In Situ 3D Digitization of the "Little Foot" *Australopithecus* Skeleton From Sterkfontein

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ABSTRACT

Here we describe the methodology we used to digitize an excavation site of a very ancient fossil hominid in South Africa, which has been recently dated using cosmogenic techniques. We detail the practical aspects of acquiring 3D views with a laser range scanner and the post-processing computer graphics pipeline required to obtain an accurate 3D representation.

INTRODUCTION

The discovery in 1997 of *Australopithecus* lower leg bones exposed in a calcified deposit deep within the Sterkfontein caves of South Africa gave promise that excavation might reveal for the first time anywhere a complete *Australopithecus* skeleton, referenced as Stw 573 and nicknamed "Little Foot" (Figure 1). Subsequent excavation of the concrete-like breccia did indeed reveal a virtually complete skeleton but also showed that there had been ancient collapse and disturbance to the bones which were at different stratigraphic levels in a steeply sloped, irregular and rock-strewn talus (Clarke 1998, 1999, 2002, 2008). Stw 573 has been recently dated by cosmogenic dating techniques to circa 3.7 mya (Granger et al. in press).

It was important to record this not only for the taphonomic information concerning the position of and disturbance to the skeleton (Clarke 2002, 2006, 2007), but also for the stratigraphic information on the deposition, collapse, and calcification of the talus slope (Bruxelles et al. 2014). Accordingly, a silicone rubber mould was made of the excavated surface in which the skeleton was exposed and epoxy resin casts were made and painted to provide some accurate colored replicas for display and record. However, because of the size of such casts, it is not practical to produce them in large numbers for distribution in the way that fossil hominid casts are usually made available. Thus the opportunity to make an *in situ* 3D record by laser range scanning provided the potential to produce easily acces-

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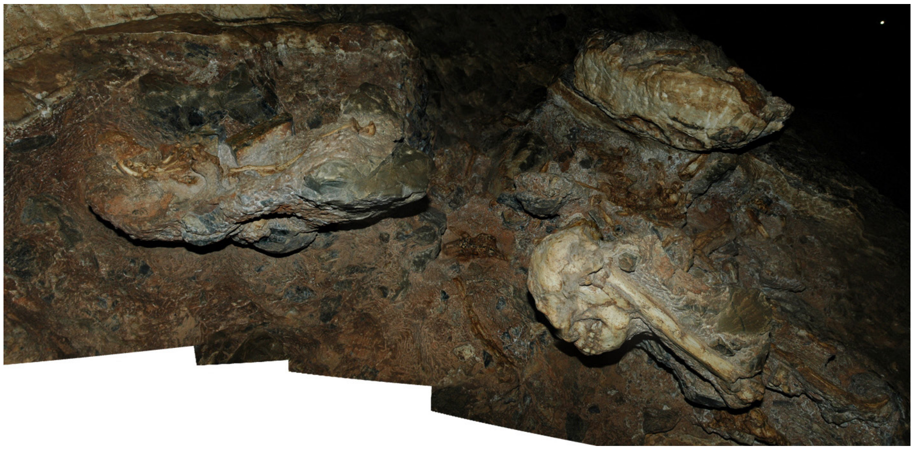

Figure 1. Panorama of the ``Little Foot'' excavation site.

sible 3D images of this skeleton as it lay in the talus slope. It would also provide an additional, permanent three dimensional record (together with the casts) of the position of the various skeletal elements (Figure 2) in the talus slope before they were removed in blocks for further processing.

3D scanning of cavities (e.g., González-Aguilera et al. 2009; Ruther et al. 2009) or walls of prehistoric sites (e.g., Fritz and Tosello 2007) is now widely developed for paleoanthropological studies. This technique is especially used to compile a 3D-geolocated database of paleo-anthropological fossils or artifacts (see some applications in South Africa in Nigro et al. [2003] and Hausler et al. [2004]). Nevertheless, there are a lot of practical problems, such as efficiently positioning the scanner or lighting sources, as emphasized in McPherron et al. (2009). In the following sections, we will describe not only the acquisition phase but also the post-processing of 3D data, which is complex and extremely time-consuming.

MATERIAL AND METHODS

PRESENTATION OF THE 3D DIGITIZERS

We used two different laser scanners (Figure 3): a Konica-Minolta VIVID 910 (Anon 2013a), which is widely used for industrial metrology and cultural heritage applications, and a NextEngine HD scanner (Anon 2013b), which is a low-cost desktop device that is used to an increasing extent to digitize small archaeological objects.

Both devices are based on the same triangulation technique: one (VIVID 910) or several (NextEngine HD) laser stripes are emitted; a digital camera, whose position is known according to the laser emitter, acquires the stripe reflection on the object which appears as a deformed line; based on the position of the dots of this line in the camera field of view, triangulation makes it possible to infer the 3D position of the points of the stripe. A complete surface can be digitized by moving the stripe vertically. Moreover, a photograph without the stripes is also taken in order to ob-

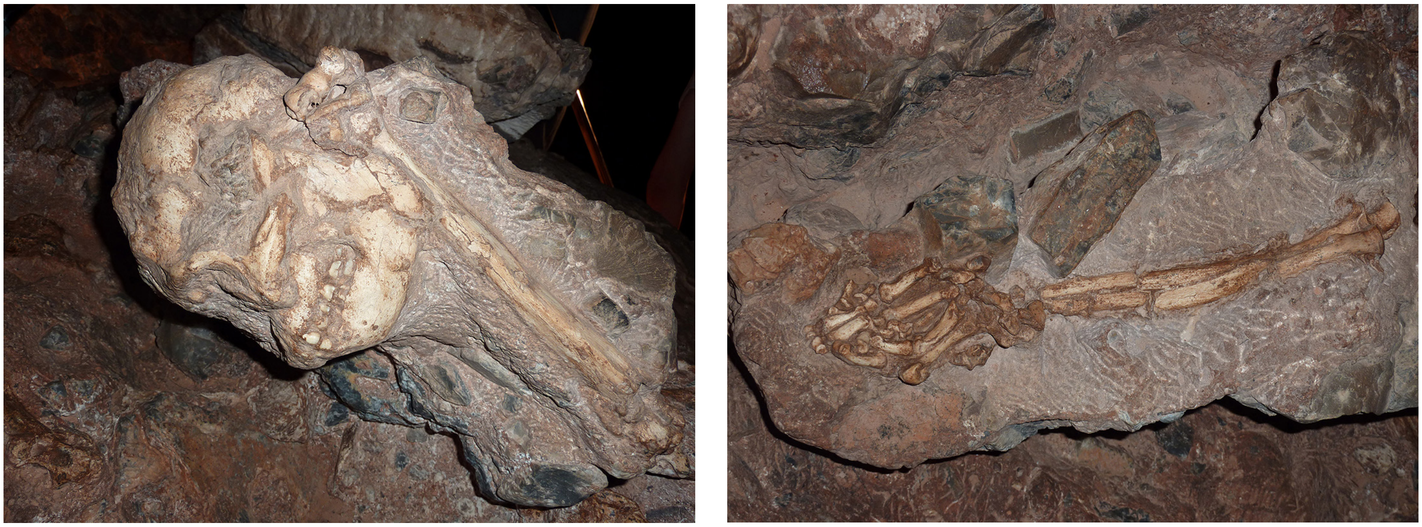

Figure 2. Left: the skull and left humerus; Right: the left forearm and hand. Notice how the anatomical association is preserved.

Figure 3. The 3D digitizers in situ: left the NextEngine HD; right: the Minolta VIVID 910.

tain a colored (also called "textured"') 3D reconstruction.

First, we tested both scanners (with the TELE lens for the VIVID 910) on the same object (a fossil occipital skull bone) and assessed the same accuracy, which we estimated to be around 0.2mm, as noted in Guidi et al. (2007). The main differences between the two systems are given in Table 1.

The NextEngine HD was then used to digitize some particularly interesting details such as the skull or arm with a detailed texture, whereas the VIVID 910 was chosen to get an overall 3D digitalization of the excavation site.

SOME PRACTICAL POINTS

The digitization process involves taking several 3D acquisitions of the scene from different viewpoints with the following constraints:

- **limit occlusions as much as possible**, i.e., the areas which are not seen by the camera or not covered by the laser stripe, in order to obtain an exhaustive acquisition;
- **get precise data**, especially in terms of resolution (by selecting the most appropriate lens) and color quality (by tuning the lighting) in order to obtain a high level of geometric and/or photometric details;
- **acquire overlapping views** in order to precisely register and blend the views into a global 3D reconstruction; and,
- **minimize the scanning time**, in particular by determining the appropriate acquisition resolution (i.e., the 3D point density [Anon 2011]) and by carefully planning the scanner positioning (Russo and Arya 2009).

As we can see in Figure 4, in a cave it is hard to control the lighting without heavy equipment (projectors, screens, etc.). Moreover, positioning the scanner tripods may be difficult (and even impossible) on a bumpy floor. But dealing with the faults is the most complicated issue—the depth of field of the devices is not sufficient to scan the inside and their sides are so narrow that they create many occlusions.

When we scanned the floor with the VIVID 910 scanner, we registered each view with the previous one by designating three or more *pairs* of points in both images with the proprietary Polygon Editing Tool software. Notice that the points are localized in the color photograph of the view which is much easier than pointing vertices in a 3D reconstruction during the post-processing global registration step.

POST-PROCESSING OF 3D VIEWS

Post-processing of 3D views involves a computer graphics pipeline tailored to the application (see, for example, Allen et al. (2004) or Vrubel et al. (2009)). In our example, we decomposed it into the following steps:

1. **Selection of 3D views**. The goal is to reject useless views because they are either redundant with respect to the others or they contain no ex-

TABLE 1. COMPARISON OF THE 3D DIGITIZERS.

	VIVID 910	NextEngine HD
Field of View	**up to 1.5×1.5 m with the WIDE lens**	limited to 0.33×0.25 m in Wide mode
Color Acquisition	only 640×480 pixels, very sensitive to external lighting	**3 Mpixel sensor with a built-in white light source**
Scan Time (1 view)	**~3 s**	~3 min
Cost	~$50,000	**~$3,000**

Figure 4. Some practical difficulties: dealing with uncontrolled lighting, measuring and tuning the adequate depth of field, and positioning the scanner tripod on a chaotic surface without touching the fossil.

ploitable information (in particular, if there is too much occlusion).

2. **Global registration**. During the acquisition phase, we performed a first alignment which minimizes only the average distance between the overlapping surfaces of two consecutive views. This must be refined by taking the overlapping surfaces of all views simultaneously into account. This is a key to obtaining an accurate 3D reconstruction and, over the last decade, many algorithms have been proposed which are often based on the "Iterative Closest Point" method (see, for example, Deng [2011] or Rusinkiewicz and Levoy [2001]).
3. **Fusion and simplification**. Once the views are registered, all the meshes must be fused into one. However, the points from the different views are not exactly at the same position due to the quantification, imprecision, or artifacts of the scanning process. A choice or an average has to be made. Fusion is also closely linked with the simplification step, which consists of reducing (by deletion or fusion of close points) the number of points. This is essential to avoid obtaining a too complex 3D reconstruction which otherwise would be composed of n×p points in the case of n views (typically 10 to 30) of p points (typically 50 to 300,000). Another problem is to fuse the colors as the same point may have a different color in the different views due to the lighting conditions.
4. **Beautifying the 3D reconstruction**. The goal is to remove the visual defects. These may be spikes or "noisy"' parts due to the acquisition process or the simplification step but they can be generally reduced by smoothing. A major challenge is to delete the holes induced by occlusions. Some algorithms detect the holes in a 3D mesh and infer surface patches that lie on their boundaries. These patches must follow a curvature continuity constraint so that they will not be too visually detectable.
5. **Rendering the result**. This step consists of dis-

TABLE 2: SOFTWARE FUNCTIONALITIES USED FOR POST-PROCESSING.

Step	**MeshLab**	**Commercial Software**
Global Registration	“Align tool”' with default parameters	Several software packages were used according to the results: “Align tool” in the NextEngine software, and “Register/Fine” in RapidForm XOR2 (reverse engineering software)
Fusion	“Flatten visible layers”	
Simplification	“Clustering decimation”	“Decimate” in RapidForm XOR2
Beautifying	“Smoothing, fairing” but the hole-filling command is too limited	“Fill hole/curvature method” in RapidForm XOR2
Rendering	“Face ambient occlusion” and light control	Coloring and rendering with ZBrush 3.5 (digital sculpting and painting program)

playing the final 3D reconstruction by defining the viewpoint, lighting and all shading information (i.e., modifying a color based on its angle and distance to light sources to create a photorealistic effect). Moreover, it is possible to “map” a color, an artificial texture, or a photograph on the geometry. For example, in Figure 8 (below), we have colored the bony parts in light yellow whereas we associate a stone texture (slightly rugged and unpolished) with the floor.

For the NextEngine data, one author (BM) used the software provided by the scanner. For the VIVID 910 data, one author (GS) used only the open-source (and free) software MeshLab (Anon n.d.), whereas another author (BM) combined the functionalities of several commercial software packages as presented in Table 2.

RESULTS

In Figure 6, we present the 3D digitization of the left forearm of Little Foot. As we can see on the corresponding photograph in Figure 5, the forearm is broken into several parts and the finger bones are clenched (more details can be found in Clarke [1999, 2008]). We acquired 18 views with the NextEngine scanner which were registered and fused to result in a 3D colored reconstruction of more than 1 million triangles. In particular, Figure 7 highlights the accuracy of the 3D reconstruction of the metacarpi.

The process required to obtain a 3D reconstruction of the overall site was quite complex as there were many occlusions, which made it necessary to multiply the acquisitions, to be very careful in the registration step, and to automatically fill many holes. Two trained people spent 3 days acquiring 57 frontal, 23 right lateral, and 12 left lateral views with the MIDDLE lens, which corresponds to a field of view of around 0.6×0.6m. At the end, we selected 37 views to reconstruct a 3D mesh of 1.2 million triangles, which corresponds to an estimated accuracy of around 0.5mm on the real ground. This allows us to precisely locate and easily recognize all the fossil bones which are in yellow in Figure 8.

Unfortunately, as emphasized in Table 1, color acquisition is very poor with this device. Moreover, we were unable to have a good and stable lighting in the cave, so color data were unusable.

For these two reconstructions, the estimated processing time is at least one week full-time for a skilled person.

In Figure 9, we propose to interact with a 3D model which is a simplified reconstruction (250,710 vertices and 500,000 faces) of the Little Foot excavation site. In particular, we defined point of views to focus on the skull and on the left arm.

DISCUSSION

ABOUT THE PRACTICABILITY

After this 3D digitization process, we can draw the same conclusions as those reported in McPherron et al. (2009). We were able to scan an area of 1 to 2m^2 a day on a very bumpy field; processing raw data in order to get a usable 3D mesh took around 10-fold the scanning time; the most complex practical problem was certainly positioning the scanners in order to maximize the digitized surface while minimizing occlusions, and we were unable to scan some small areas due to the limited depth of field. Controlling the light intensity and color is also a major challenge even if the texture is not acquired in the overall site digitization.

In conclusion, we consider that the current and affordable 3D surface scanning technology is mature enough to be set-up in an excavation site and to get results that are accurate enough for many paleoanthropology applications. Nevertheless, it is essential to plan some time (at least a day) to test the scanning device *in situ* or in a comparable site in order to tune the parameters and prepare the scanning protocol and positioning of the devices. Two months before going to South Africa, we thus spent a day testing the Minolta Vivid 910 in a cave in the South of France which

Figure 5. Photograph of the left arm of "Little Foot."

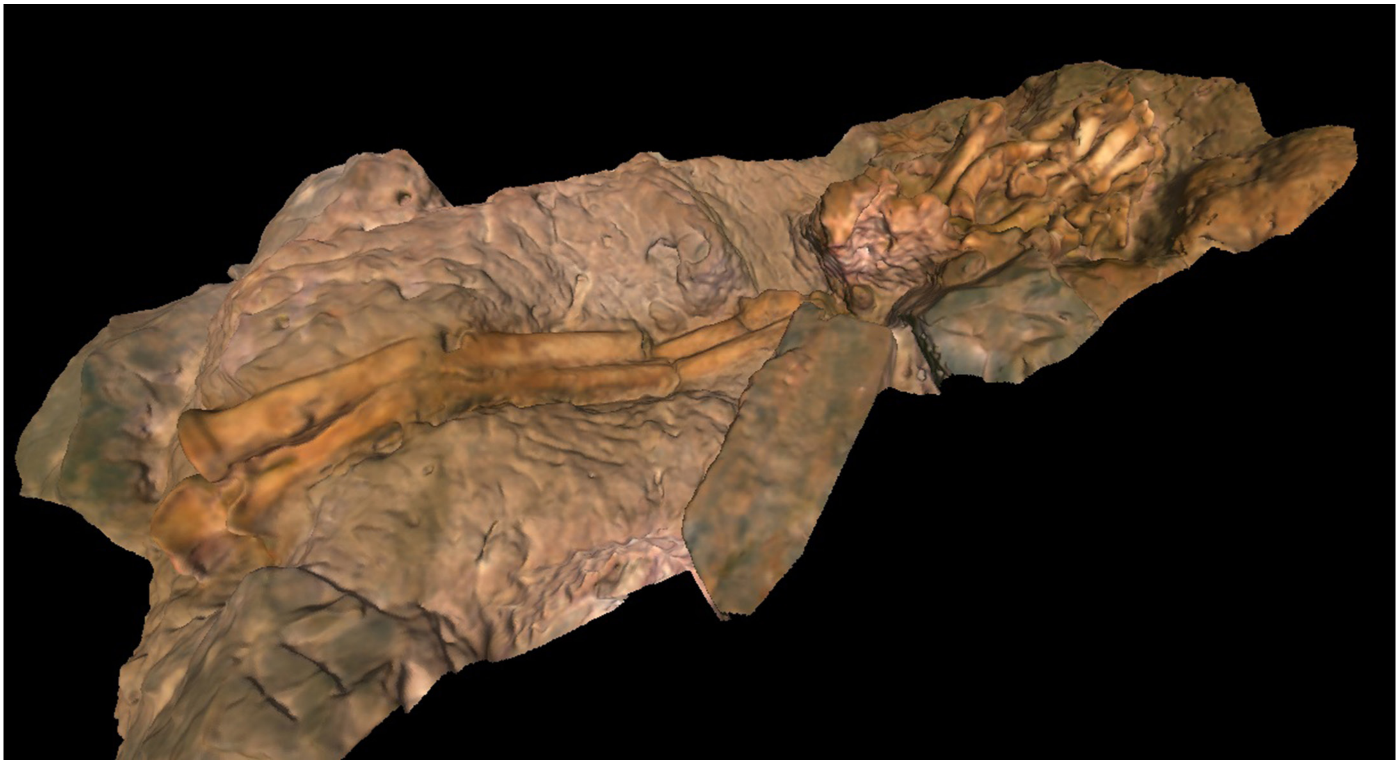

Figure 6. The corresponding 3D reconstruction (535,668 vertices / 1,067,723 triangles) of the left arm based on 18 views (each around 100 to 400,000 points) acquired by the NextEngine scanner.

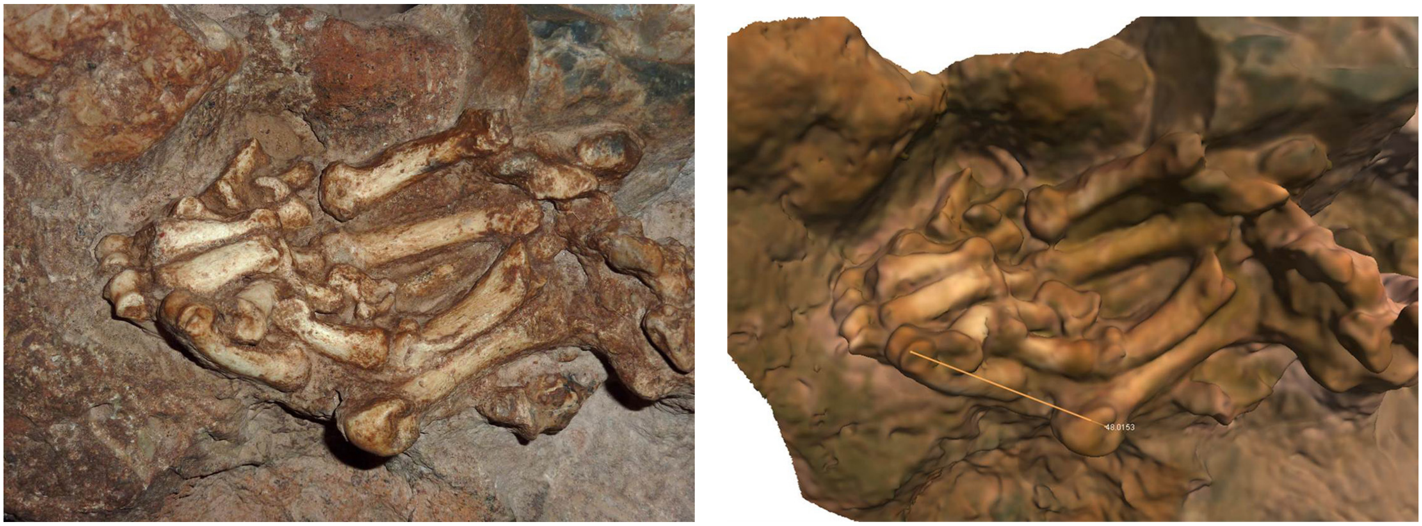

Figure 7. Left: a zoom on the left hand; Right: notice how accurate details are visible on the 3D reconstruction (the light line is 48mm long).

presented the same physical configuration as that in Sterkfontein. This allowed us to precisely define the overlap surface required to accurately register the different views and to test the entire post-processing pipeline.

In future work, we plan to use a hand-held 3D surface scanner. They are lightweight and much easier to manipulate and position to acquire the shape of some chaotic areas. In Johnston et al. (2004), the authors scanned a large plesiosaur fossil encased in stone. In Barash and Been (2011), the authors tested the device on a cast of the Kebara skeleton. Some hand-held scanners require dotting the area to scan with small white reflective targets in order to self-position and register consecutive views. This constraint could make scanning an excavation site with fragile fossils quite complex. However, a new generation of scanners without any markers is now available—view registration is performed by using only the geometry and this seems to give interesting results, as we can see on a real excavation site in (Anon n.d.). Nevertheless, the field of view of such hand-held scanners is still quite reduced and they cannot be used for overall digitization but only for some complex areas, in particular to emphasize the fossil parts.

SOME PALEOANTHROPOLOGICAL APPLICATIONS

First, we plan to use the 3D models to analyze the taphonomic process as described in Duday and Guillon (2006) and recently applied in Val (2013). In particular, we would like to develop the ideas proposed in Pickering et al. (2004)—for example, how are the arm bones broken, how are the hand bones positioned, how are the different bones positioned in the debris, how is it correlated to the stratigraphy?

More generally, the 3D models are a memory of the geological context of "Little Foot." It highlights all the layers around the fossils and even enables us to observe their complicated geometry. Once the skeleton was removed, it was disconnected from its stratigraphic context, and further analyses could be difficult to interpret without the scan. With 3D models, it will be possible to come back to an interactive and non-interpretative view of the context.

It would be also possible to integrate (in the manner of Lambers et al. [2007]) these 3D models with a more general 3D geological model of the surrounding Sterkfontein cave system or with 3D range data of the valley of Blauawbankspruit River (Bruxelles et al. 2009). This would allow paleoanthropologists to gain further insight into the geomorphological evolution of this area and describe the paleo-landscapes of hominids, which could help to specify the taphonomy of the fossils.

We can also present the site in its original form to the research community and the general public. 3D models allow us to visualize (eventually in 3D by using stereo glasses) but also to interact with (via a joystick or more sophisticated interfaces such as haptic feedback devices) the excavation site, thus paving the way to "virtual excavation" (Benko et al. 2004) or a new kind of museography presentation (Bruno et al. 2010).

All the fossil bones are now excavated. It will then be possible to scan them in 3D at very high resolution by using CT (around 0.1mm) or μ-CT (around 20 to 40μm) scanning (Mafart et al. 2004). By registering these data to the 3D models acquired in *situ*, it will be possible to combine high accuracy and exact original positioning for all the fossil bones, as tested in Barash and Been (2011).

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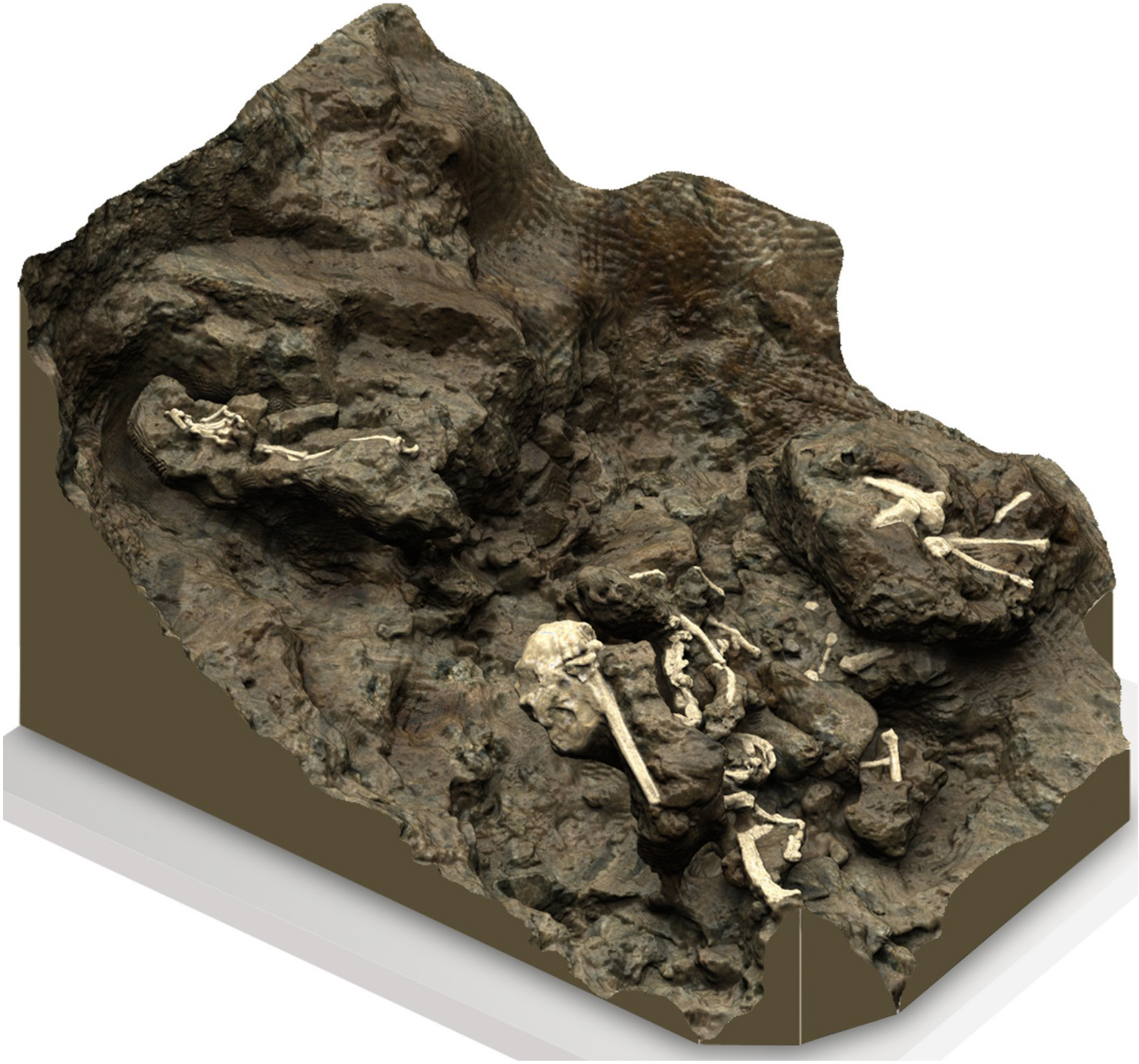

Figure 8. 3D reconstruction of the excavation site (1,224,885 vertices and 2,446,034 triangles) based on 37 views (each around 100 to 400,000 points) acquired by the VIVID 910 scanner. The colors have been added manually by "painting" the fossil bones. A movie showing a fly-over exploration of the excavation site is available as Supplement 1 on the Paleoanthropology journal website (duration = 1 mn, resolution = 1,920 x 1,080 pixels).

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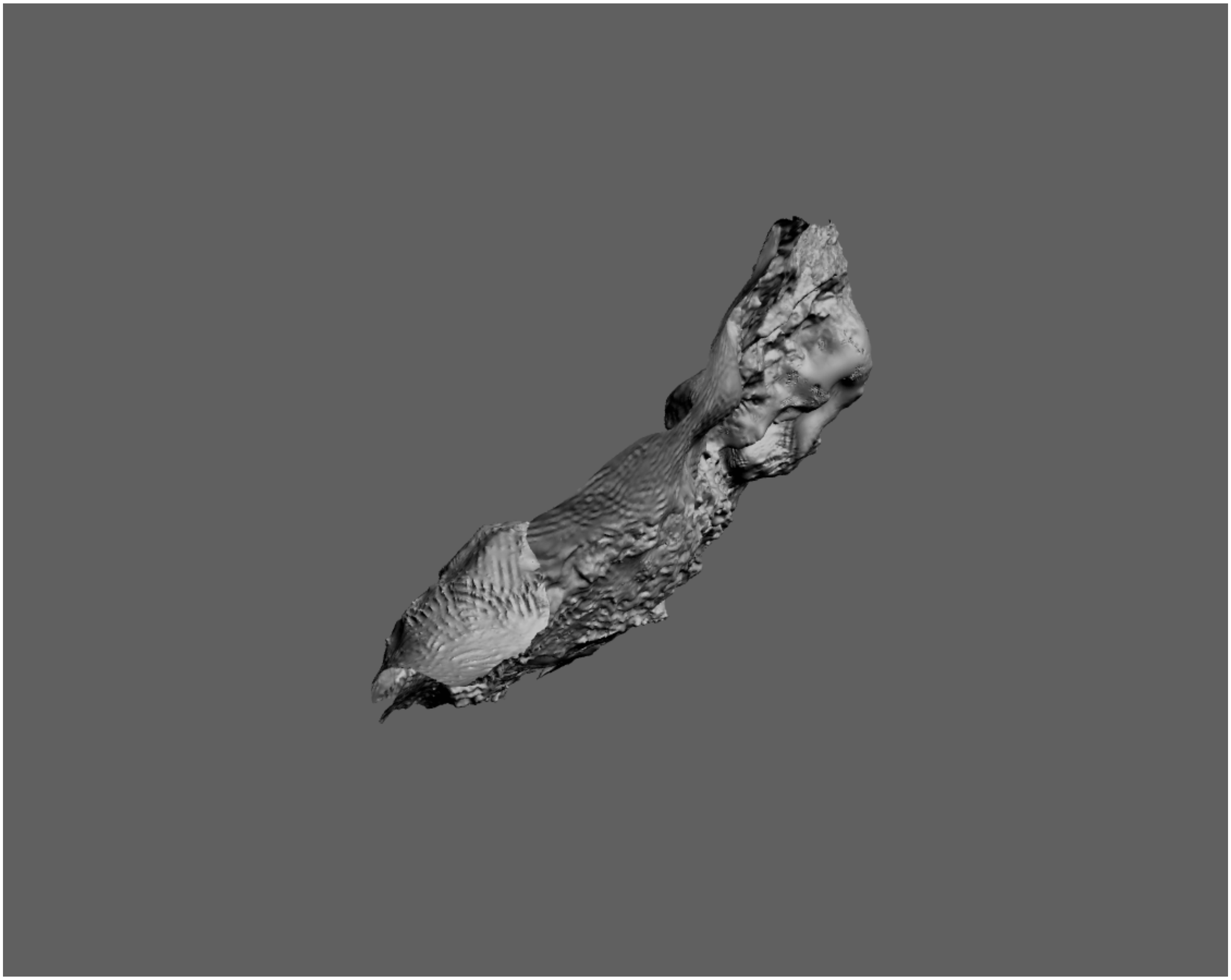

Figure 9. Interactive version of the 3D reconstruction of the excavation site (250,710 vertices and 500,000 faces). This 3D pdf file is preferably viewed in Adobe Reader 9.3 or higher. To rotate, click and hold the left mouse button and move the mouse; to zoom, click and use the mouse wheel. A 3D toolbar appears after you click the 3D model.

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