# 3D Survey in Extreme Environment: The Case Study of Laetoli Hominin Footprints in Tanzania

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Many cultural assets are in risky situations and they are destined to disappear. Sometimes problems are caused by the anthropic component (e.g. wars) or by natural disasters (e.g. earthquakes and landslides). At other times the cause of deterioration is due to the slow and inexorable action of atmospheric agents and other natural factors present in extreme areas, where preservation of Cultural Heritage is more complex.

This contribution deals with 3D documentation of paleontological excavations in extreme contexts that are characterized by unfavorable climatic conditions, limited instrumentation and little time available. In particular, the contribution is focused on the search for a good working procedure which, despite the problems mentioned above, can lead to valid results in terms of accuracy and precision, so that subsequent scientific studies are not compromised. The proposed case study concerns the recent discovery of fossil footprints at the Site S in Laetoli, within the Ngorongoro Conservation Area (Tanzania), which is a UNESCO World Heritage Site. With the new discovery of Site S it was necessary to implement a 3D survey operative protocol with limited equipment and in a very short time. The 3D models, obtained through the "Structure from Motion" (SfM) technique and topographic support, were used to perform morphological and morphometric investigations on the new footprints. Through the analysis it was possible to estimate height and weight of the footprint makers (hominins of the species Australopithecus afarensis). The collected evidence supports marked intraspecific variation in this species, pointing out the occurrence of a considerable difference in size between sexes and suggesting inferences on reproductive behavior and social structure of these ancient bipedal hominins.

The contribution shows how important is to obtain good 3D documentation, even in extreme environment, in order to reach reliable results for scientific analysis.

Key words:
SfM, 3D documentation, palaeoanthropology, Laetoli, footprints.

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## INTRODUCTION

This contribution deals with 3D documentation of paleontological excavations in extreme environmental context, characterized by unfavorable climatic conditions, light equipment and little time available. In particular, the contribution is focused on the search for a good working procedure which despite the problems mentioned above,

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can lead to valid results in terms of accuracy and precision, and can result as reference for further scientific activities in similar contexts.

The workflow is here presented through the description of the multidisciplinary field work carried out on fossil footprints at Laetoli (Tanzania) in September 2015.

In the chapter “Laetoli: old footprints and new discoveries”, a brief history of this renowned paleontological site is traced, emphasizing its importance for the knowledge of early human evolution. Particularly, old and new paleontological discoveries, made at the site since the 1970s, are briefly discussed, as is their outstanding contribution to increase our knowledge on the morphology and behavior of the species *Australopithecus afarensis*. In the chapter “The extreme environment of the African Savannah”, the geographic, geomorphological, climatic, floristic and faunistic, anthropic and hygienic-sanitary characteristics of the study area are described. The contents of this section highlight how Laetoli is an extreme context subjected to many factors that endanger the conservation of its unique Cultural Heritage. The chapter “Workflow: 3D survey for documentation and analysis” presents the procedure adopted in 2015 from survey planning to fieldwork acquisition, from data processing to morphological and morphometric analysis of hominin footprints. In the last paragraph the conclusions of the work are drawn with hints on future developments related to the conservation of the Laetoli site.

## LAETOLI: OLD FOOTPRINTS AND NEW DISCOVERIES

Laetoli is one of the most important paleoanthropological sites in the world. Although known for its scientific relevance since the mid-1930s [Reck and Kohl-Larsen 1936; Kohl-Larsen 1943], the sites reaches planetary knowledge in the 1970s thanks to the discovery of the holotype and other findings of *Australopithecus afarensis* [Leakey et al. 1976; Johanson et al. 1978], as well as of fossil bipedal footprints [Leakey and Hay 1979; Leakey and Harris 1987] on a cemented ash layer produced by a volcanic eruption and dated at 3.66 million years ago [Deino 2011]. The hominin trackways were found by Mary Leakey and collaborators in 1978 at Laetoli Site G and were referred to three individuals (G1, G2, G3) of different boy size: the smallest individual (G1) walked side by side on the left of the largest individual (G2), while the intermediate-sized individual (G3) superimposed its feet over those of G2 [Leakey 1981]. The trackways are usually ascribed, not without controversy [Tuttle et al. 1991; Harcourt-Smith 2005], to *Au. afarensis* [White and Suwa 1987], which is the only hominin species found to date in the Upper Laetoli Beds (i.e. the geological unit that hosts the printed ash layers, which form the so-called Footprint Tuff) [Harrison 2011].

Hominin footprints are very rare and most of them are ascribed to the genus *Homo*. For this reason, the Laetoli footprints, made by members of the hominin species *Au. afarensis* – the same species as the famous “Lucy” from Ethiopia – are extremely important and unique.

Almost forty years after the important discovery of the first footprints, other bipedal tracks were found in Laetoli (Fig. 1). The new trackways reopened old debates and helped to clarify some aspects of the body size of *Au. afarensis* and to suggest inferences on the reproductive behavior and social structure of these ancient hominins.

The new Site S, located about 150 m to the south of Site G, was discovered in September/October 2014 during systematic survey and excavation activities (Cultural Heritage Impact Assessment) aimed at evaluating the impact of a proposed new field museum at Laetoli. A year later, fourteen hominin tracks, associated with tracks of other vertebrates, were unearthed in three test-pits, respectively labelled L8, M9 and TP2 from north to south [Masao et al. 2016] (Fig. 2). A multidisciplinary Italian-Tanzanian research team was involved in studying the findings. Seven bipedal tracks in different preservation state were exposed in L8, four in M9 and two additional tracks of the same individual were found in the eastern part of TP2 [Masao et al. 2016]. Following the code used for the Site G prints [Leakey 1981], the new individual was referred to as S1. One more track referable to a second individual (S2), smaller than S1, was found in the SW corner of TP2 [Masao et al. 2016]. Another test-pit, labelled M10, yielded very abundant non-hominin footprints.

Detailed analysis of the excavation profiles and extended geological observation in the whole Laetoli area indicate with reasonable confidence that the footprints of S1 and S2 lie on the same stratigraphic horizon as those at Site G. It can be consequently inferred that the tracks of the two sites were likely left by a single group of hominins walking on the same palaeosurface, in the same direction and with similar moderate speed [Masao et al. 2016].

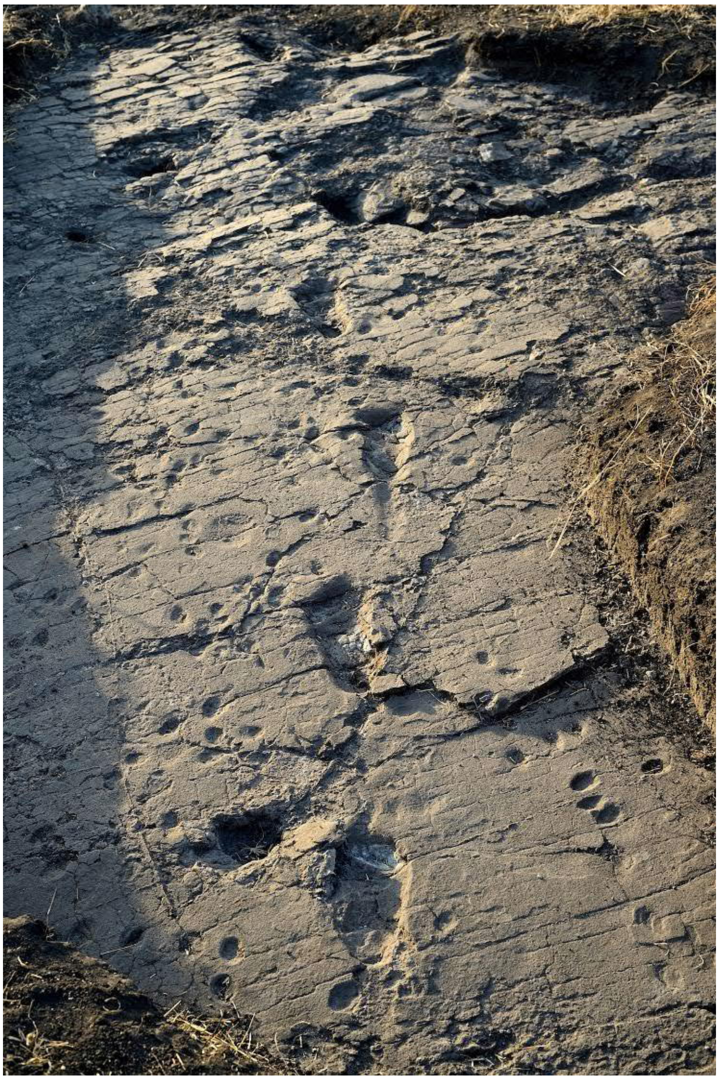

*Fig. 1. Test-pit L8 at Laetoli Site S. In the northern part of the test-pit (at the top), the Footprint Tuff is particularly altered, damaged by plant roots and dislodged along natural fractures*

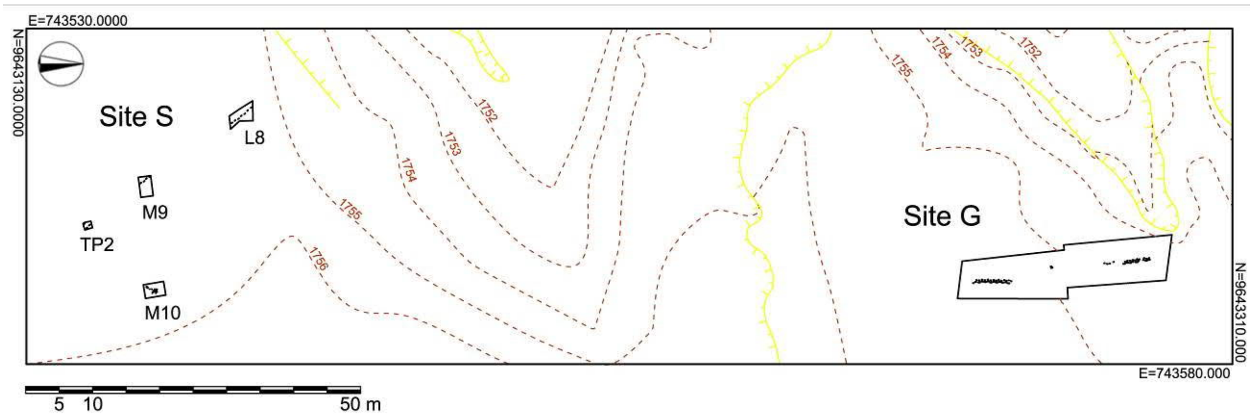


*Fig. 2. Location map of the old Site G and the new Site S*

The topographic and photogrammetric surveys carried out during the 2015 fieldwork, and explained in the next paragraphs, served to obtain morphological and morphometric data for subsequent analysis. Footprints dimension and distance (e.g. step and stride) were used to estimate walking speed, stature and body mass of the Laetoli track-makers. All the above data were also measured for G1-G2-G3 through a 3D model of a first-generation cast of the southern portion of the Site G trackways [Masao et al. 2016].

The analysis of the new data showed that the two individuals S1 and S2 were taller and had a larger body mass than the G individuals. These results extended the dimensional range of the Laetoli track-makers and identified S1 as a large-sized individual, probably a male. The estimate stature of about 165 cm for S1 is remarkable, exceeds any australopithecine, and falls within the range of modern *Homo sapiens* maximum values [Masao et al. 2016]. These results also supported a nonlinear evolutionary trend in hominin body size [Jungers et al. 2016], contrasting with the idea that the emergence of the genus *Homo* and/or the first dispersal out of Africa was related to an abrupt increase in body size. Moreover, ascribing the S1 tracks to an adult male allowed reconsidering the sex and age of the other Laetoli individuals, which have been the subject of several interpretations since Mary Leakey's work. According to the body-mass estimates from the recent surveys, G1 and G3 fall within the range of putative *Au. afarensis* females, whereas G2 and S2 span across the upper female and the lower male ranges. A possible tentative conclusion is that the Laetoli individuals are: S1, a male; G2 and S2, females; G1 and G3, smaller females or juvenile individuals [Masao et al. 2016]. Both the new composition of the group and the impressive body size difference suggest a considerable sexual dimorphism in *Au. afarensis*, as hypothesized by many scholars on the basis of skeletal remains [Johanson and White 1979; Kimbel and White 1988; McHenry 1991; Richmond and Jungers 1995; Lockwood et al. 1996; Plavcan et al. 2005; Harmon 2006; Gordon et al. 2008]. In turn, this view supports social organization and reproductive strategies closer to those of the polygynous gorillas than to other moderately dimorphic species, like chimpanzees, bonobos or most of the extant and, possibly, extinct humans [Masao et al. 2016] (Fig. 3).

*Fig. 3. Reconstruction of the paleoenvironment of Laetoli 3.6 million years ago with the five hominins leaving their footprints*

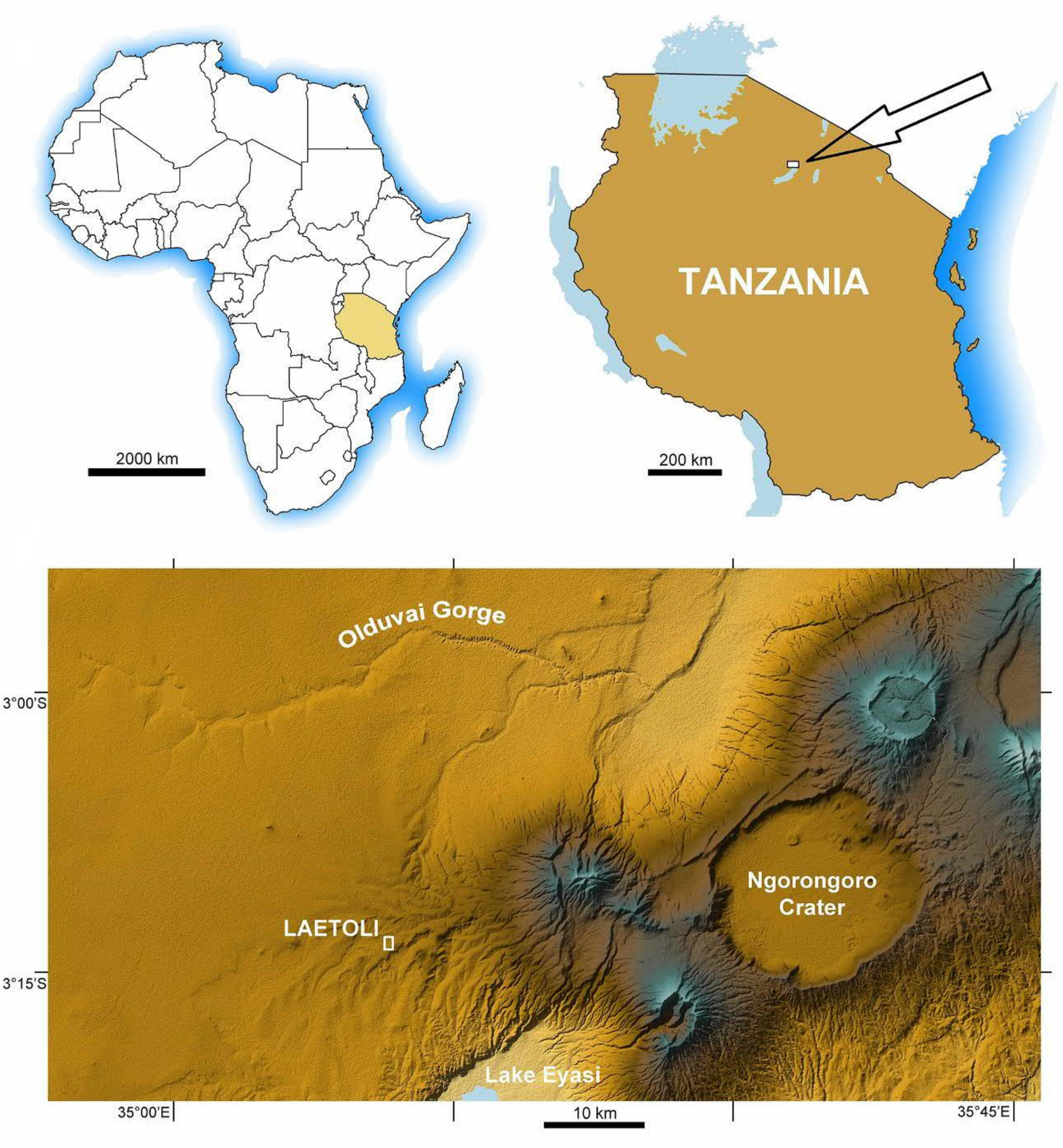


*Fig. 4. Geographical location of the Laetoli site*

## THE EXTREME ENVIRONMENT OF THE AFRICAN SAVANNAH

The geo-paleontological site of Laetoli is located in northern Tanzania (Latitude: 2°59'46.39" S, Longitude: 35°21'8.64" E) and extends over a vast plateau at about 1,700 m above sea level, to the west of the volcanic complex of Sadiman (2,870 m), Lemagrut (3,135 m) and Oldeani (3,200 m), between the south-eastern limits of the Serengeti plains and the Lake Eyasi basin (Fig. 4). Because of its proximity to the Equator, the daily distribution of day and night hours is regular: 12 hours of light and 12 of dark. This means that the working day is quite short because the sunset is at 6:00 pm. The location of the study area is about 16 km west of the small village of Endulen (the nearest village to the site) and about 45 km SW of the famous Olduvai Gorge. The entire territory of Laetoli falls administratively in the Region of Arusha and in the District of Ngorongoro, and within the "Ngorongoro Conservation Area" (NCA), a large protected area of 8,292 $km^2$. The NCA was established by the Tanzanian government in 1959 with the primary purpose of protecting landscapes, environments, flora and fauna, and of combining the conservation of local natural resources with the traditional pastoral practices of the Maasai people, which represents the largest ethnic group in the region (Fig. 5).

*Fig. 5. Current environment of Laetoli area: maasai and giraffe in the Savannah*

The plateau is characterized by a mostly tabular or slightly corrugated general morphology. In some areas, the gentle lines of the landscape become more complex and articulated, as the territory is strongly influenced by narrow and variably deep valleys/gorges/gullies originated by small streams with seasonal trends, with springs located on the nearby mountains. Where the consolidated Footprint Tuff is not exposed, the soil is mostly formed by greyish fine sands, deriving from the erosion of the volcanoclastic bedrock. It is worth noting that under equatorial climatic conditions (see below) this process can be extremely hard both in the “dry season” and in the “rainy season”, due to the intense erosional energy of wind and water, respectively.

The Laetoli area has a tropical sub-montane semi-arid climate and is characterized by an average annual temperature of 17.6 °C and an average annual rainfall of 886 mm. The seasonality is considerable, mainly due to the high variability of rainfall and monthly atmospheric humidity gradient, which is not very relevant for temperatures. Rainfall is mostly concentrated in the “rainy season”, which corresponds to the Southern Hemisphere summer (from November to May). On the contrary, months corresponding to the Southern Hemisphere winter (from the end of May to October) are characterized by a long “dry season” with periods of almost complete absence of rains and with atmospheric humidity levels lower than 50 %. Strong dryness causes the pulverization of soil that, combined with the notable windiness of the area, can give rise to frequent “dust storms” which cause difficulties for researchers on fieldwork activities. Seasonal differences in temperature, as already reported above, remain on modest levels for the whole year: averages of 27-36 °C in daytime and 17-19 °C in night-time during the “southern summer”; diurnal averages of 26-30 °C and nocturnal of 13-15 °C during the mild “southern winter”.

The current vegetation cover of this area is primarily determined by topographical and climatic conditions and soil composition [Anderson 2008] (Fig. 6). It has also been influenced by fires of both natural and anthropic origin, as well as by the grazing activity of the huge amount of wild herbivore mammals (especially in the rainy season) and of domestic livestock (cattle, sheep and goats) bred by local tribes with nomadic and semi-nomadic pastoral economy [Holdo et al. 2009]. The vegetation of this territory, widely studied and mapped in detail [Herlocker and Dirschl 1972; Andrews and Bamford 2008], mainly includes various types of thorny thickets and dry bushland, consisting of shrubby and/or arboreal deciduous species of the genus *Vachellia* and *Senegalia* (*V. tortilis*, *V. kirkii*, *V. seval*, *V. drepanolobium*, *S. mellifera*) and *Commiphora* (*C. trothae*, *C. africana*). Specifically for the site of Laetoli, the local plant cover is mainly characterized by a low bushland, dominated by the Whistiling thorn acacia (*V. drepanolobium*), by a scattered woodland, with the Umbrella thorn acacia (*V. tortilis*) and the Honey thorn acacia (*S. mellifera*), which develop along small seasonal streams and near slight humid depressions, and by grassy expanses consisting of various species of Graminaceae (genus *Sporoboro*, *Digitaria*, *Themeda*, *Aristida*, *Brachiaria*, *Cenchrus*, *Chloris*, *Killinga*, etc.) with scattered specimens of shrubs and small trees as the Wild date tree (*Balanites aegyptiaca*). Along small perennial watercourses, that cross the plateau, are sparse riparian woods dominated by the Yellow fever tree (*V. xanthophloea*), scattered specimens of the Apple-ring acacia (*Faidherbia albida*) and different species of wild figs of genus *Ficus*, in particular the Sycamore fig (*F. sycomorus*). Regarding the aforementioned vegetation, the component that causes the greatest disturbance to researchers is certainly the presence of numerous thorny species, which sometimes hinder survey activities.

The Laetoli site, as a large part of the plateau that extends west of Endulen, still has a rich and very interesting fauna, thanks to the low human demographic density of the area, to the persistence of thorny xerophilous scrublands with difficult penetrability and economic use by local pastoral communities, and to the high level of protection guaranteed by the NCA. In addition to numerous species of invertebrates (e.g. insects and arachnids), to few species of fishes and amphibians limited to rare perennial watercourses and ephemeral seasonal wetland, there are many species of reptiles, birds and mammals that characterize the fauna of this territory. Among reptiles, there are many species of the order Squamata (lizards and snakes), including some species of snakes potentially very dangerous to humans, such as the Egyptian cobra (*Naja haje*), the Spitting cobra (*N. nigricollis*), the Black mamba (*Dendroaspis polylepis*), the Green mamba (*D. angusticeps*) and the Puff adder (*Bitis arietans*). Among birds, numerous sedentary and nesting species typical of sub-arid environments, as well as migratory regular or wintering step species are present. Among mammals, there are numerous species of rodents and their predators: small or medium-sized carnivores, in particular mongooses, the Wild African cat (*Felis lybica*) and the Caracal (*Caracal caracal*). There are also many large-sized species, such as various antelopes, from the Grant's gazelle (*Nanger grantii*) to the massive Eland (*Taurotragus oryx*), in addition to the Grant's zebra (*Equus quagga boehmi*), the Maasai giraffe (*Giraffa camelopardalis tippelskirchii)* and the African bush elephant (*Loxodonta africana)*. Many of these large mammals, in particular zebras and elephants, tend to frequent the Laetoli area seasonally, especially during the most humid and vegetation-rich periods. Even the large carnivores, such as the Spotted hyena (*Crocuta Crocuta*), the Cheetah (*Acinonyx jubatus*), the Leopard (*Panthera pardus*) and the African lion (*Panthera leo*) occasionally frequent the most remote areas that surround the site, mainly during periods with great seasonal presence of herds of ungulates. Primates include the small Senegal bushbaby (*Galago senegalensis*), the Brown greater galago (*Otolemur crassicaudatus*) and the Vervet monkey (*Chlorocebus aethiops*) in the riverine forests; the Olive baboon (*Papio aubis*) in scrubland and deciduous xerophilous forests but also in open steppe areas, as well as near the most populated territories including the surroundings of Endulen.

Regarding the anthropic aspects, the demographic density of the entire area is quite low and there are few permanent settlements with a population of more than a thousand inhabitants. With regards to scientific field activities, this means that it is not easy to get consumer goods *in situ*, but it is necessary to get food, water and materials from larger villages, such as Karatu, which is a 4-hour drive from Laetoli.

For what concerns hygienic-sanitary aspects, the whole area normally does not present serious problems related to tropical pathologies that are widespread in the nearby low-altitude regions, thanks to the considerable altitude of the plateau between Endulen and Laetoli (about 1,400-2,000 m above sea level) and very dry climate for most of the year. Despite this, in the wettest areas and especially along the few perennial watercourses, there are small stable population of hematophagous dipterans of the genera *Anophele* (potential vectors of protozoa of the genus *Plasmodium*, responsible for malaria) and *Aedes* (carrier of various viruses responsible for serious diseases). Therefore, the risk of malaria, as well as that of yellow fever, is still present, although contained and mainly diffuse during the wettest periods of the year. Other species of hematophagous dipterans belonging to the families Tabanidae (Horse-flies) and Simuliidae (Black-flies) can inflict painful bites and cause serious skin irritations.

*Fig. 6. Current vegetation cover of Laetoli area*

## WORKFLOW: 3D SURVEY FOR DOCUMENTATION AND ANALYSIS

The problems related to the extreme Laetoli environment, which can be found in other similar environments in Africa and other areas, are two types: those that hinder the survey and study of Cultural Heritage, and those that endanger its preservation. The first include short time available, adverse weather conditions, lack of electricity, problems related to natural lighting, etc., and can be minimized with a good survey planning. The second, due to multiple environmental factors (climate, vegetation, animal behaviors, etc.), can be addressed through a comprehensive conservation plan.

In this paragraph we discuss the difficulties concerning fieldwork activities and present the workflow that we implemented, analyzing the problems and proposing the solutions adopted during the research in September 2015.

To structure a good survey plan, clear goals are necessary. In our case, the survey of the new tracks at Site S was focused on obtaining 3D models for documentation and morphometric analysis. The survey method is the “Structure from Motion” (SfM) technique, an image-based process supported by *in situ* topographic measurements [Remondino et al. 2006]. This technique was chosen because of its technical advantages (relatively short time of data acquisition and processing, light and handy equipment, reduced costs) and excellent results in terms of resolution [Cefalu et al. 2013]. The photogrammetric technique was also chosen to survey the Site G during a study campaign on footprints conservation in the 1990s by the team of the Getty Conservation Institute [Getty Conservation Institute 1996].

As mentioned above, hominin and non-hominin tracks were recognized in four test-pits at Site S, namely L8 (about 2 x 4 m), M9 (2 x 2 m), TP2 (1 x 1.3 m), and M10 (2 x 3 m) (Fig. 7).

To optimize the work, each test-pit was entirely surveyed at lower resolution and then detailed 3D models of some inner portions (single prints or groups of close prints) were acquired. After the excavation, targets of the control point system were immediately positioned. We placed four perimeter targets on the ground at the corner of each test-pit, and four inner targets around each sub-area surveyed in detail (14 targets in L8, 10 in M9, 14 in TP2, and 14 in M10) (Fig. 8).

The equipment used in the fieldwork was a DSLR camera with 15 megapixels resolution (4,752 x 3,168 pixel) and two different lenses: 24 mm f/2.8 for general shots of the excavation areas and 50 mm f/1.4 for details of the tracks.

When necessary, the camera was mounted on a 3 m-long telescopic rod. A measuring tape and a water level were used for the measurement of the control points (i.e. circular targets with 35 mm diameter). Topographic measurements are usually recorded by a total station theodolite. We opted for the aforementioned tools, certainly lighter and easier to handle, after considering measuring only 4 points for each test-pit to scale the general 3D models. The detailed 3D models of the single footprints were aligned to the general models with the coordinates of the inner targets. We also ascertained that this measuring technique can provide high precision results because of the small size of the surfaces to be detected.

For the perimeter targets measurement, we placed two rods equipped with a spherical level on successive pairs of targets and we marked points at the same height on the rods for each pair by using the water level device. The vertical distance between these points and the targets, as well as their mutual distance, were recorded. Repeating this process for all pairs of targets, the relative plan position and the height of the control points were determined respectively by trilateration and levelling.

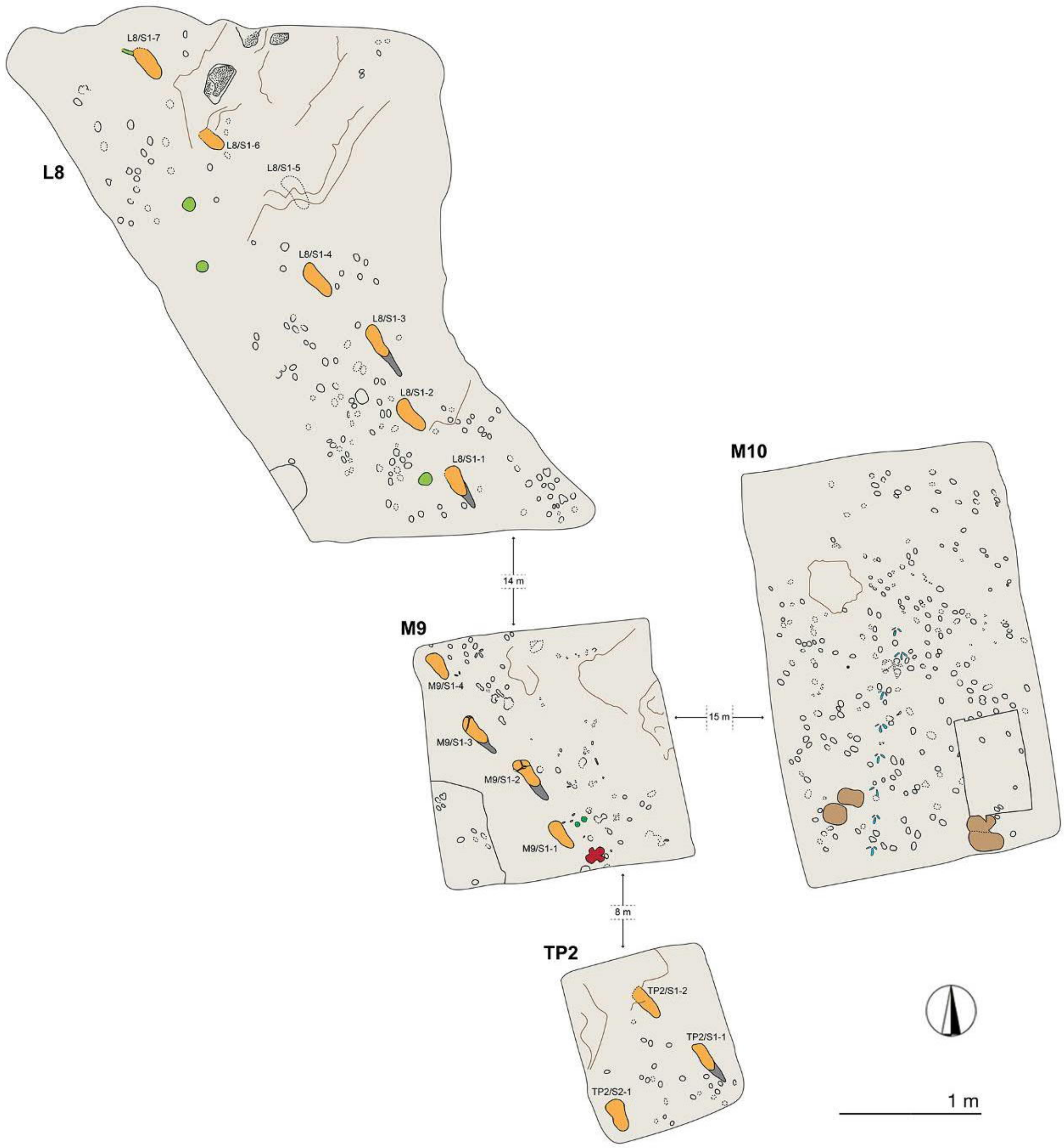


*Fig. 7. Plan view of the four test-pits excavated at Laetoli Site S. Dashed lines indicate uncertain contours. Some of the most interesting tracks are colored: hominins in orange (heel drags in dark grey), equid in dark green (M9), rhinoceros in red (M9), giraffe in light brown (M10), guinea fowl in blue (M10). Large roots and bases of trees are*

*in light green (L8). The main faults/fractures are indicated by brown lines. Raindrop impressions occur in the northern part of L8 (dotted areas)*

A preliminary accuracy check was carried out during fieldwork, by using trilateration graphic rules in plan and by the method of successive levelling for heights. By assigning a z-coordinate to the first control point, all subsequent coordinates were derived from addition and subtraction of heights between two successive points. The check was performed by computing the algebraic sum of all height differences, and by verifying that the obtained value was close to zero. Finally, the error obtained in each test-pit was distributed to every z-coordinate of the points, in order to minimize it (Tab. 1).

There were mainly two issues to consider during the photographic acquisition: scene lighting and texture resolution of 3D models. As for the former, since the excavation areas were outdoor, we did not have the possibility to control light intensity and direction. We tried to shoot especially during the central hours of the day (i.e. with sub-vertical sun rays) in order to reduce shadows, but it was not always possible due to the excavation schedule and little time available. A diffuse lighting would be perfect, but it is not always possible to obtain without the aid of artificial lights. The problem of high-contrast shadows was reduced in post-processing, as described below.

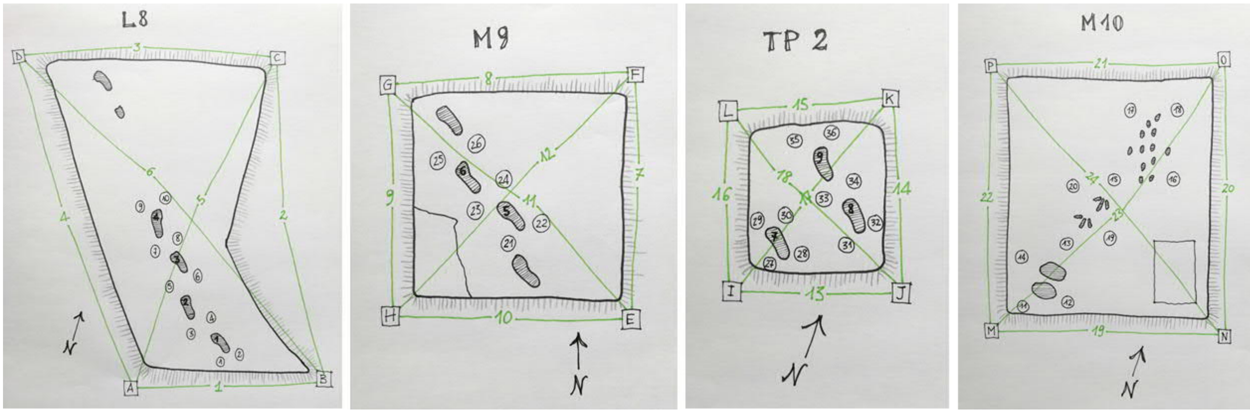


*Fig. 8. Eidotypes of the four test-pits*

*Table 1. Fieldwork measurement acquisition and error calculation*

| TEST-PIT ID | MEASURE ID | 1ST TARGET ID | 1ST TARGET ALTITUDE (m) | 2ND TARGET ID | 2ND TARGET ALTITUDE (m) | DISTANCE (m) | Δ MEASURED (m) | Δ CORRECTED (m) | |
|---|---|---|---|---|---|---|---|---|---|
| L8 | 1 | A | 0,775 | B | 0,725 | 2,561 | 0,050 | 0,051 | |
| L8 | 2 | B | 0,774 | C | 0,921 | 3,271 | -0,147 | -0,146 | |
| L8 | 3 | C | 0,486 | D | 0,613 | 3,441 | -0,127 | -0,126 | |
| L8 | 4 | D | 0,702 | A | 0,482 | 3,591 | 0,220 | 0,221 | |
| L8 | 5 | A | 0,523 | C | 0,620 | 4,176 | ERROR (m) | ERROR DIVIDING (m) | FINAL ERROR (m) |
| L8 | 6 | B | 0,453 | D | 0,724 | 4,894 | -0,004 | -0,001 | 0,000 |

I TRIANGLE CHECK

| 1ST TARGET ID | 1ST TARGET ALTITUDE (m) | 2ND TARGET ID | 2ND TARGET ALTITUDE (m) | Δ MEASURED (m) |
|---|---|---|---|---|
| A | 0,775 | B | 0,725 | 0,050 |
| B | 0,774 | C | 0,921 | -0,147 |
| C | 0,620 | A | 0,523 | 0,097 |
| | | | | ERROR (m) |
| | | | | 0,000 |

II TRIANGLE CHECK

| 1ST TARGET ID | 1ST TARGET ALTITUDE (m) | 2ND TARGET ID | 2ND TARGET ALTITUDE (m) | Δ MEASURED (m) |
|---|---|---|---|---|
| A | 0,775 | B | 0,725 | 0,050 |
| B | 0,453 | D | 0,724 | -0,271 |
| D | 0,702 | A | 0,482 | 0,220 |
| | | | | ERROR (m) |
| | | | | -0,001 |

III TRIANGLE CHECK

| 1ST TARGET ID | 1ST TARGET ALTITUDE (m) | 2ND TARGET ID | 2ND TARGET ALTITUDE (m) | Δ MEASURED (m) |
|---|---|---|---|---|
| C | 0,486 | D | 0,613 | -0,127 |
| D | 0,702 | A | 0,482 | 0,220 |
| A | 0,523 | C | 0,620 | -0,097 |
| | | | | ERROR (m) |
| | | | | -0,004 |

IV TRIANGLE CHECK

| 1ST TARGET ID | 1ST TARGET ALTITUDE (m) | 2ND TARGET ID | 2ND TARGET ALTITUDE (m) | Δ MEASURED (m) |
|---|---|---|---|---|
| C | 0,486 | D | 0,613 | -0,127 |
| D | 0,724 | B | 0,453 | 0,271 |
| B | 0,774 | C | 0,921 | -0,147 |
| | | | | ERROR (m) |
| | | | | -0,003 |

The texture resolution control of 3D models, i.e. the “Ground Sampling Distance” (GSD), can be performed *a priori* using geometric formulas. The calculation is based on the principle of similar triangles, which are found in the geometry of the shooting (Fig. 9). The variables are the “size of the sensor” (Sw) and the “focal length” (Fl) of the camera, the “size in pixel of the images” (Iw) (which depends on the sensor resolution), and the “distance” (H). The triangle with the base Sw and height Fl is similar to the triangle which has the base Gw (width of the image on the ground) and height H, consequently the two triangles have proportional respective sides (Sw : Gw = Fl : H). The GSD is the ratio between the Gw and the Iw multiplied by 100 (GSD = Gw /Iw x 100). Connecting the proportion with the formula of GSD, the final formula GSD = (Sw x H x 100) : (Fl x Iw) is obtained. Among the variables, the one that can be easily managed is the distance H, since all the others depend on the photographic equipment available.

It is not possible to determine a priori the density of the point cloud coming from a photogrammetric process.

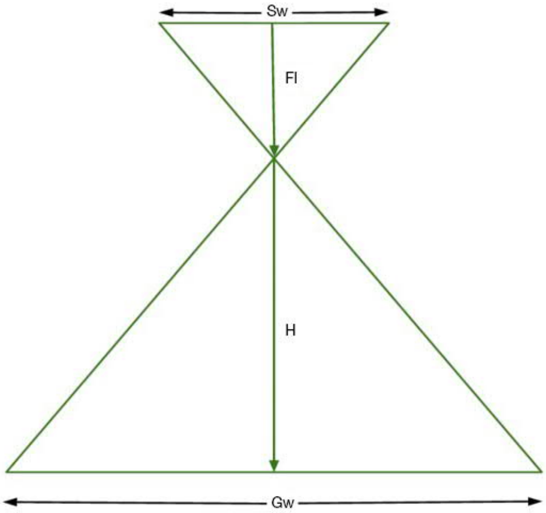


Fig. 9. Similar triangles and nomenclature

In the case of the Laetoli footprints, the goal was to obtain a texture resolution less than 0.1 cm/px. This was achieved by choosing suitable shooting distance both for the acquisition of the whole test-pits and for that of individual footprints (Tab. 2). The photographic survey was carried out by three shooting modes: (1) using the camera with the 24 mm lens, mounted on a telescopic rod at 3 m above the test-pit ground; (2) using the camera freehand with the 24 mm lens, in order to acquire additional shots of each test-pits; and (3) using the camera close to the ground with the 50 mm lens, in order to acquire detailed sub-areas. More than 2,000 photos were taken, for a total of about 50 GB. Especially when working in remote areas, where it is difficult to come back in case of lack of data, it is important not to economize on shots and possibly make a selection *a posteriori*.

*Table 2. Ground Sampling Distance calculation*

**Ground Sampling Distance for the entire test-pit**

| | | |
|---|---|---|
| Sw | 22,3 | = the sensor width of the camera (millimeters) |
| Fl | 24 | = the focal length of the camera (millimeters) |
| H | 3 | = height or distance (meters) |
| Iw | 4752 | = the image width (pixels) |
| Ih | 3168 | = the image height (pixels) |
| **GSD** | **0,06** | **= Ground Sampling Distance (centimeters/pixel)** |
| Gw | 2,79 | = width of single image footprint on the ground (meters) |
| GH | 1,86 | = height of single image footprint on the ground (meters) |

**Ground Sampling Distance for single footprint**

| | | |
|---|---|---|
| Sw | 22,3 | = the sensor width of the camera (millimeters) |
| Fl | 50 | = the focal length of the camera (millimeters) |
| H | 1 | = height or distance (meters) |
| Iw | 4752 | = the image width (pixels) |
| Ih | 3168 | = the image height (pixels) |
| **GSD** | **0,01** | **= Ground Sampling Distance (centimeters/pixel)** |
| Gw | 0,45 | = width of single image footprint on the ground (meters) |
| GH | 0,30 | = height of single image footprint on the ground (meters) |

The whole fieldwork lasted three days, from the 5th to the 8th of September 2015.

Data processing was carried out once we came back to Italy and started with checking measurements in plan and height. This step is preliminary to the definition of the control point coordinates. The trilateration method was used to obtain x,y coordinates of the control points in plan. For each test-pit, six measurements were taken at the same height: the length of the four sides of the perimeter and the length of the two diagonals. Redundant measurements were used to compute the errors. In addition to a preliminary graphical control by CAD software (*Autodesk Autocad*[1]), we used an automatic calculation software (*MicroSurvey STAR*NET*[2]) to adjust, by least squares technique, a new set of x,y coordinates and heights of the control points. The report provided by the software shows that the residues of adjustments never exceeded 10 mm, which is fully acceptable figure considering the size of test-pits. We used the adjusted x,y,z coordinates of the control points to scale and locate, in the 3D space, the 3D models built by the SfM technique.
The pictures were catalogued and post-processed in *Adobe Lightroom*[3] to amend the effects of different lighting conditions and homogenize them. The tone adjustment consisted in lighten the shadows and darken the highlights. These settings work best if the shots are recorded in *raw* format.

Subsequently, a photogrammetric software (*Agisoft Photoscan Pro*[4]) was used to generate 3D spatial data starting from the pictures, through the following phases: alignment of the images; creation of the dense point cloud; transformation of the dense point cloud into a surface (mesh); application of the texture to the mesh (Tab. 3). A series of orthophotos (with and without textures) were extracted from the 3D models (Figs. 10, 11) [Chiabrando et al. 2015]. A check on point cloud density was also carried out by a software for 3D point cloud and mesh processing and analysis (*CloudCompare*[5]). The average density found in the Laetoli point clouds is around 20 points/cm$^3$ for the test-pits and 1,500 points/cm$^3$ for the detailed footprints (Fig. 12).

*Table 3. Report of the photogrammetric processing.*

| ID DATA | PICTURES (n°) | TIE POINTS (n° points) | DENSE CLOUD (n° points) | MESH (n° faces) | TEXTURE (pixel) |
|---|---|---|---|---|---|
| **L8** | 171 | 15.755 | 6.523.219 | 6.000.000 | 6.000 x 6.000 |
| L8/S1-1 | 31 | 4.885 | 12.788.392 | 1.000.000 | 4.096 x 4.096 |
| L8/S1-2 | 31 | 5.105 | 11.956.726 | 1.000.000 | 4.096 x 4.096 |
| L8/S1-3 | 34 | 6.721 | 14.577.445 | 1.000.000 | 4.096 x 4.096 |
| L8/S1-4 | 38 | 5.754 | 13.849.615 | 1.000.000 | 4.096 x 4.096 |
| **M9** | 277 | 16.752 | 5.520.206 | 5.000.000 | 6.000 x 6.000 |
| M9/S1-2 | 97 | 7.095 | 3.044.911 | 1.000.000 | 4.096 x 4.096 |
| M9/S1-3 | 90 | 6.695 | 3.024.744 | 1.000.000 | 4.096 x 4.096 |
| **TP2** | 180 | 14.476 | 4.803.978 | 4.000.000 | 6.000 x 6.000 |
| TP2/S2-1 | 89 | 6.326 | 9.388.424 | 1.000.000 | 4.096 x 4.096 |
| TP2/S1-1 | 55 | 4.434 | 3.624.823 | 1.000.000 | 4.096 x 4.096 |
| TP2/S1-2 | 56 | 3.991 | 4.127.016 | 1.000.000 | 4.096 x 4.096 |
| **M10** | 127 | 11.254 | 4.969.463 | 5.000.000 | 6.000 x 6.000 |
| M10/AF1 | 33 | 3.704 | 1.879.530 | 1.000.000 | 4.096 x 4.096 |
| M10/AF2 | 34 | 3.512 | 2.204.826 | 1.000.000 | 4.096 x 4.096 |
| M10/AF3 | 42 | 4.322 | 3.306.688 | 1.000.000 | 4.096 x 4.096 |

At the end of field season, we also surveyed a first-generation fiberglass cast of the southern portion of the Site G trackway (about 4,7 m in length) kept in the Leakey Camp at Olduvai Gorge (Fig. 13). Data acquisition and processing were performed following the same workflow described above for Site S. We positioned four perimeter control points and 11 inner targets. The latter were used to model in detail six selected tracks. The 3D data were used to compare the old trackways discovered by Mary Leakey and the new ones unearthed in 2015.
The 3D data obtained by the above procedures were also used in the morphometric analysis of the hominin tracks through a contouring and modelling software (*Golden Software Surfer*[6]) that transforms x,y,z data into maps (Fig. 14). The x,y,z-format files were imported into the software and transformed into grid files. The software uses randomly spaced x,y,z data to create regularly spaced grids composed of nodes with x,y,z coordinates. The

[1] https://www.autodesk.com/products/autocad/overview
[2] https://www.microsurvey.com/products/starnet/
[3] https://www.adobe.com/it/products/photoshop-lightroom.html
[4] https://www.agisoft.com/
[5] https://www.danielgm.net/cc/
[6] https://www.goldensoftware.com/products/surfer

*triangulation with linear interpolation* gridding method was applied, because it works better with data that are evenly distributed over the grid area. This method uses data points to create network of triangles without edge intersection and computes new values along the edges. It is fast and does not extrapolate beyond the z-value of the data range. The grid spacing was set at 1 mm.

On the contour maps we took morphometric measurements: footprint length (maximum distance between the anterior tip of the hallux and the posterior tip of the heel); footprint max width (width across the distal metatarsal region), footprint heel width; angle of gait (angle between the midline of the trackway and the longitudinal axis of the foot); step length (distance between the posterior tip of the heel in two successive tracks); stride length (distance between the posterior tip of the heel in two successive track on the same side) (Fig. 15). All the above measurements were also taken manually both on the original tracks during the September 2015 field season, and on 1:1 scale sketches of the test-pits, hand-drawn on transparent plastic sheets [Masao et al. 2016].

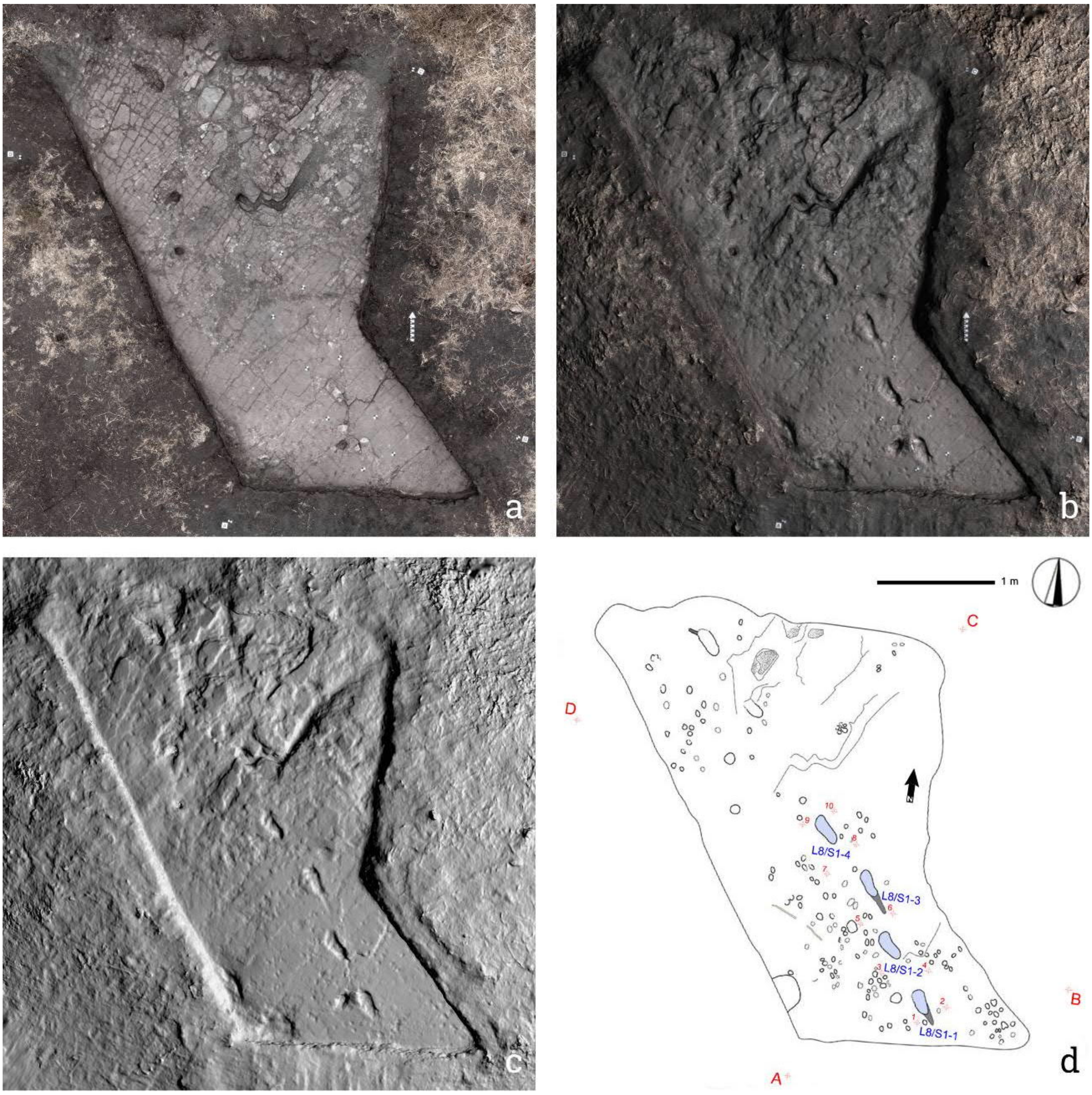


*Fig. 10. Orthophotos and drawing of L8 test-pit: (a) textured model, (b) textured and shaded model, (c) shaded model, (d) drawing*

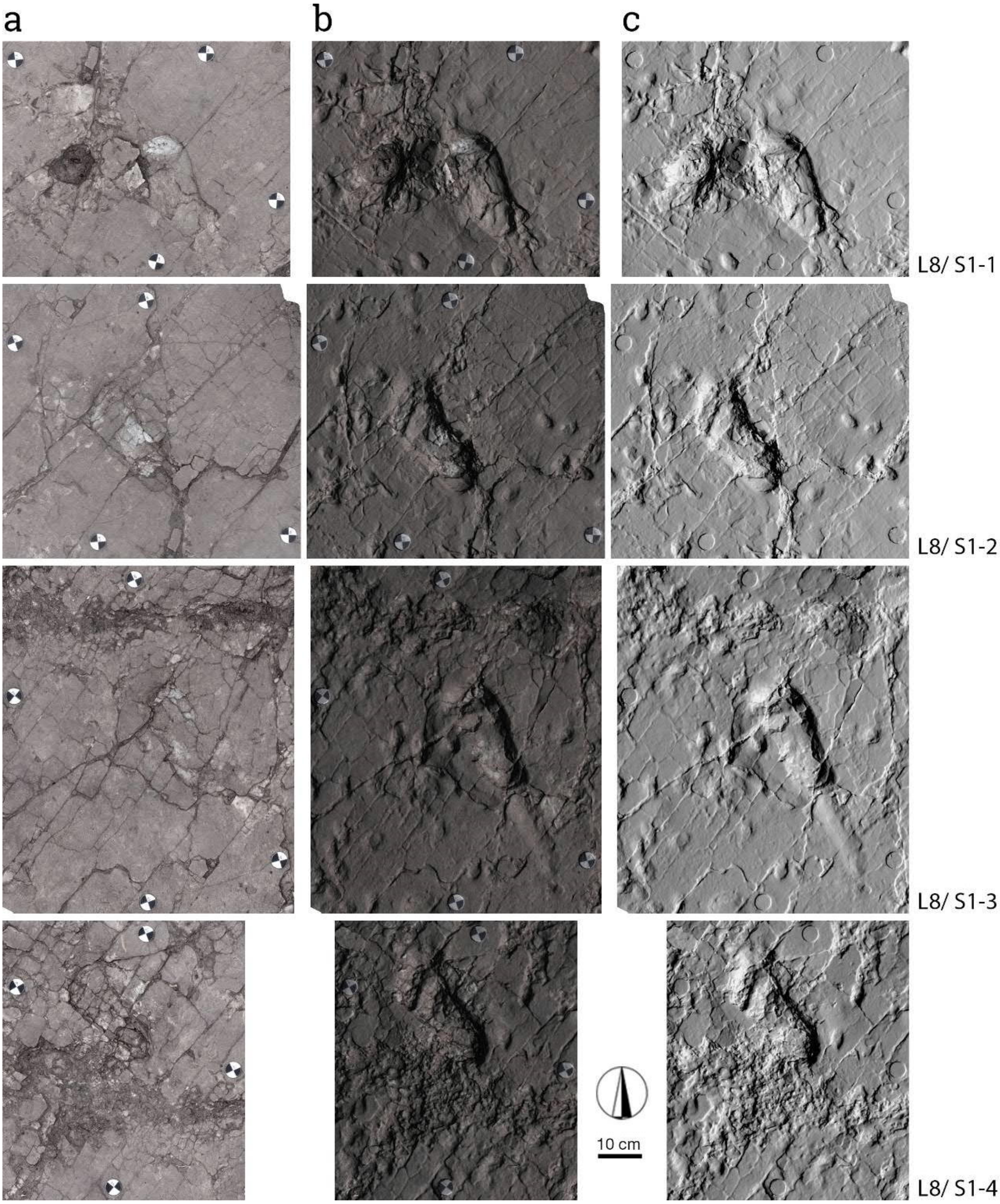


*Fig. 11. Orthophoto of the best-preserved footprints in L8: (a) textured model, (b) textured and shaded model, (c) shaded model*

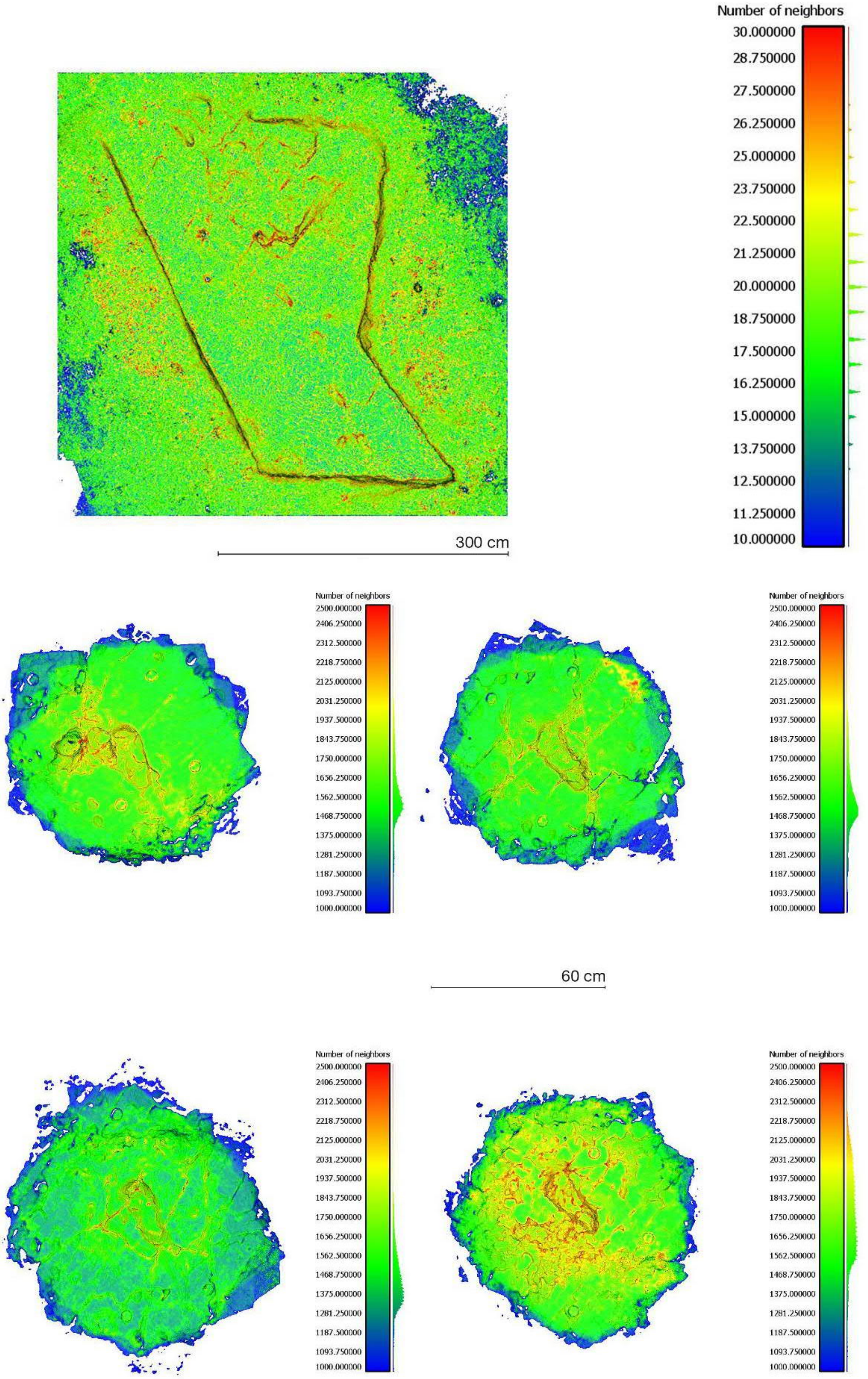


*Fig. 12. Density of the point cloud by determining the number of nearest neighbors in a sphere with 0.5 cm radius*


*Fig. 13. Orthophoto of a cast of the southern portion of the Site G trackway: (a) textured model, (b) textured and shaded model, (c) shaded model*

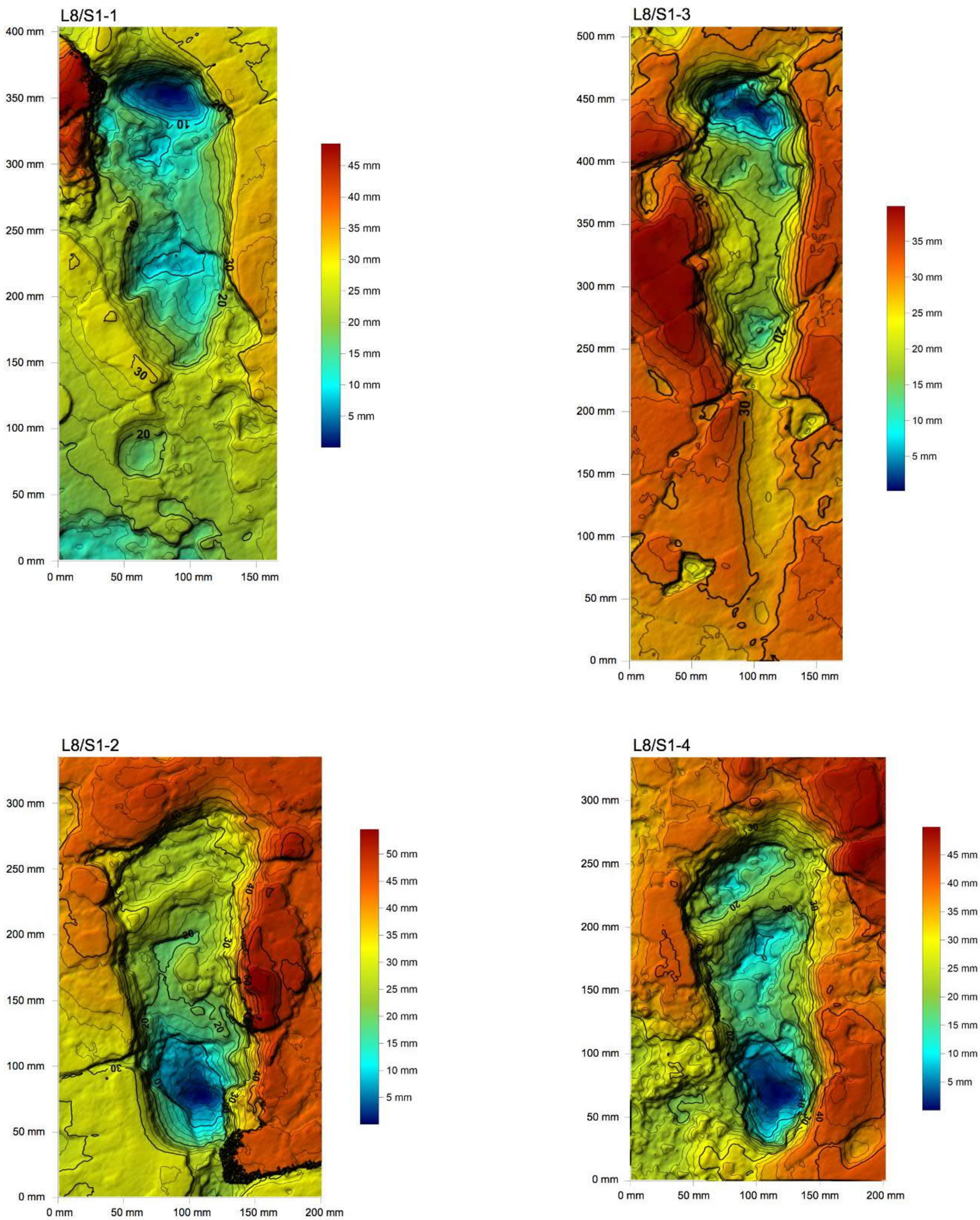


*Fig. 14. Shaded 3D photogrammetric model of close-up of the best-preserved tracks with contour lines. Color is rendered with 10-mm isopleths for the trackway and 2-mm isopleths for the single tracks*

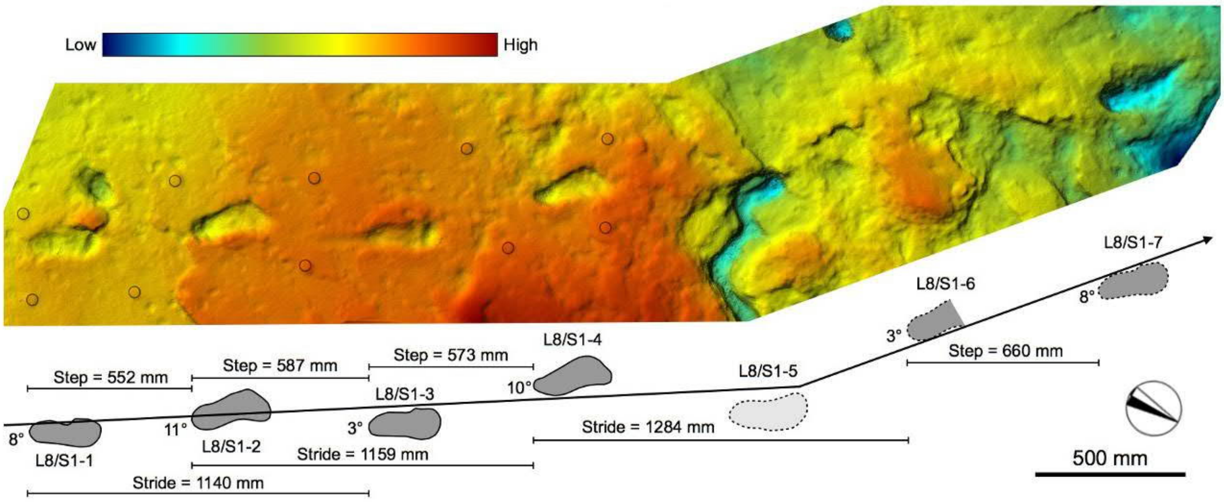


*Fig. 15. Shaded 3D photogrammetric model of the L8 trackway. Color is rendered with 10-mm isopleths. The empty circles indicate the position of the targets of the 3D imaging control point system*

## CONCLUSIONS

Many cultural assets are in risky situation and they are destined to disappear. Sometimes problems arise from human presence/behavior (e.g. wars) or from natural disasters (e.g. earthquakes or landslides). At other times the cause of deterioration is due to the slow and inexorable action of atmospheric agents and other natural factors acting in extreme areas, where the preservation of Cultural Heritage is much more complex.

The proposed workflow and its results are an ideal starting point for further conservation actions, because they allowed obtaining a 3D state-of-art documentation of Cultural Heritage that could disappear in a relatively short time due to environmental factors. Moreover, the obtained data were (and will be) a valuable support for the study of paleontological findings. The procedure described above make the getting of 3D documentation relatively easy and fast, minimizing most of the severe issues that researchers can face in extreme geographical contexts.

In the case of the Laetoli footprints, conservation is particularly difficult because most of the footprints exposed in the test-pits are already severely threatened by natural agents and are at risk of disappearing even if unexcavated. Apart from the unearthed tracks, many other unknown footprints could still be underground, in danger. Numerous perpendicular fractures lead to the disintegration of part of the tuff layer, and plant roots are dislodging the sequence of strata.

In the 1990s, the Site G footprints were subjected to a complex project of consolidation, re-burial, and protection [Musiba et al. 2012]. On that occasion various scholars expressed their concerns about the conservation status of the site [Feibel et al. 1996; Getty Conservation Institute 1996; Agnew and Demas 1998]. To block or reduce this relatively fast deterioration, we need an effective and rapid strategy supported by further analysis. The loss of the Laetoli tracks would be a huge loss for humanity. These footprints, like a spotlight on a prehistoric scene, come from a series of fortuitous and rare events: the volcanic eruption, the rain that made the ash wet, the hominins that walked on it, another eruption and other ash that covered and preserved the printed surface until its discovery 3.66 million years later. The Laetoli footprints are a unique source of information on the morphology and biology of early bipedal hominins and represent, to date, the earliest direct evidence for such a locomotion pattern among our ancestors. Laetoli is also the only site in the world providing data about body size variation within a single population of australopithecines. Therefore, Laetoli is among the most significant and iconic sites for the study of human origins. For this reason, the whole scientific community is called upon to collaborate in the development of a long-term conservation project of this heritage [Cherin et al. under review].

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[7] www.paleoantropologia.it/en

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## AUTHOR’S CONTRIBUTIONS

The work presented here was carried out in collaboration between all authors. E.B.I. and F.T.M. discovered the new footprints and co-directed field work. M.C. and G.M. co-directed field work. M.C., A.B., G.B., D.A.I. F.T.M., S.M. and G.M. carried out field work and analyzed the data. S.M. wrote the chapters “Introduction”, “Laetoli: old footprints and new discoveries”, “Workflow: 3D survey for documentation and analysis” and “Conclusions”; A.B. wrote the chapter “The extreme environment of the African Savannah”. M.C. supervised the final version of the article. All authors defined the research theme, discussed analyses, interpretation and presentation, and have contributed to, seen and approved the manuscript.

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