manmade structures is generally easier than on irregular natural features, such as the walls of a cave. Laser scanning, on the other hand provides 'point clouds' of X, Y, Z data giving a grid type cover of the surface. In which detail the scanned surface recorded can be determined through the chosen point interval. A complete model consists of millions of individual surface points. Point clouds in the African heritage database vary between some 40 million points for single buildings such as the fortresses of Kilwa and Lamu, to six billion points for the 3D model of the churches of Lalibela together with the surrounding terrain.

For a rock surface such as Wonderwerk Cave, the point cloud representation is clearly more appropriate than a widely spaced array of individual points (Fig. 6b). The disadvantage of the point cloud approach is that there is no direct way of deliberately selecting specific points of interest and one has to make do with the relatively random selection of points in laser scanner's scan path. However, this drawback can be largely overcome by increasing scan point densities in critical areas, thus 'homing in' on desired features. Subsequent processing can further improve the definition of relevant points of interest. Feature points and lines can also be extracted by photogrammetrically integrating images taken with metric cameras or with calibrated amateur cameras. These considerations are relevant for the modelling of linearly defined structures but not for the irregular shapes of cave walls and therefore laser scanning was chosen as the most suitable method for the documentation of Wonderwerk Cave.

For the scan of the interior of Wonderwerk Cave the scanner was setup at sixteen strategically positioned points throughout the cave, to guarantee full cover of all cave walls and excavation areas (Fig. 7). Multiple scans from different vantage points eliminated as far as possible 'measurement shadow' i.e. obscured objects/surfaces or those not illuminated by the laser. The individual scan areas were selected to cover the entire cave wall surface while the principle was applied that each new scan had to contain parts of previous scans thus providing overlaps essential for subsequent registrations of the scan into one single point cloud. Point intervals or scan resolutions were chosen to be a minimum of 3 cm in horizontal spacing and 2 cm vertical. When choosing point intervals one has to find a compromise between high resolutions on the one hand and the increase of scan time and extreme, difficult-to-process point volumes on the other. One would naturally tend to consider high densities desirable as they provide more detail, but the price to pay can be considerable in terms of field time and even more so when confronted with software and hardware limitations associated with the processing stage of large point volumes. The relatively high resolution of 2 cm by 3 cm was chosen as it is intended to drape photographic images over large areas of the surface, a process which provides improved results with increased surface detail.

Registration of the scans with respect to each other can be achieved by joining associating overlapping sections of point clouds as mentioned above. In this approach an algorithm is applied which shifts and rotates surfaces, or sections of point clouds, with respect to each other until the distance between the corresponding surfaces is minimised according to statistical criteria. A potentially more accurate approach to scan-registration makes use of spherical or circular targets which are positioned so that four or more of these targets can be scanned from every scanner setup. This is done by means of sub-scans at highest resolution which are integrated into the respective surface scan. The positions of the targets are also determined accurately in a coordinate system which extends uniformly over the entire site. For the Wonderwork project, conventional survey techniques using a theodolite were employed for the determination of the target positions. The 16 individual station scans were then integrated into a single point cloud by referencing the scanned targets to the corresponding surveyed targets. Surface matching was used for registration wherever it was impossible to incorporate the necessary number of targets in a scan.

Fig. 7. Photograph showing interior of Wonderwerk Cave facing into the cave, and scanning targets.

Before various scans can be combined into a single point cloud the individual scans are cleaned of unwanted objects, i.e. objects of no relevance for the 3D model of the building or landscape in question. It is also necessary to fill scan holes in order to construct so-called 'watertight' models. Once the single point cloud was created, a surface model of the cave walls and the cave floor, as well as the different excavation areas, was generated by connecting neighbouring surface point by means of triangular surface components using the 3D modelling software Geomagic (Fig. 6c).

3.3. Results

The resulting 3D surface model of Wonderwerk Cave offers a variety of interactive features and has made it possible to:

- carry out measurements (length, breadth, depth, angles etc.) with an accuracy in the centimetre range between any two points inside the cave and also with respect to its environment. Of special interest here is the distance between the deepest point inside the cave and its nearest surface point outside the cave (see below).
- generate sections through the 3D model in any chosen orientation or location, in either point cloud or surface format. In this way 2D ground plans (Fig. 6a), profiles or sections can be created. Ground plans or horizontal sections can be integrated into a site – GIS/SIS, while both horizontal and vertical sections can be used in CAD applications. In this way, areas and volumes of any section of the cave and the surrounding hill, such as to determine the overburden (see below), can be determined.
- generate 3D visualisations as seen from any selected point inside the cave to any direction outside, or alternately from outside towards the cave.
- create virtual scenarios for conservation use, such as the design of structures inside the cave (see below).
- drape images over parts of the surface or the entire surface to show for example excavation sections or rock art.
- provide a high precision 3D matrix into which artifacts and other finds can be placed in order to examine associations within and between excavation areas, as well as with natural features within the cave.
- provide an accurate position, to the nearest centimetre, of the existing excavation grid, wherever this was marked with surface pegs.

As will be outlined briefly below, these features are of use for scientific research in the site, conservation and development as well as serving both an educational and historical role in order to document the natural, archaeological and anthropogenic features of the cave.

4. Applications of the Wonderwerk Cave laser scan and surveys

4.1. Relating the cave interior to its exterior

An issue of particular interest for research at Wonderwerk Cave is the presence of archaeological deposits dating from 0.187 to 0.780 kyr at the very back of the cave i.e. some 140 m from the cave entrance. This is a zone of relative darkness, only poorly illuminated by daylight reflected inwards from the entrance. This back area, labelled Excavation 6, was excavated by Peter Beaumont. One question left open by Beaumont's excavation was the possibility that there might have been another entrance at the back of the cave which provided direct access to the Excavation 6 area but which is now blocked (Beaumont and Vogel, 2006:119). A recess located in the side wall of the cave leading off from Excavation 6, that is currently filled with sediments as well as a buried stalagmite, provides one potential route for such an alternative entrance (Fig. 6a). A method of elucidating this issue without further excavation is to accurately establish the precise location of the recess relative to the slope on the hillside outside. The 3D laser scan and 3D model of the cave combined with a topographic map of the surrounding landscape offered the easiest and most accurate means of resolving this question.

To this end, a standard topographic survey of the hill above the cave and in its immediate surrounding area was executed. The resulting survey produced a contour map of the 122 m high conical hill at 5 m contour intervals, including the cave entrance which lies at its base (Fig. 8).

The cave survey now comprised of three separate surveys: the laser scan (A), the theodolite survey of the targets and of the excavation markers inside the cave (B) and the topographic (theodolite) survey of the surrounding area (C). In order to relate the three surveys to each other, a uniform reference system needed to be created. This was achieved by first arbitrarily allocating coordinates to one of the 'targeted' survey points of survey B, as well as defining the direction to a second target in the same survey as axis parallel. This process defined the common reference system. Survey B was then referenced to the same coordinate system by scanning the targets as part of the point cloud and then transforming all points of the point cloud via the common targets. The mathematical algorithm for the process is known as 3D rigid body transformation, i.e. a transformation which does not allow changes in shape or scale of the point cloud. Survey C was finally added to the now-combined surveys A and B, by linking the Survey C to the same targets. A 3D surface model of the outside area (C) was created. Due to the common coordinate system this model was linked to the point cloud of the cave's interior without requiring any further manipulation of the data.

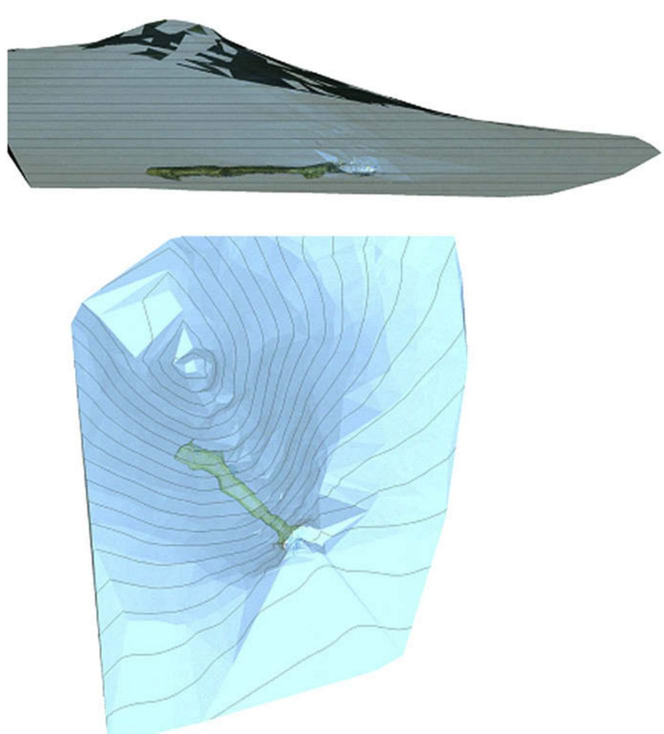

Fig. 8. Location of Wonderwerk Cave relative to the hillside in which it sits. Top – side view; Bottom – overview. Contour intervals are 5 m.

The results shown in Fig. 8, demonstrate that the back of Wonderwerk Cave is deeply buried in the hillside and that it is highly unlikely that a now-buried entrance existed in the past. Thus, the occupation of Excavation 6 is among the earliest known evidence for intentional hominin exploitation of a deep cave context.

4.2. Cosmogenic burial dating

A further and extremely valuable research application of the cave surveys has been in the realm of dating. Cosmogenic burial dating is a relatively new tool for dating ancient sediments. It is based on the measurement of the ratio of the radioactive decay of two cosmogenic isotopes, ^{10}Be and ^{26}Al, that are produced in quartz in a sample that was initially exposed and then shielded from cosmic radiation (Lal and Arnold, 1985). When the dosed quartz grains are buried, production of these nuclides is slowed or ceases. Because ^{26}Al decays faster than ^{10}Be, their ratio changes as a function of time and provides a means for estimating the burial age of the sediment containing the quartz grains (e.g. Klein et al., 1986; Granger et al., 1997).

The estimation of burial time can be obtained provided the sediment had a sufficient initial dose of cosmogenic isotopes, and that it was buried quickly (relative to its total burial history). Another and important requirement is that the sample has remained buried deep enough to eliminate exposure to cosmic radiation, mainly from deep penetrating muons (Granger and Muzikar, 2001). This is expressed in depth of sediment or in the case of a cave, the amount of overlying rock shielding the deposit. The latter requires that the thickness of the cave roof is known. Granger and Muzikar (2001) presented a method for correcting the influence of post-burial production of cosmogenic isotopes and improving the precision of calculated burial ages. If samples are buried at depths of many tens of meters this correction factor is greatly reduced and is less critical.

In Wonderwerk Cave, samples for cosmogenic isotope burial age dating were collected from Excavation 1 at the front of the cave and Excavation 6 at the back (Fig. 6a). To ensure that total shielding of the sediment from cosmic radiation during burial had occurred, the complete 3D scan of the cave's interior, combined with the conventional topographic survey of the hillside provided us with a precise measure of the relationship between the roof of the cave and the surface of the hill. This dataset has enabled us to calculate with high precision the shielding factor for any location within the cave (Fig. 9). The thickness of the roof ranges between 15 m over Excavation 1, to 60 m of rock over Excavation 6 (at a density of 2.6gr/cm^3). Thus the cave sediment has been sufficiently shielded from cosmic radiation and is eminently suitable for cosmogenic burial, as we have demonstrated in a previous publication (Chazan et al., 2008).

4.3. Conservation and development

Wonderwerk Cave is not only a unique archaeological and paleoecological resource, it is also a tourist attraction and educational resource of significance to the local economy and culture of the local municipality of GaSegonyana as well as for the Northern Cape Province. However, there is a need to develop the site and to provide safe access to the cave interior for visitors in a way that does not have a negative impact on the remaining archaeological deposits and the natural aesthetics of the site. One particular challenge has been to find a way to facilitate access for visitors

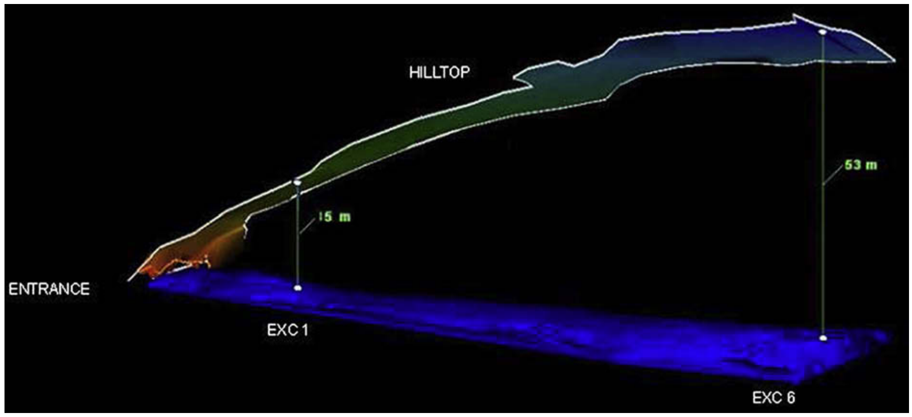

Fig. 9. Section through Wonderwork Cave showing the cave roof thickness.

including traversing the 4 m deep excavation area in the front part of the cave (Excavation 1) and to buttress a 4 m standing section.

- A number of principles common to most heritage projects guide the development of visitor access and conservation measures at Wonderwerk Cave. Critical among these are that all interventions must be completely reversible and should require minimal change to the existing configuration of the site. Aside from documenting the current state of the cave and the excavations, the 3D model has been an invaluable resource in the ongoing planning process for cultural management including engineers and architects. Among the uses of the laser scan and 3D model have been:
- To determine the optimal path for a pedestrian bridge to optimize the visitor's view of the excavation. Without extra expense and in minimal time, alternative paths and bridge forms could be tested within the virtual environment of the 3D model.
- The length of the bridge could be calculated precisely and reduced to the minimum required, thus reducing the overall bulk of the structure and saving money on construction materials, labour and time.
- The headspace between the proposed bridge and cave roof could be calculated precisely along its entire length and then visualised to assess its impact on the site.
- The exact placement of the base of the 70 degree retaining wall for the 4 m archaeological section could be tested virtually. Moreover, calculations could be made taking into account the precise slope of the section. The result has enabled us to locate the optimal position and angle of the retaining wall, the amount of material that will have to be introduced into the cave, the labour required and hence the cost.
- For all construction work planned inside the cave, the 3D model has aided us in finding the least invasive methods for implementing the conservation work (areas to be avoided, places where supports can be placed, pathways for workers to use etc.) so as to ensure minimal disturbance and damage to the site.

We are now moving beyond the engineering phase of the project to the design phase of elements such as handrails, lighting. Here again it is expected that the 3D model will allow alternative designs to be considered within a highly precise virtual environment.

4.4. Education and documentation

As part of the 'African Cultural Heritage and Landscape Database' project of Aluka, once completed, the virtual reconstructions of Wonderwerk Cave and associated non-spatial information will be made available to all via their website. This will include data on rock art and *art mobilier*, lithic and bone tools, ornaments, geology of the site and its surroundings, as well as information on the past fauna and flora. Together with the laser scan and 3D model, these will provide an important resource documenting a 2 million year long cultural and paleoclimatic record from the interior of southern Africa. It is also planned to incorporate the virtual reconstructions of the site when the current visitors' center is up-graded.

5. Conclusions

In this case study, we have shown how the application of conventional surveying and laser scanning have contributed to our knowledge and understanding of Wonderwerk Cave, South Africa. Aside from creating a permanent record with maximum detail of the natural environment – both within and outside the cave, our work has provided an enduring and realistic document of its archaeology. As demonstrated by the two examples outlined in this paper, the topographic survey and the 3D modelling have also furthered our scientific investigation – by assessing the possible existence of another now-blocked entrance at the back of the cave, or by determining the extent of sediment shielding, to calculate cosmogenic burial dating ages. Future research at Wonderwerk will harness the geomatic database to explore other facets of the site, such as spatial plotting of finds or correlating strata between different excavation areas.

In the field of site conservation and development, the metrically accurate dataset provided by the survey's spatial data acquisition has already proved invaluable in facilitating quantitative analysis and planning of work to be carried out at this site. Doubtless, it will be used for these purposes in the future, in concert with management plans for the site. Indeed, Wonderwerk Cave is an excellent example of how the 'African Cultural Heritage and Landscape Database' project can assist in protecting and preserving cultural heritage sites in Africa. Aside from providing a permanent record for future generations, it can aid in the more practical quantitative planning of conservation and restoration. Another important feature of the spatial database is its ability to visualize proposed interventions using a precise and realistic 3D model of the site. Thus, both the aesthetic and practical implications of restoration and conservation work can be assessed easily before work commences. Furthermore, site planning and management can employ this feature to envisage and model potential changes to a site in the future.

Finally, with regard to education, Wonderwerk, like the other sites already included or planned for inclusion in the Aluka database, serves to publicize African heritage. Even today, the vast majority of the continent's heritage sites are little known – abroad as well as in Africa. Aside from promoting international tourism, a key focus of the project is as a pedagogic tool for Africans as well as people living elsewhere, many of whom are not in a position to visit the sites. Although many people, especially in Africa, may currently be unable to access these datasets, this project looks to the future when computer technology will be more readily available to all, irrespective of their educational status. A virtual library of cultural heritage sites from all over Africa can serve as an efficient and relatively inexpensive educational tool to disseminate such information within the continent as well as abroad. It is hoped that knowledge of these sites will serve as a conduit for creating awareness and pride of local cultural heritage, as well as engender respect for the cultural heritage of others.

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