A computer-guided 3D multiscale reconstruction of the Kromdraai site

Jean Dumoncel, Benjamin Lans, José Braga, Gérard Subsol, Jean-Pierre Jessel, Francis Thackeray, Benjamin Moreno, Norbert Plate, Frikkie de Beer, Ntombi Ngoloyi

KROMDRAAI

a Birthplace of *Paranthropus* in the Cradle of Humankind

A South African Heritage Site

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Published by SUN MeDIA MeTRO under the SUN PReSS imprint.

This publication was subjected to an independent double-blind peer evaluation by the Publisher.

First edition 2016

ISBN 978-1-928355-06-9 (Print)
ISBN 978-1-928355-07-6 (Online)
DOI: http://dx.doi.org/10.18820/9781928355076

Set in ZapfHumnst Dm BT 9.5/12

SUN PRESS is an imprint of AFRICAN SUN MeDIA. Academic, professional and reference works are published under this imprint in print and electronic format. This publication may be ordered directly from www.sun-e-shop.co.za.

Produced by SUN MeDIA MeTRO.

www.africansunmedia.co.za
africansunmedia.snapplify.com (e-books)
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Acknowledgements

J. Braga and J.F. Thackeray

In 1999, the United Nations Educational, Scientific and Cultural Organization (UNESCO) officially listed the first three South African World Heritage sites – a truly historic national moment.

The 'Cradle of Humankind', an area in the Gauteng Province considered to represent an invaluable record of the early stages in the evolution of humanity, was listed along with Robben Island and the Greater St Lucia Wetland Park. During the same year, the South African Heritage Resources Authority established the National Heritage Resources Act No. 25 to introduce an integrated and interactive system for the identification, assessment and management of the South African heritage resources; to establish the South African Heritage Resources Agency (SARHA), and together with its council to coordinate and promote the management of heritage resources at national level.

According to the South African Government Brief 14 of 2012, the South African heritage is "characterised by peoples' identification with particular spaces and places shaped by historical events and collective memory" (www.gcis.gov.za). The South African national and provincial authorities have designated the South African heritage as one of the major domains to develop new strategies in order to balance the need for business development and the creation of jobs, with the need to maximise the benefits for the education of as many people as possible. Arising from these opportunities, the South African heritage, maintained in the present and restored for the benefit of future generations, represents an increasingly important educational/economic resource that generates substantial public interest from local and international visitors.

It is also through international scientific relationships that South Africa shares the technological skills and expertise needed to achieve greater understanding of the value that its heritage has for the world. The multidisciplinary and intersectorial 'Erasmus Mundus' programmes of the European Union are designed to contribute to the development of new professional profiles to face rapid changes in practices and to use South African national symbols, cultural and natural heritage as vectors for sustainable partnership. Within the 'Erasmus Mundus' framework, European and South African joint efforts through collaborations between universities, public and private companies, management authorities of tourism lead to innovative ideas in the knowledge triangle of education-research industry.

This book is dedicated to one of the most well-known heritage sites of the 'Cradle of Humankind' – Kromdraai – the birthplace of one of our distant relatives called *Paranthropus* (www.kromdraai-origins.org). In addition to the ongoing academic research in this area, the Kromdraai Research Project is associated with two 'Erasmus Mundus' collaborative networks, AESOP and AESOP+ ('A European and South African Partnership on Heritage and Past'), and composed of 21 South African and European universities, as well as six associated partners. They organise mobilities for masters, PhD, post-doctoral fellows and academic staff in several fields including sciences and humanities in order to meet employment needs and to facilitate intercultural exchanges and mutual enrichment of European and South African societies. These actions promote the South African natural and cultural heritage and enhance the expertise and capability of teachers, students and researchers to assimilate new technical developments.

The scientific results presented in this book would not have been obtained without the early support of the South African National Research Foundation (NRF), the Department of Science and Technology (DST) of South Africa, the Centre National de la Recherche Scientifique (CNRS, France), the French Ministry of Foreign Affairs, the French Embassy in Pretoria, the Institut des Déserts et des Steppes in Paris (France) and the Andrew Mellon Foundation.

It is a pleasure to present this volume and we hope that it shows how the study of our common past can bring people together.

FOREWORD

C.K. Brain

When Francis Thackeray brought me a copy of the text of this remarkable book, I was delighted to see the great detail in which he and his French colleagues were undertaking their research at the Kromdraai fossil site in the Sterkfontein valley. It was here, in 1938 that a 15-year-old schoolboy, Gert Terblanche found the first fossil of a robust ape-man weathering out of a block of cave-breccia on the dolomite hillside of Kromdraai, about 2 km east of the Sterkfontein Cave where Dr. Robert Broom had described a fossil of the first adult ape-man, *Australopithecus africanus* in 1936. Gert Terblanche used to work as a guide for visitors to the Sterkfontein Cave on Sundays and he showed his Kromdraai fossil to the site manager who immediately bought it from him and passed it on to Dr. Broom who then visited the Kromdraai site with Gert and obtained more pieces of this beautifully preserved skull.

For over fifty years I have been involved in excavations at the Swartkrans Cave. Close to Sterkfontein, this cave-filling has proved to be a rich source of fossils of the robust ape-men with remains of over 80 individuals coming from there. Here, we also have evidence of the co-existence of the robust ape-men with early humans who continued to evolve after the extinction of the robust ape-men. The Swartkrans cave showed me that the hominids – our ancestors and the robust ape-men – were constantly being preyed upon by predators, by leopards and sabre-toothed cats – who consumed their prey at the cave entrance, the scraps of which found their way into the fossilisation site below. My work at the Swartkrans Cave also showed us just how complicated the stratigraphy of a dolomite cave filling is likely to be. When I started work at Swartkrans I had assumed that the oldest part of a cave filling would be at the bottom with the youngest parts at the top. This proved to be wrong, with parts of the oldest calcified filling adhering to the north wall undercut by much younger infillings lying beneath them. This was because of successive cycles of erosion and deposition in the cave with some parts being carried away and some parts remaining intact. It now seems likely that these events were linked to the worldwide cycles of glacial and interglacial climatic change that have characterised the last few million years.

The ongoing investigations at Kromdraai described in this book will reveal the complexity of the fossil-bearing sediments there, and I am delighted and impressed at the quality of the work. Congratulations to the authors and may they stimulate many up-coming students to do the same. Good luck!

CHAPTER 2

A computer-guided 3D multiscale reconstruction of the Kromdraai site

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INTRODUCTION

A large range of methods is increasingly used for heritage purposes, particularly in archaeology. Several techniques can be employed, depending on the complexity in size, shape and level of detail of objects (Pavlidis *et al*. 2007). Long-range scanners are used to record buildings (Allen *et al*. 2004; Craciun *et al*. 2012) or archaeological excavations (Doneus & Neubauer 2005; Rüther *et al*. 2009; Subsol *et al*. 2015). Long-range scanning methods may be associated with photogrammetry (Lambers *et al*. 2007; Yastikli 2007; Rüther *et al*. 2012). Digitisation is often used to document the cultural heritage, in particular to generate and visualise 3D reconstructions and to record the 3D geometry of archaeological materials (Kuzminsky & Gardiner 2012) and individual items. Very few excavation sites are fully scanned (Nigro *et al*. 2003), yet many methods exist and require very long post-treatment. An accurate digitisation requires multi-scale devices and the information collected must be fused for a complete reconstruction and appropriate use. The exact spatial position of fossils is an important element for understanding the taphonomy of a site (Brain 1993). In addition to the taphonomic context, it is also important to record spatially the stratigraphic information available in the cave deposits (Bruxelles *et al*. 2014).

Since 2010, we gathered high quality survey data of the Kromdraai fossiliferous area, including Kromdraai B (KB) for its 3D modeling at various scales, from an Unmanned Aerial System (UAS) (at a km scale) to micro-computed tomography (μCT) (at a micrometre – μm – scale) (Figure 2.1). These methods not only reduce the time spent on the site when compared with traditional direct survey methods (e.g., mapping with an electronic Total station to create a digital elevation model), but also produce a range of information, such as orthographic images, elevation drawings and sections of the land surface.

We mainly combined three methods to gather 3D data at Kromdraai. First, we used multi-image photogrammetry to capture high-resolution 3D surfaces with complete texture at two different scales, from a few kilometres (Figure 2.2) to a few metres (Figure 2.6), with respectively centimetre and sub-centimetre accuracies. Second, we used terrestrial and close-range laser scanning for the detailed recording of the KB site (Figures 2.3-2.4) at a sub-

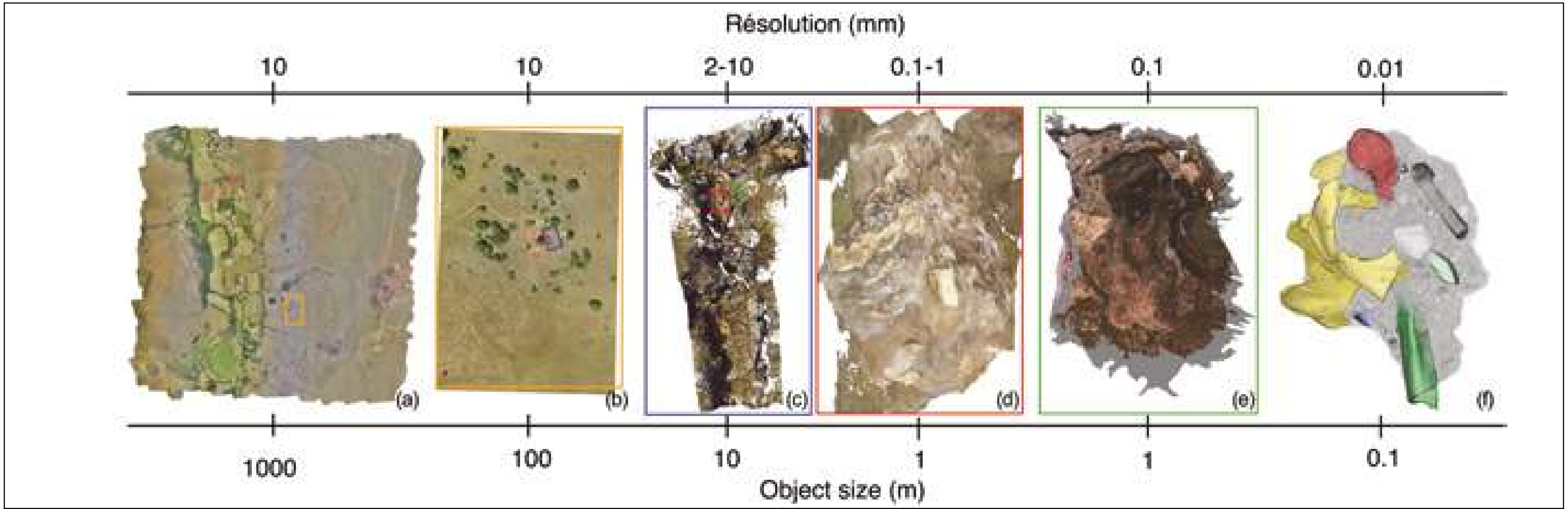

Figure 2.1 *3D modeling of Kromdraai B at various scales. From top to bottom: (a) and (b) UAS photogrammetry; (c) long-range laser scanning; (d) photogrammetry; (e) portable laser scanning; (f) micro-computed tomography.*

centimetre scale as well as to record objects (e.g., fossils) during the excavation and some aspects of the ground surface (e.g., contacts between breccias and flowstones). Finally, we exploited μCT (Figure 2.1) to observe, before their mechanical preparation and cleaning, the fossils that have been preserved inside plasters caps during the excavation for their safe removal from the site.

This chapter aims to present the 3D multiscale data from KB through several examples. We show how we captured our 3D multiscale data at Kromdraai for monitoring purposes, in particular: (i) to propose a visit of the site in a 3D virtual environment (with the use of computer graphics) that will help the reader and the KRP team to understand better the geological and depositional contexts of this site, (ii) to record the diggings over the successive excavations and to assess the changes of the site related to these archaeological activities, and (iii) to allow a precise location and visualisation of the better-preserved fossil specimens (particularly, the articulated bones) within their sedimentary units.

DATA ACQUISITION AND PROCESSING

Multiresolution data constitute the common basis for building representations of a geometric shape at different levels of details. We used three methods to digitise the site: μCT, terrestrial and close-range laser scanning, and multi-image terrestrial and aerial photogrammetry.

The μCT approach was explored to create the cross-section through plasters caps containing significant fossil remains, mostly articulated skeletal parts or fragile decalcified portions of skulls. We could then create virtual 3D models of the fossils specimens still embedded in plaster in order to plan their subsequent mechanical preparation in a more efficient way.

Terrestrial and close-range laser scanning involved the use of a laser beam. Data provided are represented by a triangular mesh – a set of three dimensional points connected by their common edges to represent

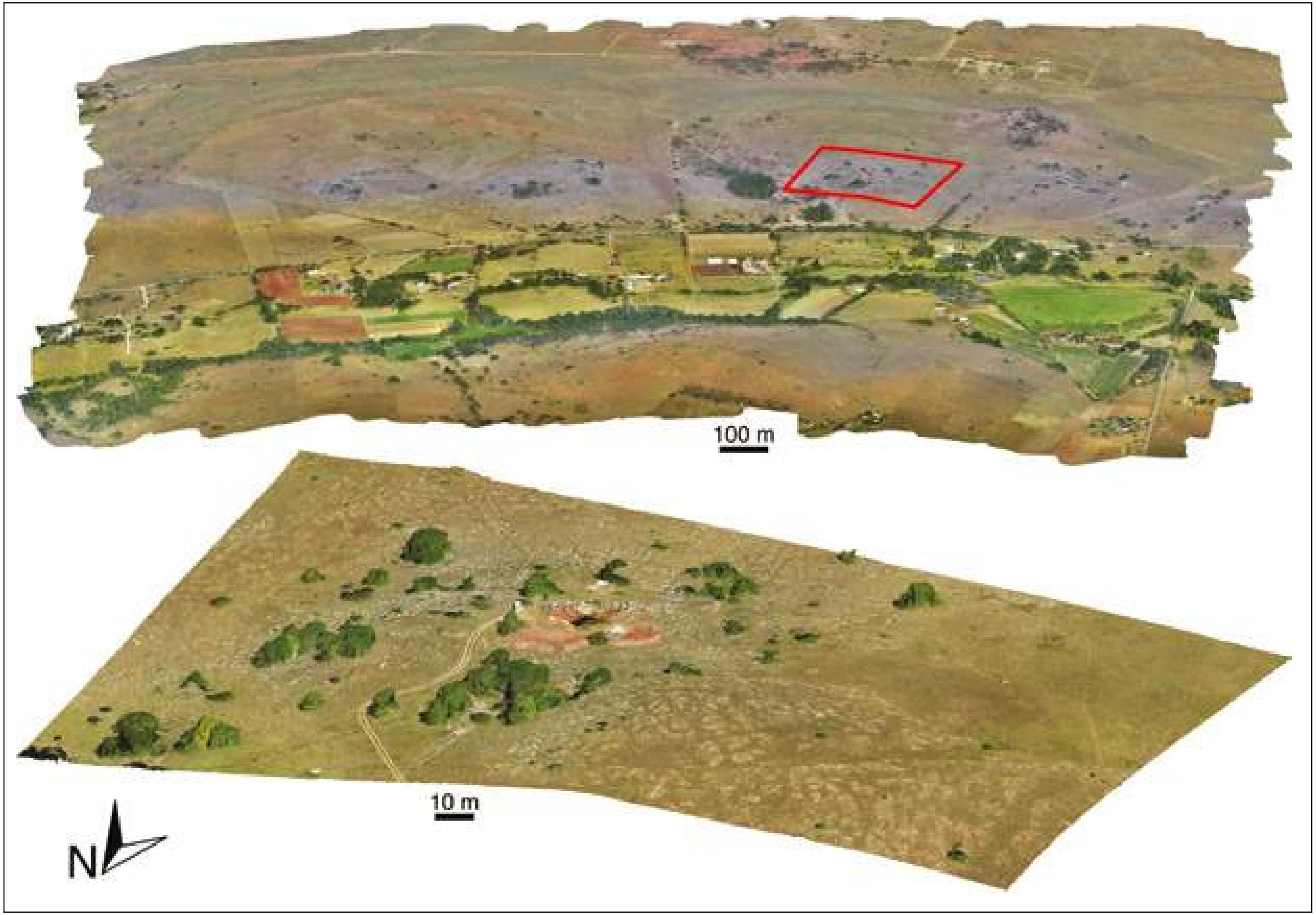

Figure 2.2 *UAS photogrammetry of the landscape around Kromdraai.*

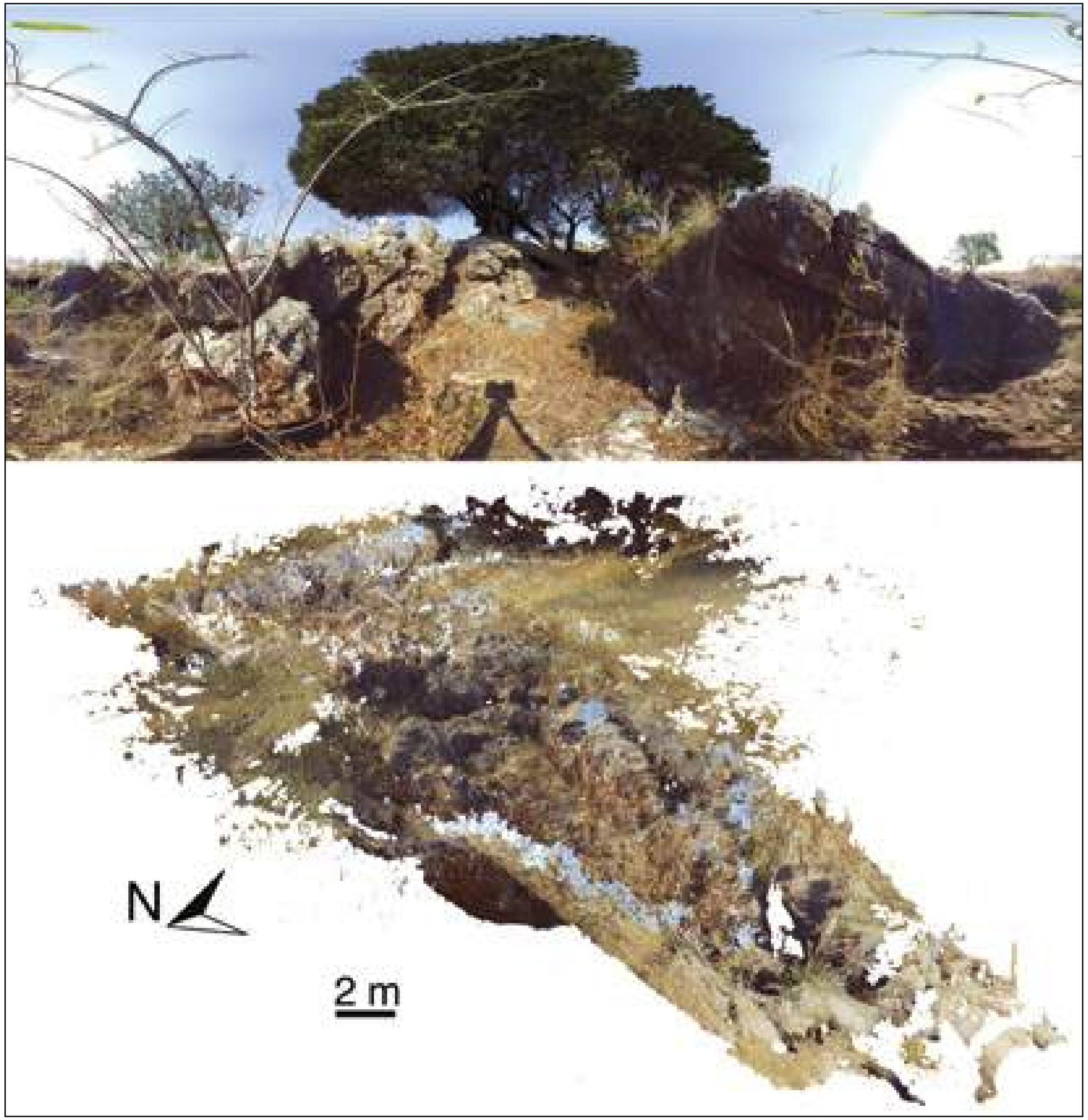

Figure 2.3 *Laser scan of the site with the FARO Focus 3D scanner showing a picture taken from the location of the FARO Focus 3D scanner in-situ (top, see the shadow of the scanner) and the resulting 3D point cloud (bottom).*

mathematically the surface of an object. This method was useful to produce a reference template (i.e., a mesh) of the KB excavation that could be subsequently used to plot geological features and fossil remains (Figure 2.3). This template was also useful to draw profiles across surface features and to infer predictions on aspects of the ground surface (e.g., contacts between breccias and flowstones).

Multi-image terrestrial and aerial photogrammetry is a rapid and cost-effective technique able to produce results similar to those of laser scanning with the use of computing power and professional photogrammetric software, but with much lower overheads. We used both land and UAS multi-image photogrammetry to produce a georeferenced 3D model of the landscape on a vast area (between 26° 1′ 19″ S, 27° 44′ 43″ E and 25° 59′ 38″ S, 27° 45′ 40″ E – WSG84) (Figure 2.2) to assess the quantities and locations of the soil removed from the site during each fieldwork season as well as the overall spatial distribution of important geological features.

In situ 3D reconstruction

Terrestrial laser scanning

We combined two different laser scanners, a FARO Focus 3D (www.faro.com) and a Creaform Handyscan VIUscan (www.creaform3d.com), both of which are widely used for cultural heritage applications. The KB site was scanned using a Faro Focus 3D, a 360 degrees scanner with an accuracy varying between 2 and 10 mm, and with a resolution of 40 megapixel

Table 2.1 *Description of long-range laser scanner acquisitions.*

Method used	Acquisition			Post-processing			
	Date	Number of scans	Number of vertices/ faces (in millions)	Number of vertices/ faces (in millions)	Dimensions (m)	Color points	Texture
FARO Focus 3D	May 2012	27	800/1000	240/400	20 x 10	Yes	No
Creaform Handyscan VIUscan	May 2012	5	0.3/0.7	0.3/0.7	1.8 x 0.8	Yes	Yes

for the colour and a range from 0.6 m up to 120 m (Table 2.1).

To avoid (as far as possible) the laser occultations, we scanned the same areas using different points of view, resulting in a large amount of data. We performed twenty-seven scans in order to cover the whole site of KB (Figure 2.3). The first step in the post-processing was to align the scans (a process also called 'registration') and to delimit an area of interest. We did this with the Faro Scene laser scanner software (www.faro.com). For the registration, we used spheres that were positioned, scanned and then detected by the Faro Scene software. The alignment of the scans was computed based on the position of the spheres. We then defined a region of interest in order to remove areas that were not relevant (e.g., vegetation). We obtained a mesh with 330 millions of vertices and 580 millions of faces. The last step was to merge the overlapping areas. Changes in resolution, noise due to scan outdoor conditions, as well as registration errors may disturb the fusion process. An automatic processing was then developed using several filters of MeshLab software (www.meshlab.sourceforge.net) to reconstruct the 3D model. In order to simplify the dataset, we chose to work on subdivisions of the mesh. Accordingly, we divided the mesh along the x- and y-axes with a set of blocks, each of 500 mm side length and width with an overlap of 50% between adjacent blocks. The workflow (Figure 2.4) has been automatised with MATLAB (www.mathworks.com) using MeshLab filter scripts as follows for each block:

- Merging. Data located inside the block were concatenated in a single file.
- Surface reconstruction. A surface reconstruction 'Poisson' filter (with an octree depth of 11) was applied. We chose this filter because it smooths the noisy data and manages possible registration errors (Kazhdan *et al*. 2006). The result is a mesh generated from a set of surface samples.
- Colour transfer. As the light was not constant during the acquisitions, there was no homogeneity of colours between meshes. We chose to keep the colours of the best represented area and to apply them to the reconstructed surface. Therefore, we assigned a colour to each point of the reconstructed surface using the mesh that contained the larger number of triangles inside the block and using a distance criterion (less than 10 mm). Then, we used the same criteria to assign a colour to the remaining uncoloured point using the other meshes. This step allowed us to remove extrapolated and uncoloured faces created by the Poisson surface reconstruction.
- Cleaning up and cropping. We removed the isolated pieces (less than 30 faces) and the unreferenced points. Finally, we removed the overlapping areas between blocks by reducing the length and width by 100 mm in order to avoid side effects.

The final mesh comprised 240 millions of points and 400 millions of triangles (or faces). We developed a user interface in MATLAB to allow the user to select and to view areas of interest. The user can select any area on a zenithal view and the program generates the corresponding mesh. Some holes were visible due to laser occultations, but the fossiliferous breccias were generally well covered.

Portable laser scanner

We used a Creaform Handyscan VIUscan (with a resolution and an accuracy of 0.10 and 0.05 mm, respectively) to record a specific area of KB with more realistic textures, but also to scan objects during the excavation as well as some extracted blocks. This device produces a white light during the scanning to ensure the recording of a uniform texture. At the same time, laser lines are projected onto the surface to be recorded. The final result is a 3D point cloud, which is transformed into a polygonal mesh. A texture recorded during the scanning is then mapped onto that mesh (Figure 2.1).

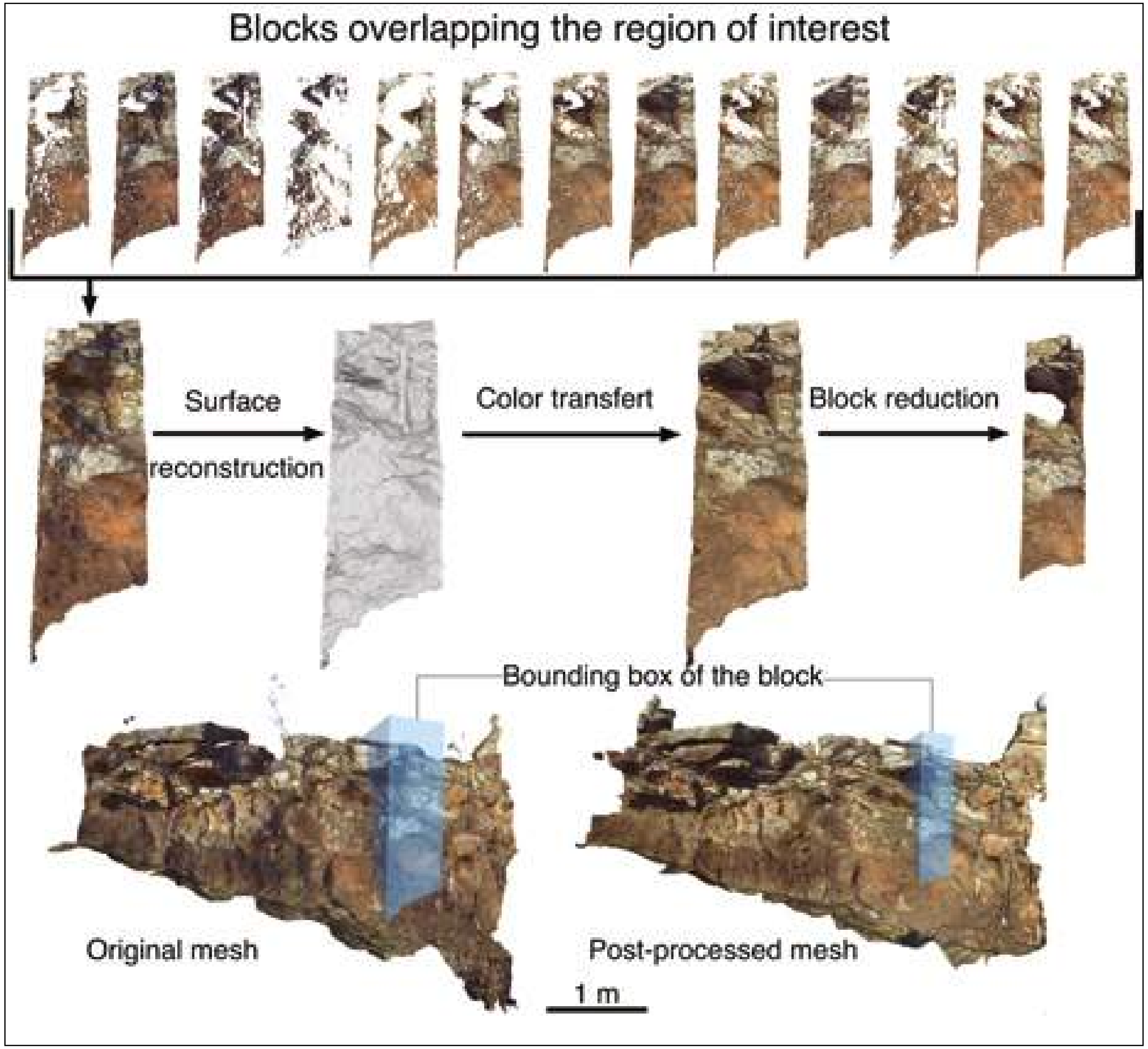

Figure 2.4 *Workflow applied on data provided by the Faro Focus.*

Photos-based 3D reconstructions

By using several images of the same scene, photogrammetry allows the reconstruction of a 3D point cloud from at least two photographic views. The method of 'structure from motion' (SFM) (Ullman 1979) reconstructs a three-dimensional representation of a dense point cloud of the scene. The initial data are simple photographs of the scene under various angles with some overlapping areas. The SFM method finds correspondence points between photographs and connects them to calculate the positions in 3D of these points and to generate a 3D structure of the scene. A complementary approach of dense multi-view stereo can be used to interpolate the surface generated from the point cloud. We then obtain a cloud of dense points on which a 3D triangular mesh is approximated. The colours of points are directly defined according to the photos. A texture can therefore be applied to the 3D model to obtain a photo-realistic 3D model expressed in a local system of coordinate.

Several tools compute 3D data from 2D images with the use of SFM algorithm. We chose the PhotoScan software (professional edition; www.agisoft.com), which proposes a user-friendly interface. Its workflow can be followed by non-experts in computer science, and it offers several useful exportation tools (e.g., orthophoto, digital elevation model). This workflow consists in three steps: (i) aligning the photos by detecting the successive positions of the camera processed and by matching homologous points to generate a 3D point cloud; (ii) generating a triangle mesh with a colour given to each vertex; and (iii) mapping a texture onto the mesh by mixing the photos. Some post-processing has been done to clean the mesh by removing isolated pieces (less than 50 faces) and by decimating the mesh.

UAS photogrammetry

We used UAS photogrammetry with a SenseFly eBee drone (www.sensefly.com) (Table 2.2), which is an appropriate device for the acquisition of a set of photographs of a scene under various points of view (Nex & Remondino 2014). We then generated a 3D model with the method described above. In this case, time-stamped GPS data were recorded during the flight. The Photoscan software could generate a geo-referenced 3D model using GPS data. The advantage of an automatic alignment is the avoidance of human manipulation and potential errors. We chose relatively large areas to produce an easily exploitable 3D model with a reduced number of points (Table 2.2). We also selected more focused areas with higher resolution 3D models, depending on our needs.

Table 2.2 *Description of photogrammetry acquisitions.*

Method used	Acquisition			Post-processing			
	Date	Number of photos	Camera	Number of vertices/faces (millions)	Dimensions (m)	Colour points	Texture
Drone photogrammetry	March 2015	43	Canon IXUS 127 HS	0.5/1	200 x 300	Yes	Yes
Drone photogrammetry	March 2015	918	Canon IXUS 127 HS	0.5/1	2 600 x 2 400	Yes	Yes
Land photogrammetry	June 2015	68	Sony DSC-TX10	0.4/0.8	3 x 3	Yes	Yes
Land photogrammetry	June 2015	225	Nikon D3300	0.4/0.8	10 x 10	Yes	Yes
Land photogrammetry	December 2014	209	Sony DSC-TX10	0.5/1	25 x 27	Yes	Yes
Land photogrammetry	September 2014	139	Sony DSC-TX10	0.5/1	19 x 18	Yes	Yes
Land photogrammetry	April 2014	47	Sony DSC-TX10	0.6/1.2	13 x 13	Yes	Yes

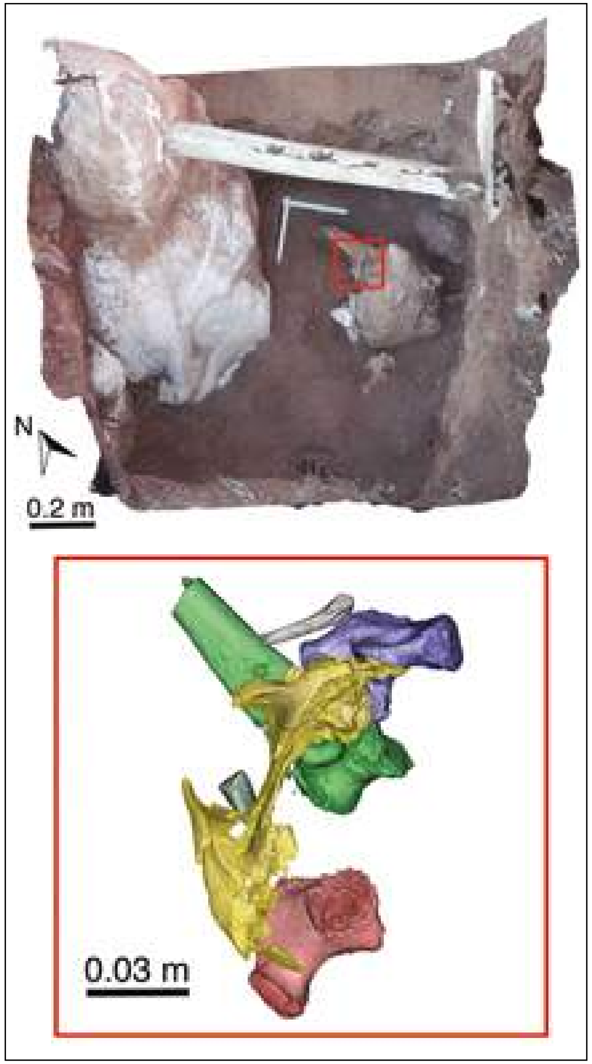

Figure 2.5 *3D photogrammetry of a block during the excavation (top) and computer-aided virtual extraction of fossils specimens (including the partial skull of a large monkey in yellow) from the same block (bottom).*

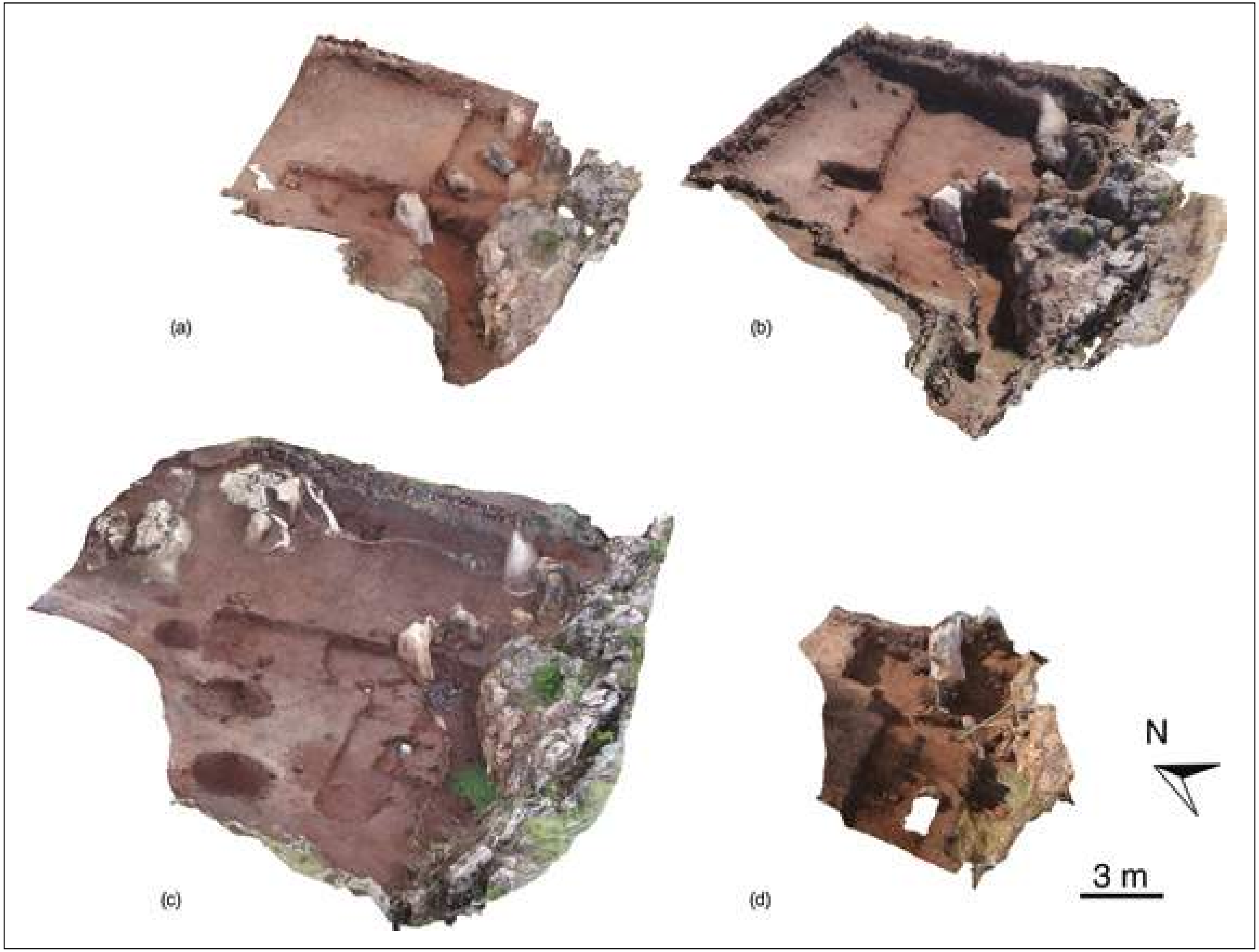

Figure 2.6 *3D photogrammetry model describing the excavation of the Kromdraai extension site at different times: (a) April 2014; (b) September 2014; (c) December 2014; (d) June 2015.*

Fusing different data

The fusion of data from distinct sources was not automatic because the spatial references and the scales of the various devices differed. Furthermore, each dataset includes unstructured points connected by triangulated meshes. Therefore, it was necessary to align these datasets by matching corresponding points or by minimising the distances between meshes.

As the UAS photogrammetry data was geo-referenced, we used them as the reference to align the KB 3D model reconstructed from the Faro scan. All the other 3D models were then aligned on the KB 3D model. We performed the alignments using the Photoscan or the MeshLab software. With Photoscan, five ground control points were manually placed in each model (KB 3D model made with Faro and UAS photogrammetry). Then, the best alignment between the models was computed. The 3D surface reconstruction of a block of fossiliferous breccia obtained from μCT (described in greater detail in Chapter 5) was aligned using the same method (Figure 2.5). The MeshLab tool consists of an automatic alignment with matching pair of points and an iterative closest point algorithm. Whenever possible, we tried to adjust the model by using an iterative closest point method, but it was not always possible since the topology of the excavation changes over the different excavation periods.

CONCLUSIONS

The methods presented in this chapter contribute to demonstrate how the study of the Kromdraai site was enhanced by the use of technical methods at different levels by creating accurate 3D registered models and data. We computed a 3D model of the Kromdraai site for which the geometry of the breccias was very well recorded and reconstructed in 3D. This model is of interest for various fields of research (e.g., geomorphology, archaeology). Since an excavation is also a destructive process, our duty was to develop methods allowing us to archive the context of the fossil discoveries (Figure 2.5) as well as the main phases of the excavation, and with the best possible accuracy (Figure 2.6). In the future, the precise position of the newly discovered fossils will help us to understand better the taphonomy of the site. The combined use of photogrammetry and tomography will also provide more robust protocols and data.

Another scale level has been added to the existing model in the view of improving our field observations at Kromdraai and, more widely, in the Blaauwbank valley. Indeed, we also used a UAS and low-altitude flights to investigate more precisely the Kromdraai site location, its immediate environment and its topographical relationship with adjacent sites. In order to produce 3D models with high levels of accuracies that can be useful for detailed geomorphologic interpretations, we will need to combine more systematically our photogrammetric survey using a UAS with topographic measurements of ground control points

Recent developments in photogrammetry, laser scanning and micro-tomography represent the last frontiers to produce large quantities of 3D information with a major scientific value. These 3D data allow interpretations not previously possible in bi-dimensional view. The combination of photogrammetry, laser scanning and μCT for 3D modeling has proven to be particularly efficient and flexible. Different levels of resolution and different viewing angles of the three recording systems allowed us to produce 3D models according to the specific requirements of the archaeological and geomorphologic analyses.

The digital data produced by the KRP will also be used to disseminate information to the general public that are not easily accessible at museum exhibitions, at conferences or on websites.

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