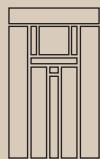


# The Journal of Ancient Egyptian Architecture



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The *Journal of Ancient Egyptian Architecture* is a peer-reviewed, scientific, open access, and annual periodical. Its purpose is to promote the publication of research devoted to ancient Egyptian architecture (domestic, civil, military, ritual/religious, elite, industrial and funerary), from the Predynastic Period to the Roman imperial era, whatever the modern geographical context (Egypt, Sudan, Near East, etc.). The subject scope includes all things relating to construction, regardless of their original importance or purpose.

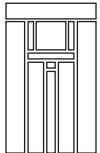
The journal publishes fieldwork reports and studies undertaken in the Egyptological tradition, including discussions of epigraphy and iconography, and also research that utilizes specific skills such as structural and materials sciences, and modern investigative techniques. In this way, JAEA seeks to encourage the development of detailed technical descriptions, and deeply theorized understanding (of architectural symbolism, propaganda, climatic and geological influences, etc.). This interdisciplinary approach will help connect adjacent areas of expertise which, alone, could not reflect the richness and complexity of the ancient Egyptian built heritage.

The periodical welcomes studies that meets any one of these goals, only on the condition that the formatting and content of articles are subject to JAEA scientific publication requirements.

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# A new survey of the upper chambers of Snefru's pyramids at Dahshur

Franck Monnier

## *Abstract:*

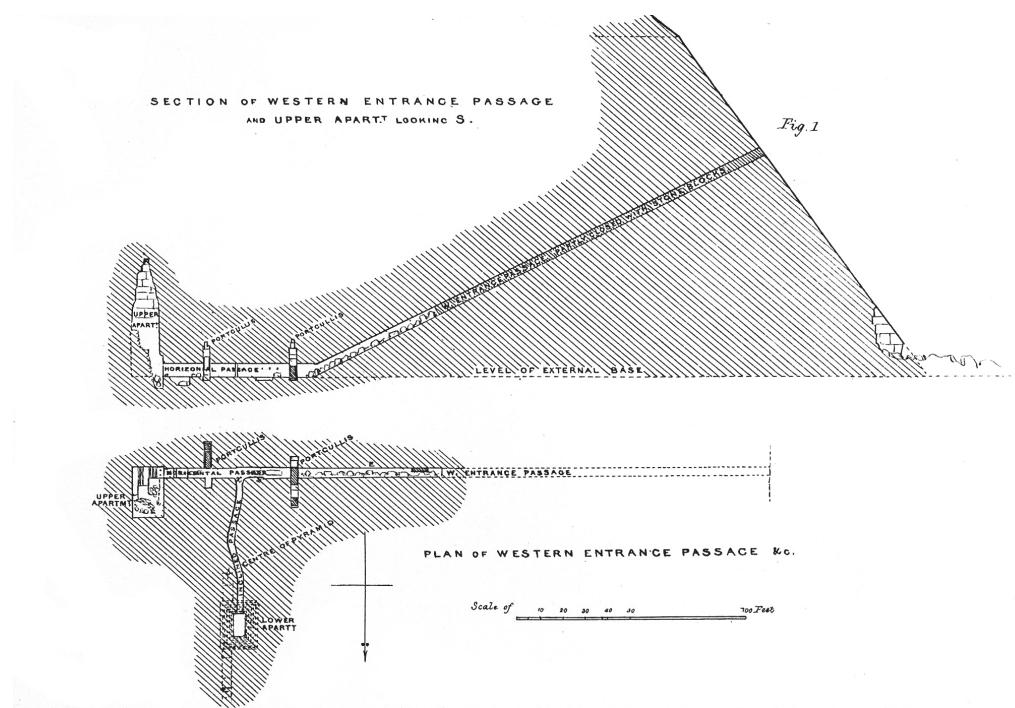
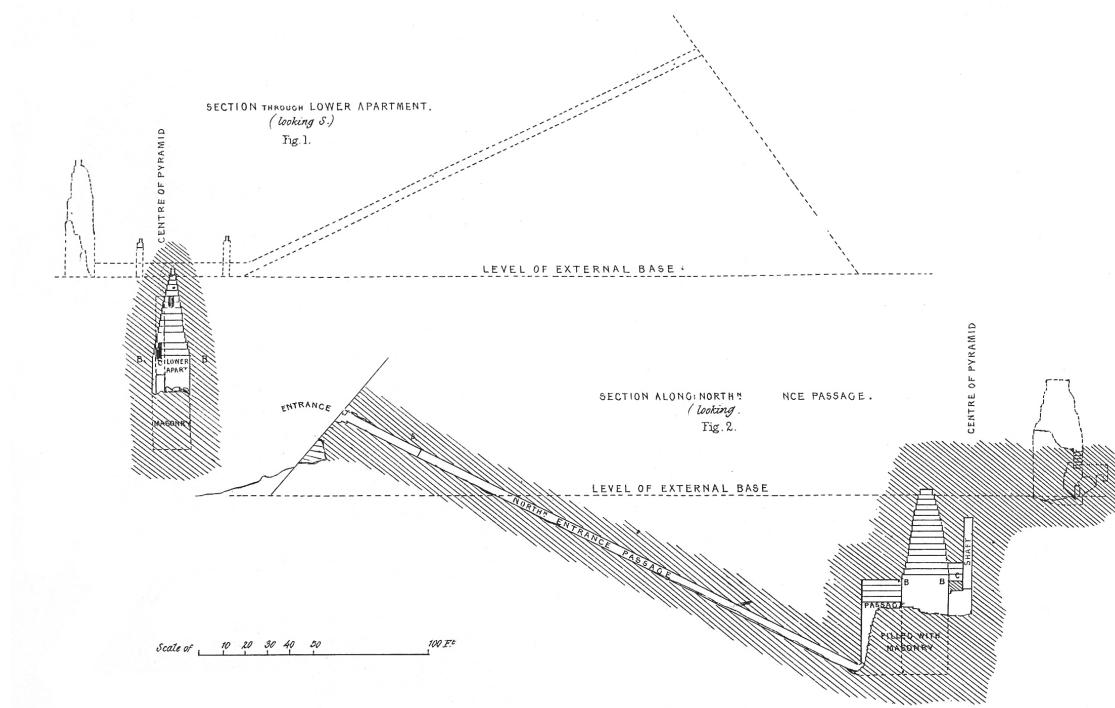
*This article presents a new survey of the corbelled chambers within Snefru's Bent and Red pyramids at Dahshur, based on photogrammetry work carried out by French company Iconem in 2018. As a consultant to the project, the author was involved in the research design and gave the company guidance on where to focus their efforts to optimize data acquisition and survey effectiveness. Once the data was processed, an analysis of the architecture was carried out and is reported here for the first time. The site survey history including pre-existing reports for the spaces of interest are first reviewed. The 3-dimensional digital models of the interior spaces are then analyzed. High-quality photogrammetry images from the project are presented here, along with new diagrams and a new description of the formation history of the funerary chambers.*

In the fall of 2018,<sup>1</sup> a new photogrammetry survey was carried out in order to investigate the potential of this imaging technique to enhance the study of pyramids. This work took place with the permission of the Egyptian antiquities authorities and in coordination with a documentary series produced by Label News.<sup>2</sup> Over the course of the survey, the French start-up company Iconem took thousands of digital photos with a drone in order to digitize the outer surfaces of the pyramid of Djoser at Saqqara, the pyramids of Snefru at Meidum and Dahshur, the pyramids of Khufu, Khafra, and Menkaure at Giza, and finally the pyramid of Redjedef at Abu Rawash. The internal funerary chamber arrangements of some of these monuments were also scanned and have been partially reconstructed in the form of 3D digital models. The method consisted of establishing positions in three-dimensional space for every point visible on the surface of each monument. The point locations were calculated by digitally processing a large number of overlapping photographs which were taken from different angles. The result is a dense point-cloud that creates a 3D digital model of the monument and incorporates the textured appearance of its surfaces, which can also be deduced from the photographs.

As an expert consultant on the project, I was given access to the datasets acquired in order to evaluate and analyse the data scientifically. The results of those studies will be published in a series of articles. This first paper inaugurates the series with a reassessment of the upper chambers of the Bent Pyramid at Dahshur-South and the Red Pyramid at Dahshur-North, based on the information gathered in the new survey, and with reference to established studies of these monuments.

<sup>1</sup> I'm very grateful to David Ian Lightbody for proof-reading the English text of the manuscript, and to Felix Arnold for his constructive comments. Any remaining mistakes are the author's responsibility.

<sup>2</sup> Pyramids: Solving the mysteries, produced by Label News and created by French director François Pomès whom I thank and acknowledge for giving me the rights to analyze and to reproduce the data obtained during these documentaries.



**Fig. 1.** Sectional and plan views of the inner arrangements of the Bent Pyramid drawn by John Shae perring (Perring (1842), pl. XV).



**Fig. 2.** Two photos of the upper chamber of the Bent Pyramid (left: toward the South-West; right: toward the North-West) taken by Abd el-Salam Hussein in the 1940s (Garnons Williams (1947), p. 305).

## The upper chamber of the Bent Pyramid

### *Early descriptions*

Modern exploration of the Bent Pyramid was started by John Shae Perring in 1839.<sup>3</sup> He carried out the difficult task of clearing the northern descending passage of stone rubble, which blocked access to the chambers within. In the process, he was able to explore the entire system of spaces and finally reached the upper chamber. He was the first to produce section drawings (fig. 1) and a textual description of the space:

The eastern end of the horizontal passage communicated with an apartment 21 feet 6 inches long, 13 feet 6 inches wide, and 52 feet 6 inches high. It had been constructed like the other, and had been built up to a great height with small stones. An excavation had been carried on, to the length of about 12 feet, into this masonry near the floor, and the apartment had been entirely ruined.<sup>4</sup>

Exploration continued thereafter, but it was not until 1946, nearly a century later, that the first real scientific survey was organized. The work was led by the Egyptian Egyptologist Abd el-Salam

<sup>3</sup> However, the English diplomat Davison entered into it in 1763 through the northern entrance and pushed along the descending corridor. He could not go further; the corridor being completely blocked by a heap of rubble. Perring was the first to successfully access the more distant rooms during fall 1839, which enabled him to explore the entire building (Perring (1842), p. 16). Regarding an unlikely earlier exploration of the pyramid by the travellers Melton and Lebrun, readers should refer to Pickavance (1981).

<sup>4</sup> Perring (1842), p. 17; Vyse (1840), p. 69.

Hussein,<sup>5</sup> but he passed away suddenly in 1949 without having had the time to publish the results.<sup>6</sup> An article in the British journal *The Illustrated London News* did, however, provide a brief account of what Hussein was able to achieve.<sup>7</sup> It contained some valuable photographs of the upper chamber when it was still in its original state (fig. 2), as well as a brief survey description:

“The upper chamber when found was filled with hewn stone except for the southern side, which had a passage about 3 ft. wide to a depth of 7 ft. Clearance of the upper part of this chamber revealed that a box-shaped building had been inserted into it. The stone for this structure was smaller than that of the chamber walls, but evidence suggested that a large portion of the masonry of this building was contemporary with the pyramid itself, and that a staircase had originally led from floor-level up to the roof of this building 23 ft. above the floor-level of the main room. Subsequent examination of the roof of this structure has shown that certain paving-stones appear to have been inserted vertically, since they are packed into position by small pieces of stone. Work at present in progress is therefore directed at removing the pavement at this point in an endeavour to find a filled shaft which should lead surely to the burial chamber. (...) The walls of the upper chamber contain cracks which are filled with ancient gypsum. This gypsum is thought to be contemporary with the building. It seems likely that these cracks appeared during the construction of the pyramid, that they were observed and filled with gypsum, and that in consequence the architect decided that the roof of the upper chamber could not support the weight of the upper part of a true pyramid and so altered the outside angle, which had the effect of lessening the eventual weight which the roof had to bear.”<sup>8</sup>

In the article, the author Captain P. A. J. Garnons Williams set out el-Salam Hussein’s plan to find a still intact burial chamber. He thought that the masonry mass filling the lower part of the upper chamber was a sort of box in which the sarcophagus of Sneferu was embedded.<sup>9</sup> The masonry mass was then dismantled in order to test the hypothesis. In the 1950s, Ahmed Fakhry continued the exploration work started by el-Salam. He briefly described the chamber and what he found in these terms:

“The upper chamber was also filled with comparatively small blocks of masonry more or less like those which filled the lower chamber to the height of at least five metres above the floor of the chamber. The dimensions of this chamber are 6.70 ms. north-south and 5.20 ms. east-west and 16.50 ms. in height. The blocks of its ceiling are badly damaged; a great part of it has fallen down and there is always a fear that other parts might fall. However, during the last twelve years no fragments of it have fallen.

A part of the small stone blocks was removed from the chamber by robbers in ancient times in the north eastern part of the chamber, and also in the south eastern corner which looks like a shaft. The ancient treasure hunters tried also to make a tunnelling through this masonry; the cartouche of Sneferu, which is the only occurrence of the name of this king inside the pyramid, is written on one of the blocks which was exposed by the ancient treasure hunters. It is written in red ochre in the quarry and is put upside down. The removal of the stone blocks was no doubt in search of the burial place of Sneferu.

In the year 1946, Abdulsalam began to remove these small blocks in the hope of finding the burial place of Sneferu underneath them. On dismantling the stones in the middle of the chamber, some cedar beams were noticed lying among the masonry. When the stones were removed from most of

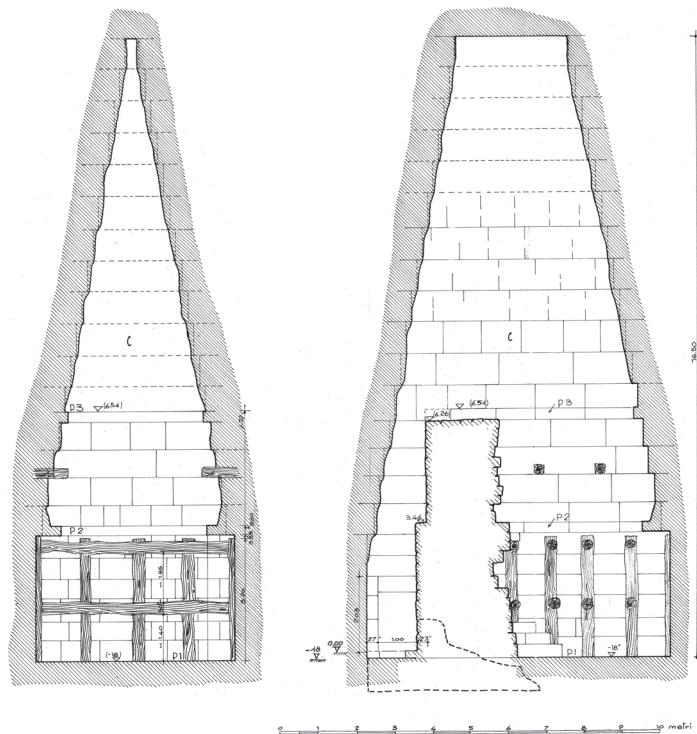
<sup>5</sup> Abd el-Hassam Hussein is then assisted by Alexandre Varille (Varille 1947).

<sup>6</sup> Fakhry (1959), pp. 10-13.

<sup>7</sup> Issue dated 22th march 1947 (Garnons Williams (1947)) and an unsigned article published the 8th April 1947.

<sup>8</sup> Garnons Williams (1947), p. 303.

<sup>9</sup> *Ibidem*.



**Fig. 3.** Section views of the upper chamber of the Bent Pyramid (left: toward the North; right: toward the West) after Maragioglio and Rinaldi (Maragioglio and Rinaldi (1963), tav. 12).

the chamber it was found that beams (halves of tree trunks) of cedar were put against the walls, four of them against each of the eastern and western walls and three against the northern wall and other beams were put on their tops. When all the stone blocks were removed, and the cedar beams stood free their shape resembled a canopy not unlike that of Hetepheres in the general outlines. In the middle of the floor there was found a key-stone which was also removed but no further dismantling was done, as it looked rather hopeless to go down any further. During the four seasons which I spent digging at Dahshur, my work inside the pyramid was limited to the opening of the western entrance only; I did not try to dismantle more stones from any chamber although there were tempting reasons to continue.<sup>10</sup>

Ahmed Fakhry was assisted by the surveyor Hassan Mustapha who made precise measurements of the whole pyramid.<sup>11</sup> Although his published report contains a section drawing of the inside of the monument, it seems that the Egyptian engineer reproduced some values which were already obtained by Fakhry. After underlining the exceptional accuracy of the measurements made by Perring,<sup>12</sup> Mustapha concluded by saying: ‘The interior of this pyramid has been examined but I can never pretend that it has been thoroughly investigated or it does not need more researches in the future’.<sup>13</sup>

10 Fakhry (1959), p. 52.

11 Fakhry (1959), pp. 65-74.

12 In fact, Perring’s measurements and survey were not that precise. In the light of their judgment, I suspect that Fakhry and Mustapha confined themselves to reproducing several of Perring’s measurements without verifying them. That would explain why the upper chamber was so badly described for such a long time.

13 Fakhry (1959), p. 73.

In the early 1960s, Italian architects Vito Maragioglio and Celeste Rinaldi compiled an architectural report with an unprecedented level of attention to detail. Today, it remains an essential resource for research scholars.<sup>14</sup> The pair did not, however, have the material resources to undertake full measurements of the interior spaces. They compiled their dataset by combining the new measures with those from the earlier reports:

‘This chamber is 16.50 m. high (Hassan Mustafa) and 16 overhangs in the four walls form its corbelled roof. The overhangs are very rough and hardly visible. (...)’

At a certain height the southern face of the massif offsets for 27 cm. The passage between the masonry massif and the south wall of the chamber was not empty, but filled up, to a certain extent, with stone blocks. The inner blocks were squared and laid with mortar, the outer blocks were shapeless and laid dry. This filling formed a kind of very steep ramp joining the entrance of the chamber with the upper level of the masonry massif. (...)

Concerning the masonry massif, only a thickness of about 2.50 m remains at the south while it appears from some photographs that originally it was practically untouched. During the dismantling of this massif, the workers took away its [top surface layer] (P3) as well as a kind of floor (P2) laid down in correspondence with the before mentioned offset. Proceeding in their excavation, they reached the floor P1 of the chamber. From some photographs the floor P2 seems to have been built with big limestone slabs and some of them were cut in order to fit each other. The central slabs of P2 were smaller than the peripheric ones, and some of them were really very small. In P1, [still] in the central part, there was an L-shaped block that Fakhry calls a ‘Key-stone’. It was removed but nothing was found underneath. Both floors (P1 and P2) were dressed but not smoothed.

Three holes, some containing beam stumps, were found in each of the east and west walls of the chamber, between P3 and P2. Moreover, a framework of vertical and horizontal beams was found between P2 and P1: the beams are cedar trunks just barked or only roughly hewn. There are three vertical beams along the north wall, four along the east, and three along the west wall, but a fourth one is certainly covered by the remaining masonry. Between the vertical beams placed along the east and the west walls, horizontal beams were inserted at two different heights. The lower beams were placed at about 2.90 m. The walls of the lower part of the chamber where they have been uncovered by the ablation of the massif masonry are very rough, but we were not able to ascertain whether such an aspect was due to rough work or caused by corrosion and stone flaking. The same thing also applies to the overhangs of the corbelled roof of the chamber. Even if they do not present any cracks or yielding due to the superimposed weight, the horizontal edges, which are very sharp and almost intact in the lower chamber, are here damaged to a great extent. In some parts it might even seem that overhangs with sharp and precise corners were not foreseen.<sup>15</sup>

To date, no other missions have been carried out to further enhance the corpus of information about the chambers of this unusual site.<sup>16</sup>

In 2016, Alexander Puchkov and I used recent photographs of the chamber to reveal that it underwent significant changes during and after its construction, and that its current state was the consequence of those modifications.<sup>17</sup> We were able to establish a chronological sequence of events that explained the current state of the room and demonstrated this with the help of new drawn sectional views. These were based on existing plans and reports, in particular those made by

<sup>14</sup> Maragioglio and Rinaldi (1964), pp. 54-122, pls. 8-13.

<sup>15</sup> Maragioglio and Rinaldi (1964), pp. 71-72.

<sup>16</sup> An illustrated description of the interior has recently been published (Haase (2007)).

<sup>17</sup> Monnier and Puchkov (2016), pp. 21-24.

Maragioglio and Rinaldi, but were updated with regard to our new observations. We were, however, missing a method to produce more accurate views, as we found that the existing surveys were not clear with respect to some details and areas, and that further clarification was needed.<sup>18</sup>

In the same year, Gilles Dormion and Jean-Yves Verd'hurt published a book on the Bent Pyramid in which they tried to demonstrate the existence of a secret chamber.<sup>19</sup> We do not agree with their analysis and conclusions,<sup>20</sup> but their study contained interesting information, in particular a reassessment of the height of the upper chamber which they claimed should be 13.90 m high and not 16.50 m, as it was usually described in reports.<sup>21</sup>

These very divergent measurements were one of the reasons we called for a new photogrammetry survey of the chamber so that a true and accurate survey of the space could be produced.<sup>22</sup> The ScanPyramids mission that was launched in 2015 had promised to accomplish such photogrammetric scans for the four biggest pyramids and to put the results online,<sup>23</sup> but that goal was not achieved and a lack of clarity remained.

#### *New architectural survey using photogrammetry*

French film maker and producer François Pomès is director of a series of TV documentaries focusing on the great pyramids. In 2018, he contacted me regarding the architecture of the monuments and expressed his interest in studying and recording them with photogrammetry. The digital imaging project was to be carried out by the French company Iconem, with the agreement of the Egyptian authorities. The goal was to fly cameras suspended from a drone over the structures, at close proximity. As a comprehensive survey was too time consuming, the team members followed my suggestions in order to focus their attention on locations where architectural information with particular value could be gathered. Although it would not utilize the drone, I also directed them to target the upper chamber of the Bent Pyramid, which could be photographed from inside at all angles,<sup>24</sup> providing an accurate architectural survey of the space for the first time.<sup>25</sup>

3D digitisation of archaeological sites has been in use for around 20 years, but its application has typically implied high costs. In the last few years, thanks to photogrammetry, the technique has become simpler, less costly, and as a result it is more widely used. It is now the most effective and cheapest method of carrying out three-dimensional survey of large structures. Implementation consists of accurately locating every point of a three-dimensional object in space, using a large number of detailed photographs that are taken from different angles. The result is a dense point-cloud that recreates a 3D model of the object and includes textural information derived from the external appearance of the object of interest. The method is particularly valuable for describing complex and irregular structures like a cave or a ruined building. It was, therefore, particularly appropriate for the documentation of the upper chamber of the Bent Pyramid, the accessibility and condition of which have always made its description very challenging.

18 Monnier and Puchkov (2017), pp. 60-61.

19 Dormion and Verd'hurt (2016).

20 Monnier (2017b).

21 Dormion and Verd'hurt (2016), p. 157-165.

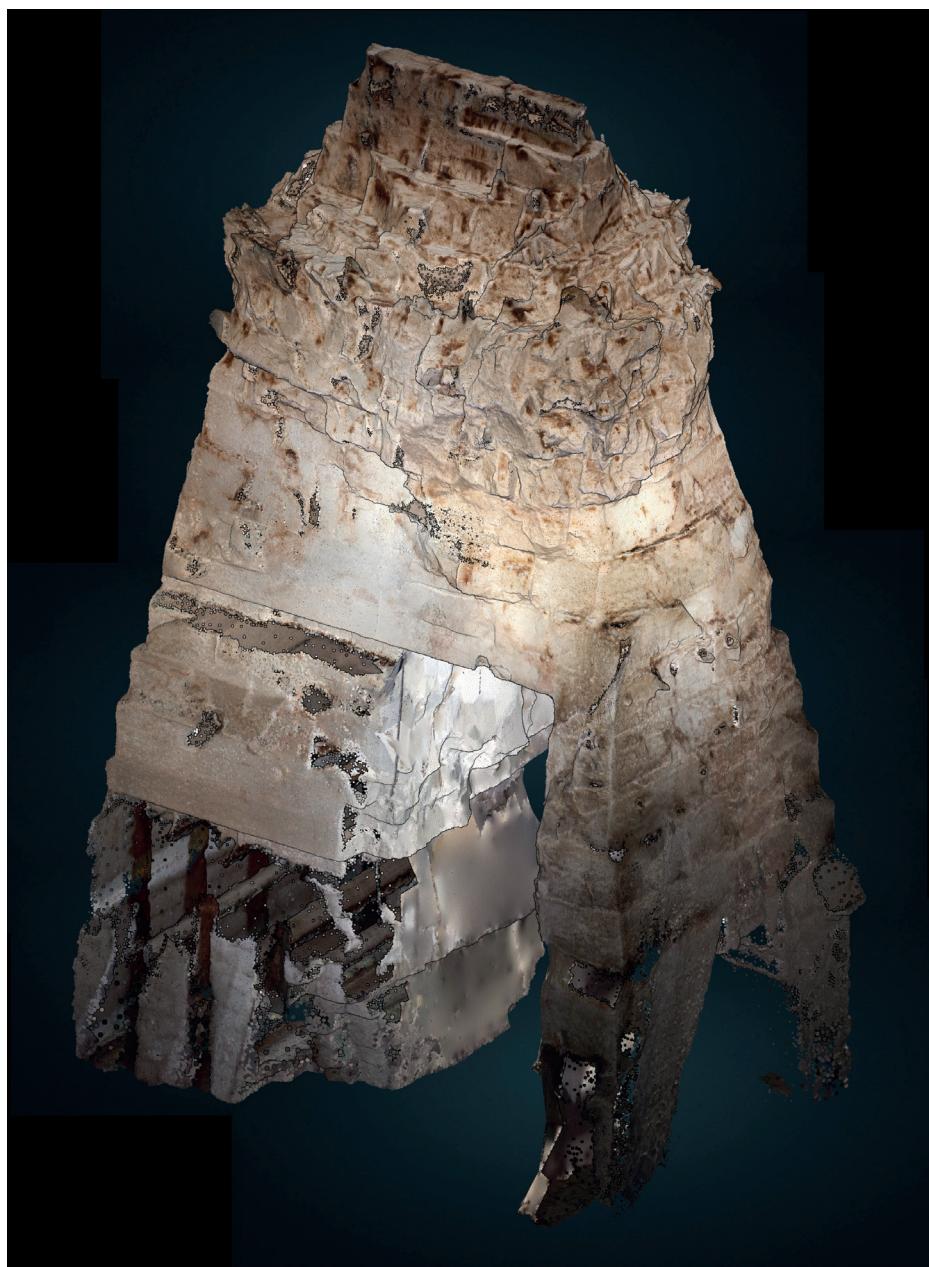
22 Monnier and Puchkov (2017), p. 60.

23 [http://www.scanpyramids.org/assets/components/pyramids/pdfs/About\\_ScanPyramids-fr.pdf](http://www.scanpyramids.org/assets/components/pyramids/pdfs/About_ScanPyramids-fr.pdf).

An overview of the mission's activities from 2015 to 2018 can be found in Monnier and Lightbody (2019), pp. 192-194.

24 It was not possible to safely access the bottom of the room, inside the wooden framework. Photos were shot from the top of the platform.

25 A preliminary presentation of the results was published in *Nile Magazine* (See Monnier (2019)).



**Fig. 4.** 3D digitization of the upper chamber of the Bent Pyramid using photogrammetry.  
General perspective view toward the North-East (© Label News).

Our initial survey of the space showed that it has a complex formation history. It underwent many changes during its construction, but also experienced some damage over time, and partial dismantlement by a succession of archaeologists in the mid-20<sup>th</sup> century (see above). Based on the surveys made by Maragioglio and Rinaldi, the rectangular plan of the chamber is 5.26 meters wide (E-W) by 7.97 meters long (N-W).<sup>26</sup> Due to the difficulty of taking 3D images inside the wooden structure and close to the floor level, we were unable to obtain results with a sufficient precision for checking, correcting, or improving on these values.<sup>27</sup>

26 Maragioglio and Rinaldi (1964), tav. 13.

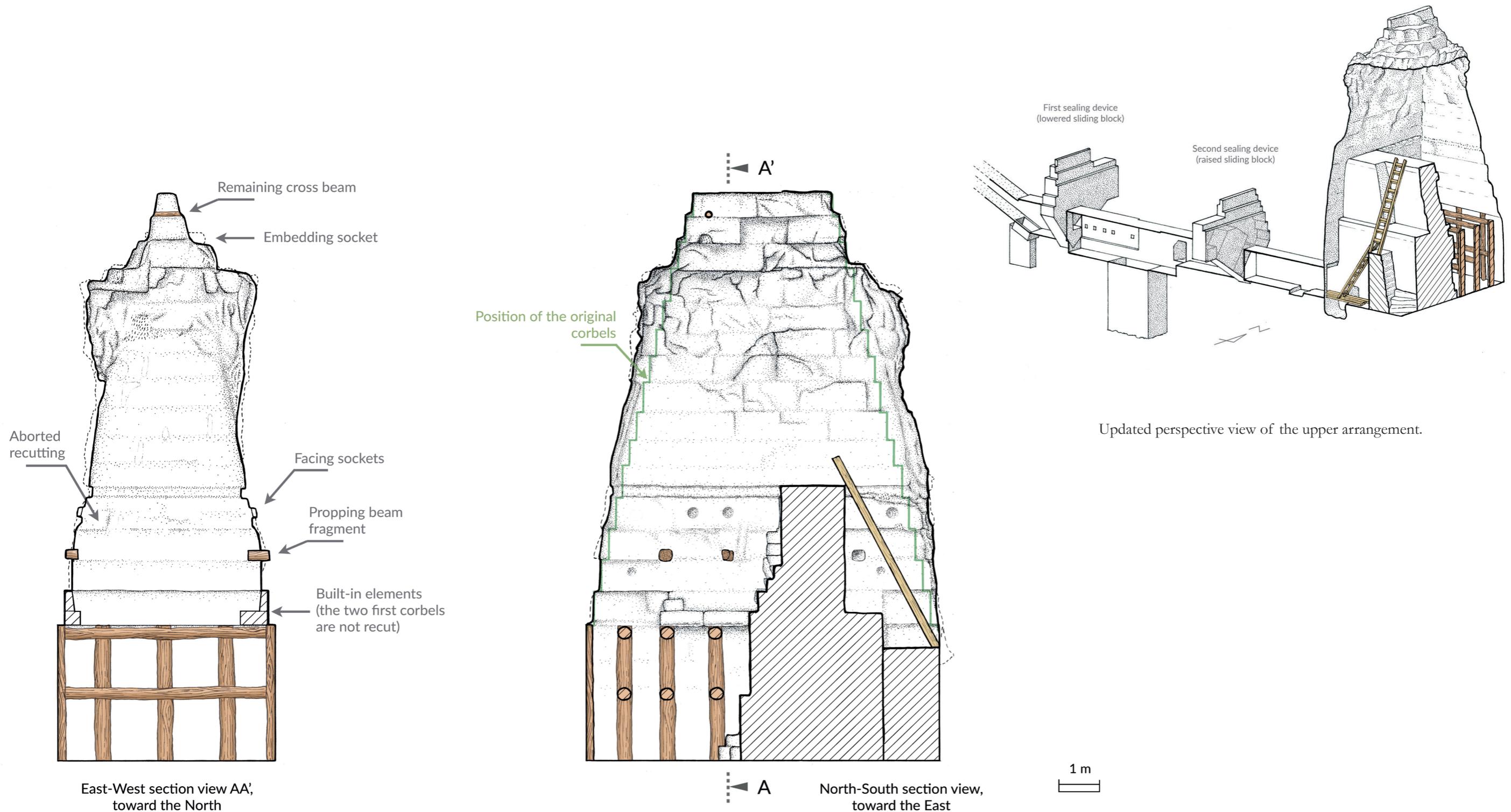
27 It would seem that it is longer than previously estimated.



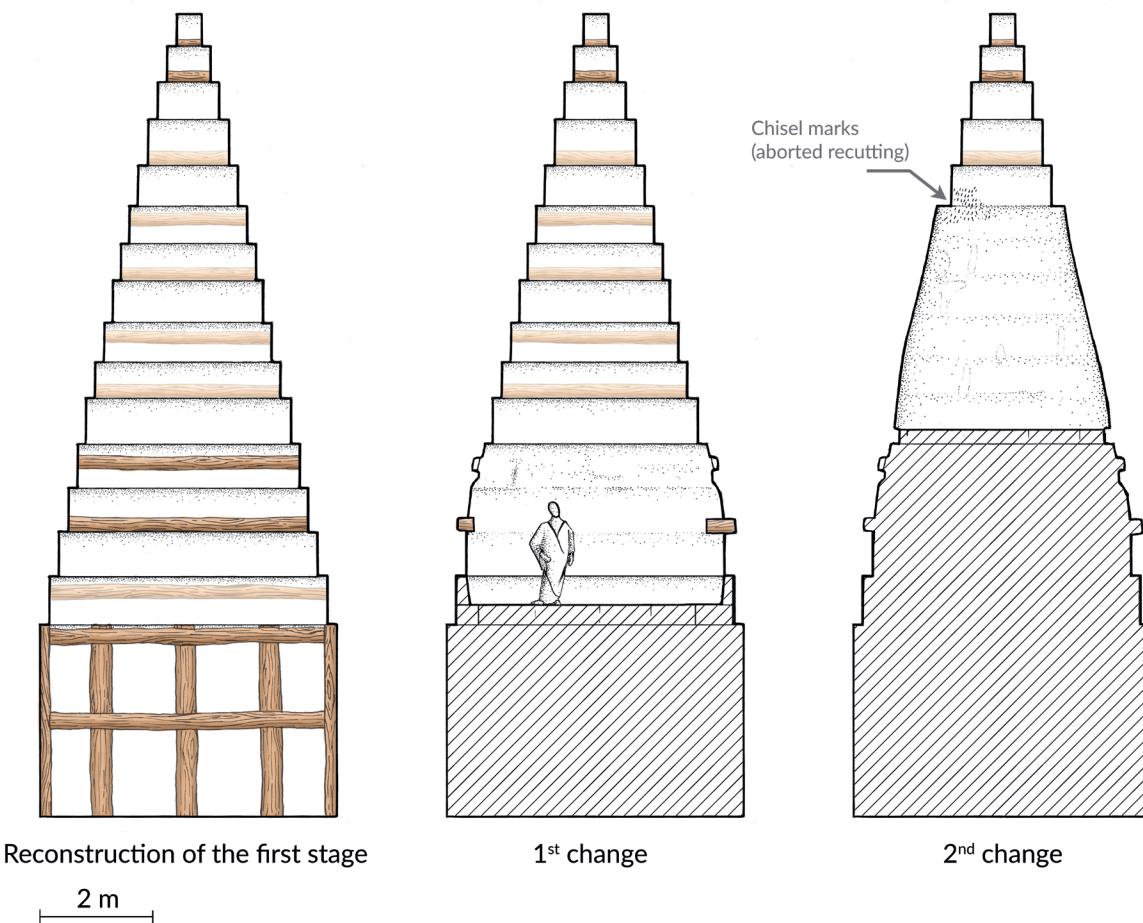
**Fig. 5.** 3D digitization of the upper chamber of the Bent Pyramid using photogrammetry. Perspective view looking toward the top of the vault, North being to the left (© Label News).



**Fig. 6.** 3D digitization of the upper chamber of the Bent Pyramid using photogrammetry. Perspective view looking toward the north wall (© Label News).



**Pl. 1.** Section views of the Upper chamber of the Bent Pyramid at Dahshur. Scale 1:100.  
(Franck Monnier)



**Fig. 7.** Reconstruction of the three construction stages of the upper chamber (section view, toward the North) in the Bent Pyramid according to Franck Monnier and Alexander Puchkov (drawing: Franck Monnier).

The chamber is covered with a high corbelled vault for protecting it from the mass of the pyramid above. According to Fakhry, there were sixteen overhangs and the room was 16.50 meters high.<sup>28</sup> Dormion stated that there were fourteen overhangs and the height was only 13.90 meters.<sup>29</sup>

It is extremely difficult to discern the levels of the overhangs and to assess their overall number on the basis of traditional photography alone, or indeed by *in-situ* observation, but the new 3D scan allowed us to determine with certainty that the number is fifteen, which is the same number as are found in the lower chamber.<sup>30</sup> In addition, the vault rises by around 11 meters, which is another point this space has in common with the lower chamber. The photogrammetry also let us correct the total height of the room to approximately 14 meters (+/- 0.1 m)<sup>31</sup> and not 16.50 meters, thereby confirming the measurement published by Dormion in 2016.<sup>32</sup>

<sup>28</sup> Fakhry (1959), p. 52.

<sup>29</sup> Dormion and Verd'hurt (2016), pp. 157-165.

<sup>30</sup> Maragioglio and Rinaldi (1964), tav. 12.

<sup>31</sup> This range of uncertainty is due to the non-flat shape of the top course and the rough condition of the dismantled floor.

<sup>32</sup> *Ibidem*.

We originally suspected that the stepped recesses of the vault were twice re-cut by the builders up to the ninth corbel.<sup>33</sup> The study confirmed our observations, but showed that the cutting continued even higher, up to the tenth overhang.

After the clearance of approximately three quarters of the masonry filling, Abd el-Salam Hussein revealed the existence of a substantial wooden shoring structure that was entirely hidden in the masonry mass. Two kinds of beams could be distinguished: the vertical ones, which are placed against the western, northern, and eastern walls; and horizontal ones propping up the side posts, which were all aligned along an east-west axis. The ends of the horizontal shoring beams are neither fastened nor embedded in any manner, but are simply held in vice-like compression between the two walls.

The first four overhangs also have a few surviving end fragments of cross beams embedded in the walls, as well as sockets and other traces showing that beams were used in those locations. One of them remains in a higher corbel.

#### *Construction chronology and defect diagnosis*

The wooden framework probably had no other purpose apart from to counteract the lateral thrusts from any wall movements. The kind of thrust it was designed to counter would not have been strains caused by structural failure and it was probably not installed to prevent a structural disaster.<sup>34</sup> It would have been useless for resisting such strains and this frequently mentioned hypothesis should be avoided. According to my studies, the existence of the wooden structure can be explained by the fact that the walls of the room, including the corbelled courses, had to be supported for the few months or years that were required to raise them.<sup>35</sup>

The builders seem to have erected the four walls using carefully cut ashlar masonry set up around the wooden shoring framework. They then laid the more roughly cut stone blocks of the pyramid's core against its exterior sides. The internal bracing would have been used to prevent small sliding movements of wall stones when they were still insufficiently loaded to lock them in place. This method is evidenced at the overhangs, where traces of circular cuts can be seen facing each other, between which wooden propping beams were held in place during the installation of the stone blocks. Other roughly squared logs were deeply embedded at some levels. As these elements are only recorded inside the vault section, it is very likely that they were designed to support platforms on which the workers could carry out the final dressing of the overhangs more easily.

It is, therefore, fundamentally important to differentiate between the different structural elements observed in this room, and to identify their different functions. The shoring of the lower part of the chamber ensured the strength of walls during their construction. The shoring beams associated with the vault stone courses, of which only traces remain on the stones, had the same role. Additional props supported working platforms for carrying out finishing work under the vault. The lower part of the chamber was not furnished with such embedded propping beams.

But why did they bury the temporary wooden structure into the masonry mass installed in the lower volume of the chamber?

In answer to this question, research scholars have often put forward the idea that the surrounding masonry was behaving unpredictably and that the walls experience a bulging that the Egyptians

33 Monnier and Puchkov (2016), pp. 21-24.

34 A frequently expressed view (Edwards (1985), pp. 86-87; Verner (2001), p. 177; Vyse (1842), p. 68).

35 Monnier (2017a), p. 92.

had to counteract by filling the room with masonry.<sup>36</sup> In this scenario the wooden framework would have been a prelude to more drastic measures that eventually culminated in the permanent abandonment of the space.

There are a number of arguments against this point of view. First, almost the entire support structure was dismantled, so no significant failure or settlement in the upper chamber had occurred by the time the removal was halted. Second, any lateral thrusts would not have been restricted to the lower half of the chamber, but to the whole volume. If the motive of the builders was to strengthen the chamber by filling it with masonry then they should have filled the entire volume (if that was their motivation then the whole structure was in danger of collapsing), but that was not the case.

During our study we noticed additional details of crucial importance that led us to understand the real intentions of the builders.<sup>37</sup> Italian architects Maragioglio and Rinaldi had previously identified two construction phases that led to the creation of the masonry mass.<sup>38</sup> First, the floor was raised to a height of 3.46 meters and paved over with well-dressed stone slabs (fig. 3). We were able to establish that great care was taken to conceal the first overhang during this work. A row of thin stone blocks was inserted under the edge formed by the recess, and the next three overhangs above it were re-cut. The adjustments are very clear, as many chisel marks are still visible in several locations on the walls. The result was the flattening of the first stone courses of the vault, and as a consequence the vertical height of the side walls was increased. The stones on the south side of the mass were carefully laid and dressed so as to let a passage extend out into the horizontal access corridor. When the evidence is taken together, it is clear that the purpose of the exercise was not to avoid a disaster but to raise the level of the floor up by more than 3 meters. The chamber could, therefore, continue to be used as a burial place. This phase of work occurred before the removal of the remaining shoring devices, and therefore took place during an early stage of the construction.

Modifications did not stop there. In a second phase of activity, the builders decided to elevate the floor once again by doubling the height of the existing mass. Again, it was covered with limestone paving slabs, and the builders re-cut five overhangs so as to give a homogeneous and smooth appearance to the side walls. One of the recesses was partially cut in order to be integrated into the new and definitive floor (the current ‘cornice’).

In order to reach the top of the platform, a temporary staircase was built with very rough stones, This filled the southern part of the room and it was still there before the first excavations began in 1947. Its presence apparently required the entrance passage’s roof to slope up, probably to facilitate the passage of the funeral procession and its bulky funerary furniture.

Abd el-Salam Hussein photographed the space before searching for the hypothetical buried sarcophagus. One of his photos shows a mound of rubble and stone fragments that had fallen from the upper part of the vault onto the floor. The clay-seamed nature of the limestone made it susceptible to significant levels of fragmentation. A full engineering material study remains to be done, but the state of the materials and the structure allow me to share some initial thoughts about its design and construction.

The overhanging inside corners of such a corbelled vault are subjected to shearing stresses whose magnitude depends on the depth of the overhangs. The degradation that is visible, which may have begun to appear as early as during Snefru’s reign, would gradually have increased in severity, and this

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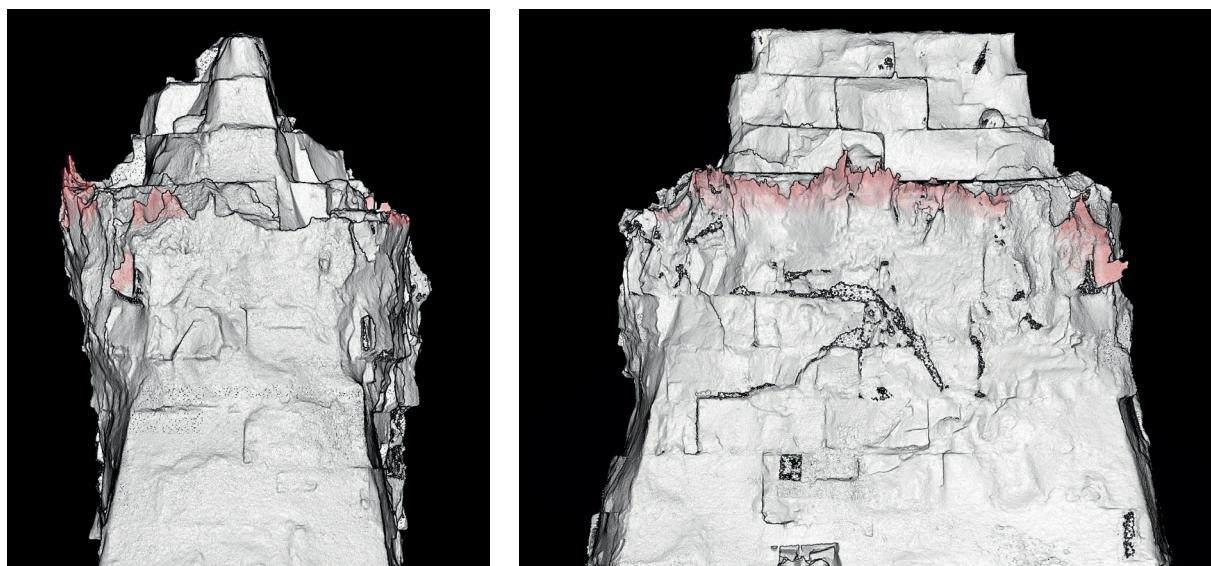
<sup>36</sup> See note 32.

<sup>37</sup> Monnier and Puchkov (2016), pp. 21-24.

<sup>38</sup> Maragioglio and Rinaldi (1964), pp. 70-72.

could have been accelerated by the reshaping of the recesses. Moreover, visible repairs carried out with gypsum mortar show that the stones responded badly to the recut. Photographs clearly show two distinct areas on the surface covering: flattened overhangs and more seriously damaged ones. Smooth surfaces that were not subjected to localised stresses remain in much better shape, however, they also suffered more minor losses. That could be due to the particular nature of the stone.

It seems that the limestone blocks exhibit fracturing perpendicular to their upper/lower surfaces and that this is almost certainly the result of something inherent in the rock from before it was quarried. When initially extracted, these fractures were closed or sealed and so presented no problem for the builders. A rock under a load will, however, expand over time (due to stress release) in the direction of an unconfined surface, and this would have happened to the limestone blocks lining the vault. As those blocks expanded, the formerly closed fractures opened up with the result that very fine chips, flakes, or other pieces of the blocks spall off. This same phenomenon is commonly seen in the bedrock walls of underground mines and deep road cuttings.<sup>39</sup>



**Fig. 8.** Highlighting of opened fissures (in red) in the twelfth corbel (left: view toward the South; right: toward the West) (© Label News).

The lower side of the eleventh overhang was enlarged by the recut of the lower recess. It is likely that this significant cantilevered section eventually broke, resulting in a heterogeneous diffusion of stresses that was dependent on the form of the modifications made to the structure. Over time, a natural vault effect occurred. For that reason, the peak within the stone roofing now looks like a natural grotto or cave.

In terms of an architectural pathology, photogrammetry allowed me to identify the existence of opened fissures and other breaks in the stone under the uppermost, well-shaped, corbels (fig. 8). The overhang of the twelfth one, which is particularly large, exposes these overhang blocks to more cracking, and large fragments could fall down. It is impossible to estimate when this might occur, but the risk is real.

This photogrammetry survey thus led us to significantly update the body of knowledge currently available regarding the upper chamber of the Bent Pyramid. Although it is the central element

<sup>39</sup> I am extremely grateful to geologists James A. Harrell and Stuart L. Dean for sharing their reflections about this with me.

of the monumental building, it was previously understood quite superficially. I hope that these results will encourage the authorities to grant permission for the launch of a more complex photogrammetry project and the establishment of a team able to undertake a comprehensive survey of the monument. This would culminate in the publication of a fully accurate architectural report in accordance with modern archaeological requirements.

## The upper chamber of the Red Pyramid

### *Early descriptions*

Little attention was paid to the funerary chamber system within the Red Pyramid after its initial exploration, which was carried out at the beginning of the 19<sup>th</sup> century by John Shae Perring. He gave this brief description:

'The third chamber is 27 feet 3 ½ inches (8.30 m) long from east to west, and 13 feet 7 ½ inches (4.14 m) wide from north to south. The sides are perpendicular for 12 feet 1 inch (3.68 m), after which fourteen courses project inwards, as in the other apartment ; and the total height from the original floor to the ceiling, is 48 feet 1 inch (14.62 m).'<sup>40</sup>

In the mid-20<sup>th</sup> century, a scientific study of the Red Pyramid was planned by Abd el-Salam Hussein and Ahmed Fakhry, but neither of them published a report of their work. In the 1960s, Vito Maragioglio and Celeste Rinaldi produced the most detailed architectural report of the monument to date.<sup>41</sup> It currently represents the main reference source for those who want to study the Red Pyramid's architecture and chamber layouts. Their dataset was fairly standard in format and no more surveys have been undertaken since then, which could provide more information about the inner chamber and passage arrangements.<sup>42</sup> The burial chamber was described using these words:

'Our measurements, except for a few centimeters, confirm Perring's. The main axis of the crypt is in an E-W direction and thus at right angles to those of the preceding chambers. The north and south walls are vertical for about 3.70 m. and then there are 14 courses which form a corbelled vault.'<sup>43</sup>

From my own observations, I suspect that the Italian architects partially reproduced Perring's survey, especially with regard to the upper chamber, without having taken the time to verify them.

### *Towards an updated description*

An analysis of photographs I took in 2012 indicated that there were inaccuracies in the existing reports. Some shots showed that the number of corbels was not 14, but 13. As I was not able to make new measurements *in-situ* to check this detail, I could not yet properly support a proposal to update the reports. The photogrammetry survey carried out in fall 2018, however, has allowed me to confirm my preliminary observations, but also to draw new sectional views of the chamber. Not only was the number of corbels wrong until now, but the height of the room was also inaccurate. It is not 14.67 meters high,<sup>44</sup> but around 13.68 meters high. This is an error in excess of one meter, and similar to the level of error that I had already detected in the Bent Pyramid's survey.

40 Perring (1842), p. 16.

41 Maragioglio and Rinaldi (1964).

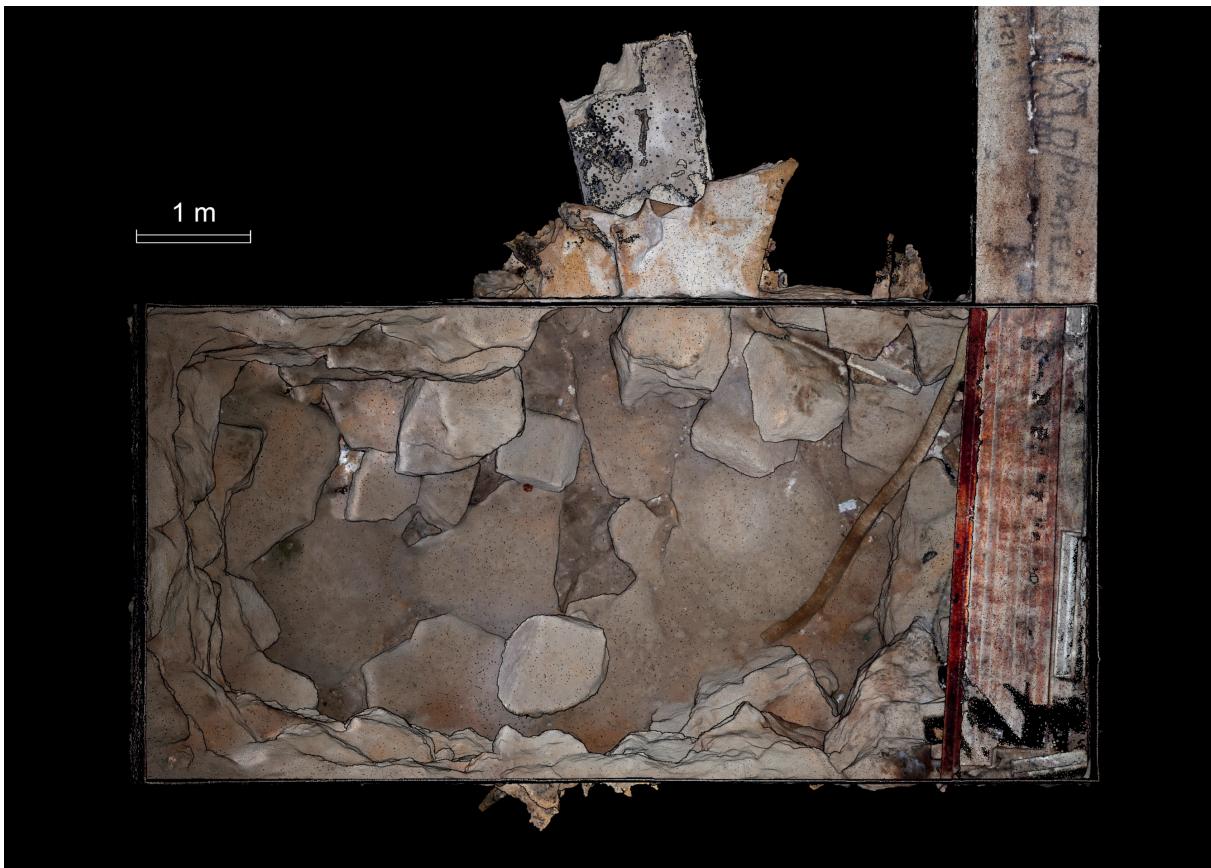
42 An illustrated description of the interior has recently been published (Haase (2019)).

43 Maragioglio and Rinaldi (1964), pp.130-132.

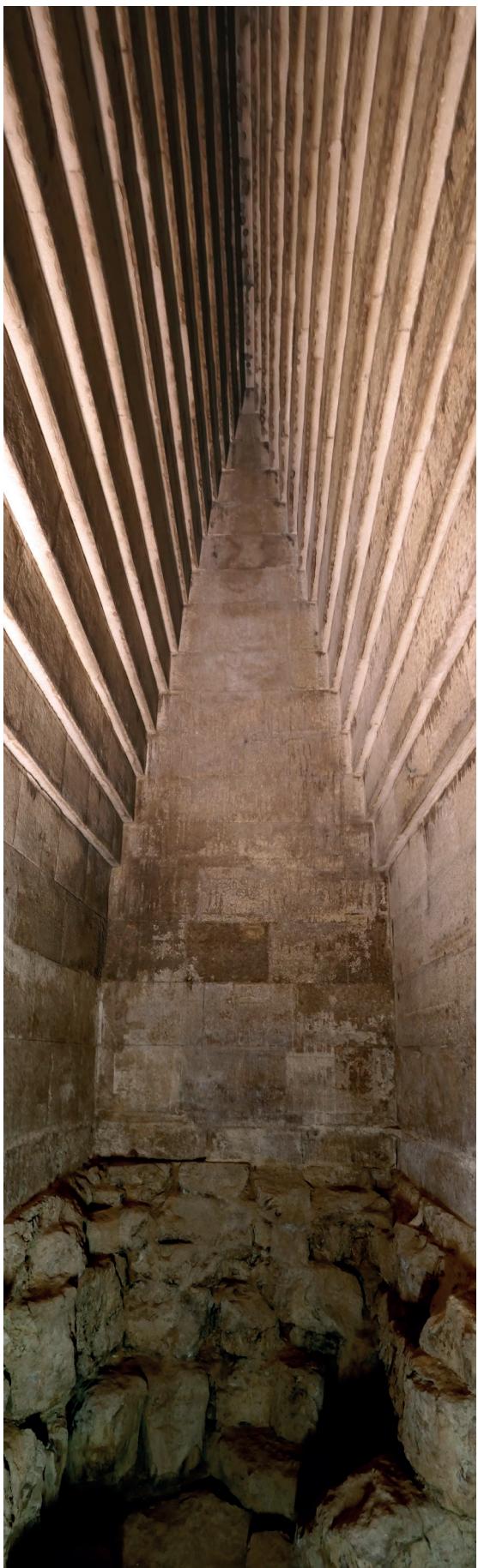
44 Maragioglio and Rinaldi (1964), tav. 19.



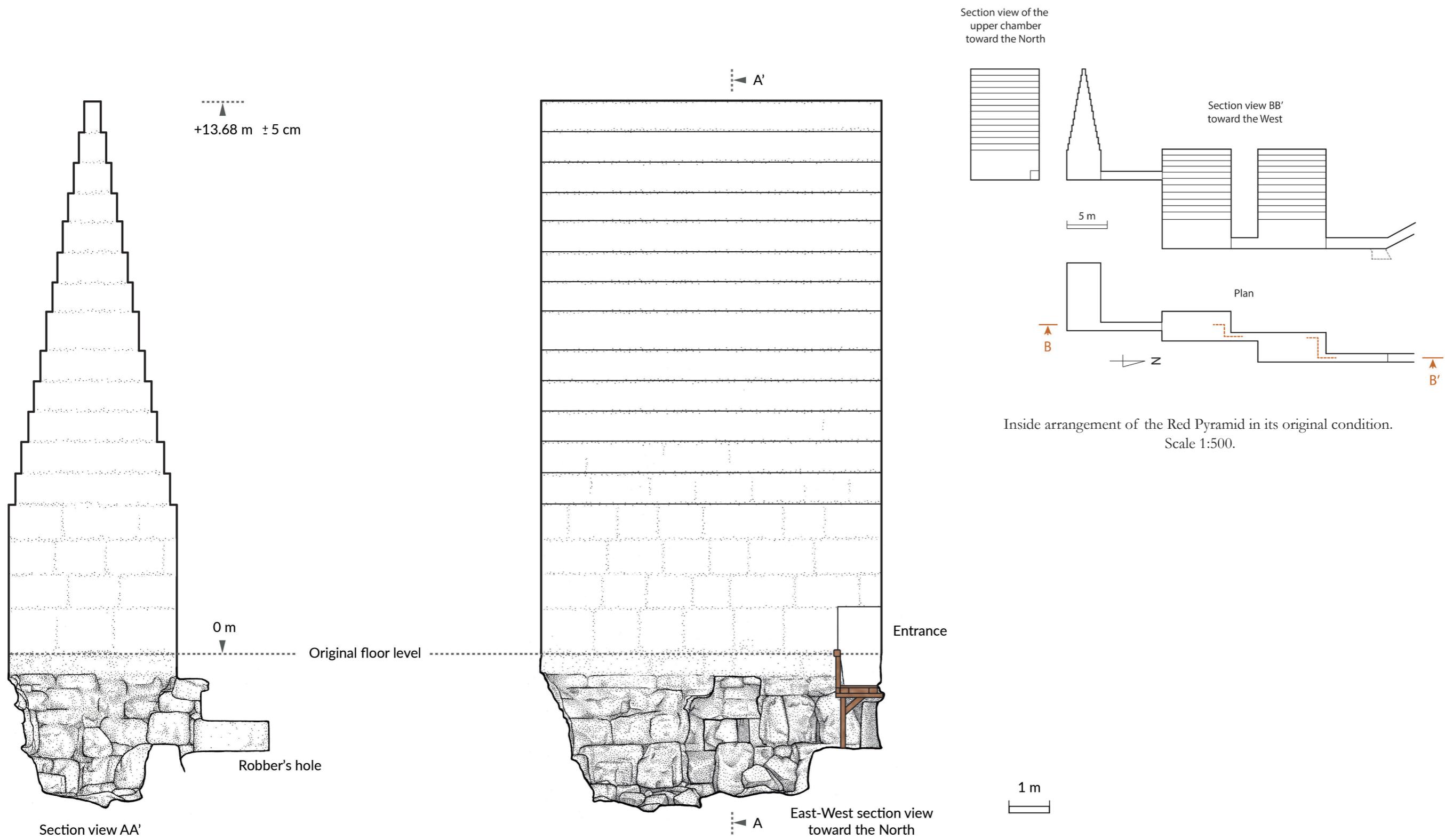
**Fig. 9.** 3D digitization of the upper chamber of the Red Pyramid using photogrammetry. General perspective view toward the South-East (© Label News).



**Fig. 10.** 3D digitization of the upper chamber of the Red Pyramid using photogrammetry. Upper view of the excavation, North being at the top (© Label News).



**Fig. 11.** View of the upper chamber of the Red Pyramid toward the west.  
(photo: Franck Monnier)



Inside arrangement of the Red Pyramid in its original condition.  
Scale 1:500.

Pl. 2. Section drawings of the upper chamber of the Red Pyramid at Dahshur. Scale 1:100.  
(Franck Monnier)

For the first time, the excavation made by looters in Antiquity into the floor of the room is published with a great accuracy. Explorers from ancient times also dug the beginnings of a tunnel into the northern wall. I don't venture an explanation for why they suspected the existence of a room or a passage in that direction, but in any event, they quickly abandoned the attempt.

The newly established photogrammetry survey of the Red Pyramid, with its detailed section and plan views, clearly shows the effectiveness of this imaging method.

## Conclusion

Both of these projects at Dahshur have demonstrated the effectiveness of the photogrammetry imaging method. It is economical, accurate, and rapid. The argument for undertaking a more comprehensive survey of the entire inner chamber system is now clear. This would allow us to record the state of the monuments in order to manage their structural conditions as they develop over time. It would also allow us to draw a complete set of accurate plans and provide a comprehensive description of the pyramids for the first time. The technology is now available to produce survey reports that can do justice to these extraordinary monuments.

## Bibliography

- Dormion, G. and Verd'hurt, J.-Y. (2016), *La chambre de Snéfrou*, Actes Sud.
- Edwards, I.E.S., (1985), *The Pyramids of Egypt* (revised edition, first published in 1947), Harmondsworth.
- Fakhry, A. (1959), *The Monuments of Sneferu at Dahshûr, I, The Bent Pyramid*, Cairo: General Organization for Government Printing Offices.
- Garnons Williams, P. A. L. (1947), 'In the Heart of a Dahshur Pyramid: Recent Investigations which may lead to the Discovery of an Intact Royal Tomb', *The Illustrated London News*, March 22, 1947, p. 305.
- Haase, Michael (2007), 'Im Inneren der Knick-Pyramide', *Sokar* 14, pp. 12-19.
- Haase, Michael (2019), 'Snofrus letzte Ruhestätte. Das Kammersystem der Roten Pyramide in Dahschur', *Sokar* 37, pp. 6-29.
- Maragioglio, V. and Rinaldi, C. (1964), *L'Architettura delle piramidi Menfite. Parte III, Il Complesso di Meydum, la piramide a Doppia Pendenza e la piramide Settentrionale in Pietra di Dahschur*, Rapallo.
- Monnier, F. (2017a), *L'ère des géants. Une description détaillée des grandes pyramides d'Égypte*, Paris: De Boccard, 2017.
- Monnier, F. (2017b), Compte-rendu de Gilles Dormion et Jean-Yves Verd'hurt, *La chambre de Snéfrou*, Actes Sud, 2016, *JAEA* 2, pp. 83-89.
- Monnier, F. (2019), 'New light on the architecture of the Bent Pyramid', *Nile Magazine* 20, pp. 44-50.
- Monnier, F. and Lightbody, D. I. (2019), *The Great Pyramid. Operations Manual*, Sparkford/Yeovil: Haynes Publishing.
- Monnier, F. and Puchkov, A. (2016), 'The building progress of the Bent Pyramid at Dahshur. A reassessment', *ENiM* 9, pp. 15-36.
- Monnier, F. and Puchkov, A. (2017), 'Enquête dans la pyramide rhomboïdale. Une curieuse chambre funéraire', *Pharaon Magazine* 28, pp. 59-64.
- Nuzzolo, M. (2015), 'The Bent Pyramid of Snefru at Dahshur. A project failure or an intentional architectural framework?', *SAK* 44, pp. 259-282.
- Perring, J. S., (1842), *The Pyramids of Gizeh, III, The Pyramids to the southward of Gizeh and at Abou Roasch*, London: James Fraser and John Weale.
- Pickavance, K. M. (1981), 'Pyramids of Snofru at Dahshûr: Three Seventeenth-Century Travellers', *JEA* 67, pp. 136-142.
- Varille, A. (1947), *À propos des pyramides de Snéfrou*, Cairo.
- Verner, M. (2001), *The Pyramids, their archaeology and history*, New York: Atlantic Books.
- Vyse, R. W. H. (1842), *Operations carried on at the Pyramids of Gizeh in 1837: with an account of a voyage into Upper Egypt, and an Appendix, III, Appendix containing a Survey by J. S. Perring of the Pyramids at Abou Roash, and to the southward, including those in the Faiyoum*, London: James Fraser.



## An animal embalming complex at Saqqara

Tatjana Beuthe

### *Abstract:*

*This paper is a new examination of the original find context of the Saqqara lion tables (CG 1321–2) in ‘Gallery C’, an underground structure in the Step Pyramid complex. The substructure may date to the 1st millennium BCE, and this structure was likely part of an embalming complex for the Apis or other sacred animals. The adjacent Western Galleries were probably re-used during this period as an animal necropolis.*

This paper aims to shed new light on later ritual activity at the site of Saqqara by re-examining archaeological material and architectural evidence from a comparatively unscrutinised underground complex. In the late 1800s, Mariette’s workmen uncovered an unusual rock-cut substructure located in the north court of the Step Pyramid complex at Saqqara.<sup>1</sup> The substructure contains nine side chambers to the west of the central north-south gallery, and four entry staircases to the east of the central gallery, as shown in fig. 1. The substructure was labelled ‘C’ on a map of the complex drawn by Lauer (fig. 2), and will be referred to here as ‘Gallery C’.

Numerous artefacts were found at the end of the northmost side chamber in Gallery C.<sup>2</sup> This chamber was labelled ‘A’ by Mariette, and lies directly opposite an entry staircase, as shown in fig. 1. The objects discovered in the chamber consisted of two lion-headed travertine<sup>3</sup> embalming tables or beds, now classified as CG 1321–2 in the Cairo Museum (see figs. 3 and 4), one block of limestone, bones found resting on the limestone block, two travertine<sup>4</sup> ‘paving stones’, and pottery vessels containing ‘black earth’.<sup>5</sup> Fig. 5 reconstructs the *in situ* positions of the artefacts, based on Mariette’s description.

In the early twentieth century, Borchardt<sup>6</sup> suggested that the lion-headed tables were placed in Gallery C following the destruction of a 2<sup>nd</sup> Dynasty royal monument that was razed to make way for the Step Pyramid complex in the 3<sup>rd</sup> Dynasty. Present day scholars tend to follow this interpretation and date the lion tables, and by extension Gallery C, to the 3<sup>rd</sup> millennium BCE Early Dynastic period.<sup>7</sup> However, evidence suggests that both Gallery C and the lion-headed tables were created approximately two thousand years later, in the 1<sup>st</sup> millennium BCE.

1 Mariette (1889), pp. 83–86.

2 Mariette (1889), p. 85.

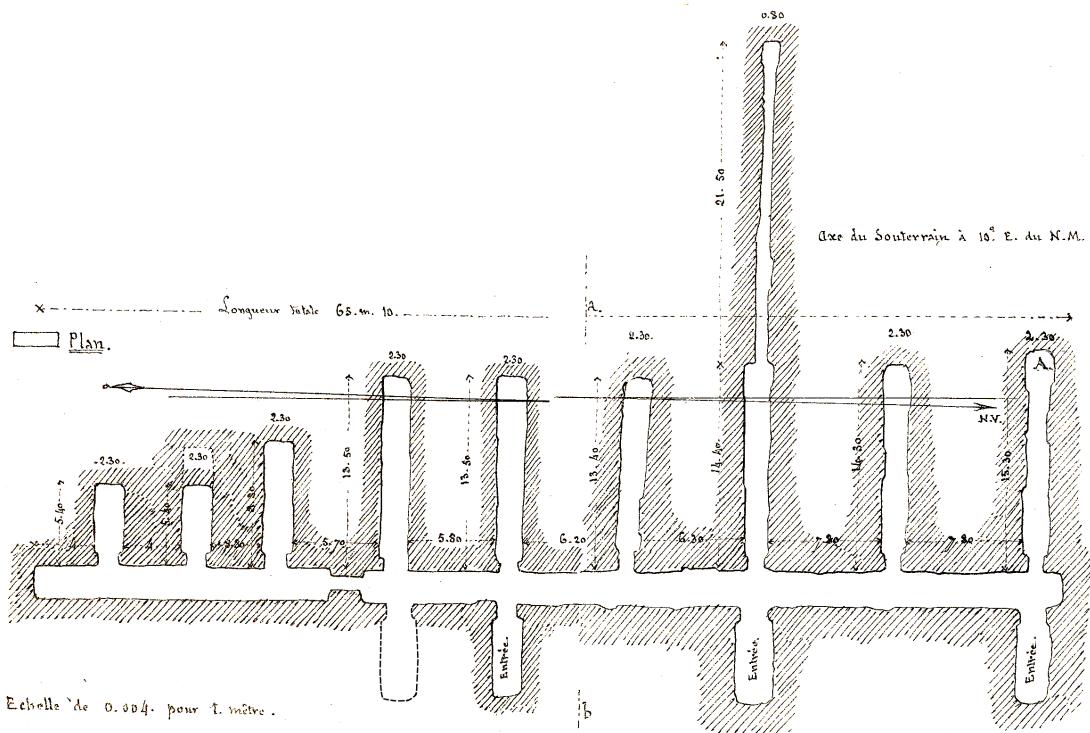
3 Identification based on Aston et al. (2003), pp. 21–22, 59–60. Previous sources refer to the tables using the terms ‘alabaster’ or ‘calcite’. However, in accordance with Aston et al. (2003), pp. 21–2, 59–60, the stone of the tables is referred to here as ‘travertine’.

4 Aston et al. (2003), pp. 21–22, 59–60.

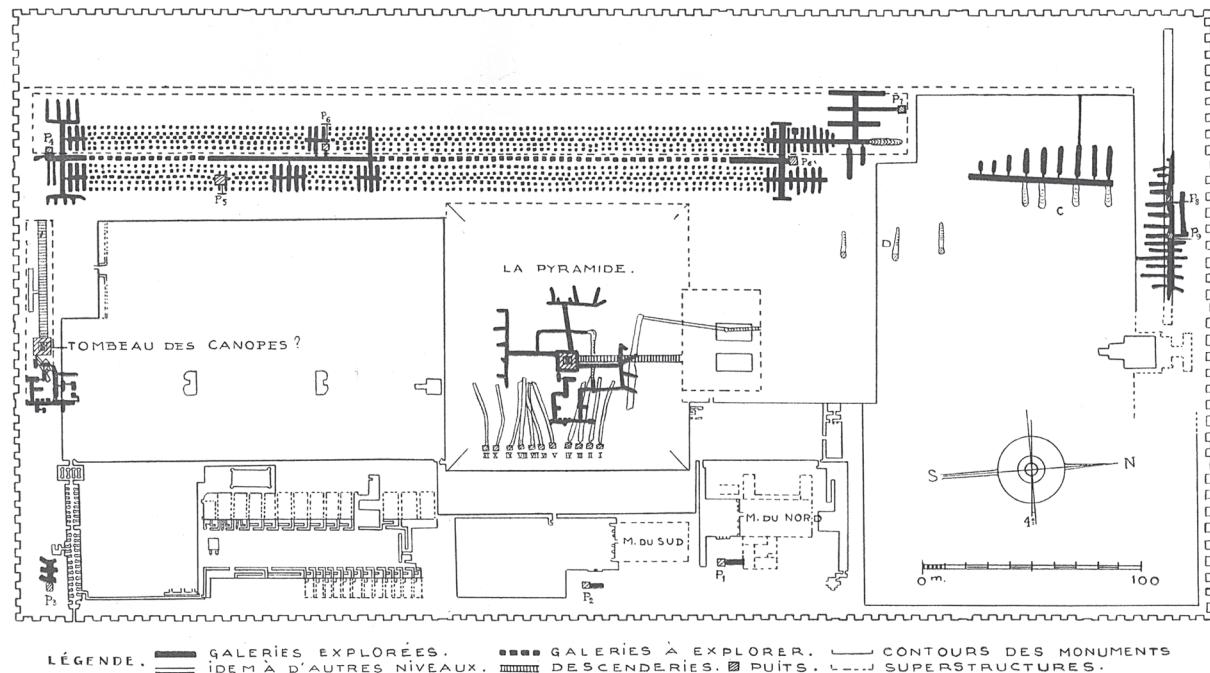
5 Mariette (1889), pp. 85–86.

6 Firth and Quibell (1935), p. 77.

7 El-Shahawy, Atiya (2005), pp. 62–63; Reader (2017), p. 81.



**Fig. 1.** Plan of Gallery C. Entryway drawn with dotted line indicates location of entry staircase not depicted on Mariette's original plan. Rightmost chamber 'A' was the apparent find location of the two lion tables and other artefacts discussed in this article. North is to the right.  
 (modified from Mariette (1889), pp. 84-85).



**Fig. 2.** Map of Step Pyramid complex. Gallery C is located in the top right of the diagram. The long Western Galleries are located to the left of Gallery C (from Lauer (1939), pl. XXII).

Lauer remarks that the four entry stairways of Gallery C did not exhibit portcullis emplacements, a common feature of entry stairways for tombs of the 2<sup>nd</sup> and 3<sup>rd</sup> Dynasties. He also notes that the orientation of Gallery C does not match the general orientation of Djoser's 3rd Dynasty structures in the complex.<sup>8</sup> Consequently, Gallery C likely dates to a later period than the Step Pyramid complex in which it is located. Finally, Lauer notes the uncommon presence of four parallel entry stairways in Gallery C.<sup>9</sup> Such a feature does not appear to be attested in any other Egyptian substructure of mortuary or ritual nature.<sup>10</sup>

Examining comparanda for the Saqqara lion tables provides further evidence that Gallery C postdates the Djoser complex. The earliest well-dated example of a lion table is the 18th Dynasty travertine table from the royal tomb of Horemheb (KV57).<sup>11</sup> However, evidence from Memphis indicates the Saqqara tables were created much later. Three lion-headed embalming tables made of travertine<sup>12</sup> and similar in shape to those found at Saqqara<sup>13</sup> were uncovered in a built structure likely employed to embalm Apis bulls at Memphis. This precinct was in use from the 25th Dynasty to the Roman period.<sup>14</sup> In 1982, excavators of the Memphite precinct noted the travertine tables from nearby Saqqara as comparanda for the Memphis artefacts.<sup>15</sup>

Other finds at the Memphite embalming complex also parallel those made by Mariette's team at Saqqara. Two travertine 'paving stones' found lying adjacent to one another in Gallery C are comparable to the two travertine paving stones deposited in a similar fashion at the Memphite embalming precinct.<sup>16</sup>

A jar uncovered in the Memphite embalming precinct was found to contain embalming residue.<sup>17</sup> Vessels from a more recently excavated embalming deposit in Luxor were described as containing 'bitumen residue and a brown-black substance'.<sup>18</sup> Consequently, the pottery vessels said to contain 'black earth'<sup>19</sup> from Saqqara Gallery C may also have been embalming residue jars.

'Table 1', a limestone embalming bed from the Memphite precinct,<sup>20</sup> was found with a packet of ox bones lying on it.<sup>21</sup> The limestone block from Gallery C also had bones lying on its surface (see fig. 5) and can thus be identified as an embalming bed. Mariette stated the skeletal remains found in Gallery C were human. However, he refers to his find as 'a few bones', and makes no reference to pelvic bones or a human cranium.<sup>22</sup> Consequently, Mariette's evaluation of the remains is doubtful, and the bones found placed on the limestone embalming bed could also have been those of an ox or another large animal.

Given the similarity of the material found in Saqqara Gallery C and the Memphite embalming precinct of the Apis, a reinterpretation of the function of Gallery C is now possible. The material found in Saqqara Gallery C is likely an embalming deposit, possibly related to the Apis bull or other sacred animals, and dated to a much later period than the original 3<sup>rd</sup> Dynasty precinct of Djoser.

<sup>8</sup> Lauer (1939), p. 39.

<sup>9</sup> Lauer (1939), p. 39.

<sup>10</sup> Dodson and Ikram (2008).

<sup>11</sup> Davis *et al.* (1912), pl. LXXVIII.

<sup>12</sup> See Footnote 3.

<sup>13</sup> Jones and Jones (1982), p. 54 (n. 8).

<sup>14</sup> Jones (1990), pp. 142, 144, 147.

<sup>15</sup> Jones and Jones (1982), p. 54 (n. 8).

<sup>16</sup> El Amir (1948), p. 52.

<sup>17</sup> El Amir (1948), pp. 52, 56.

<sup>18</sup> Bietak and Reiser-Haslauer (1982), p. 186.

<sup>19</sup> Mariette (1889), p. 86.

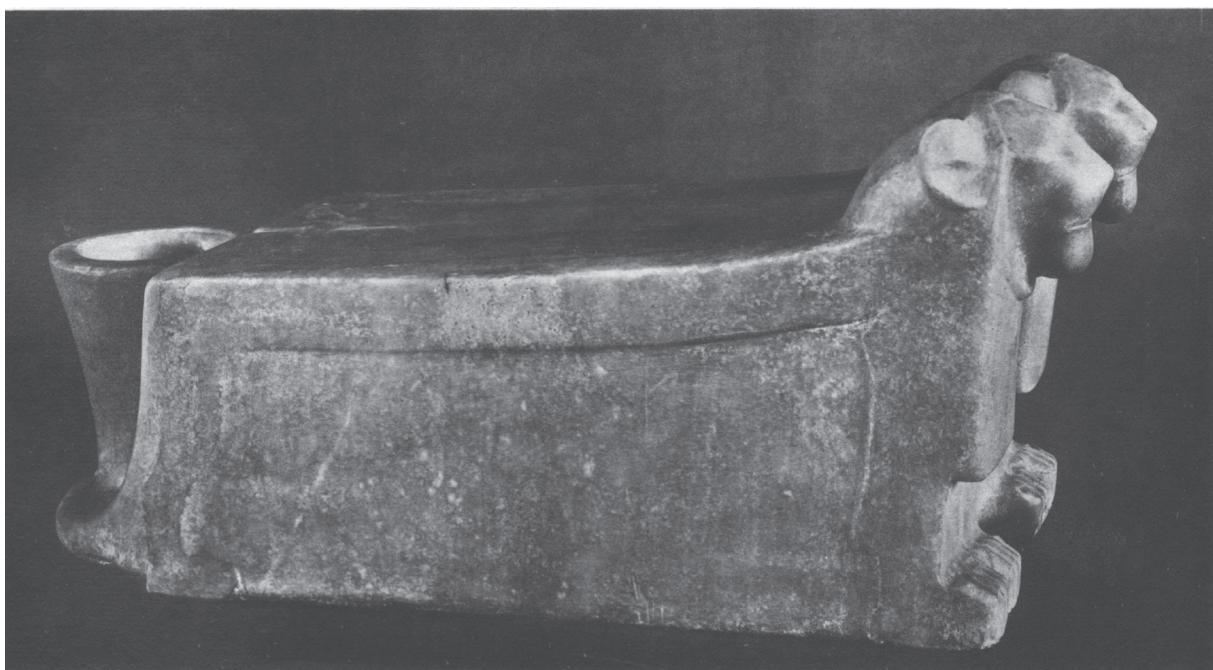
<sup>20</sup> Jones and Jones (1982), pl. XIV.B.

<sup>21</sup> El Amir (1948), p. 52, pl. XVI.5.

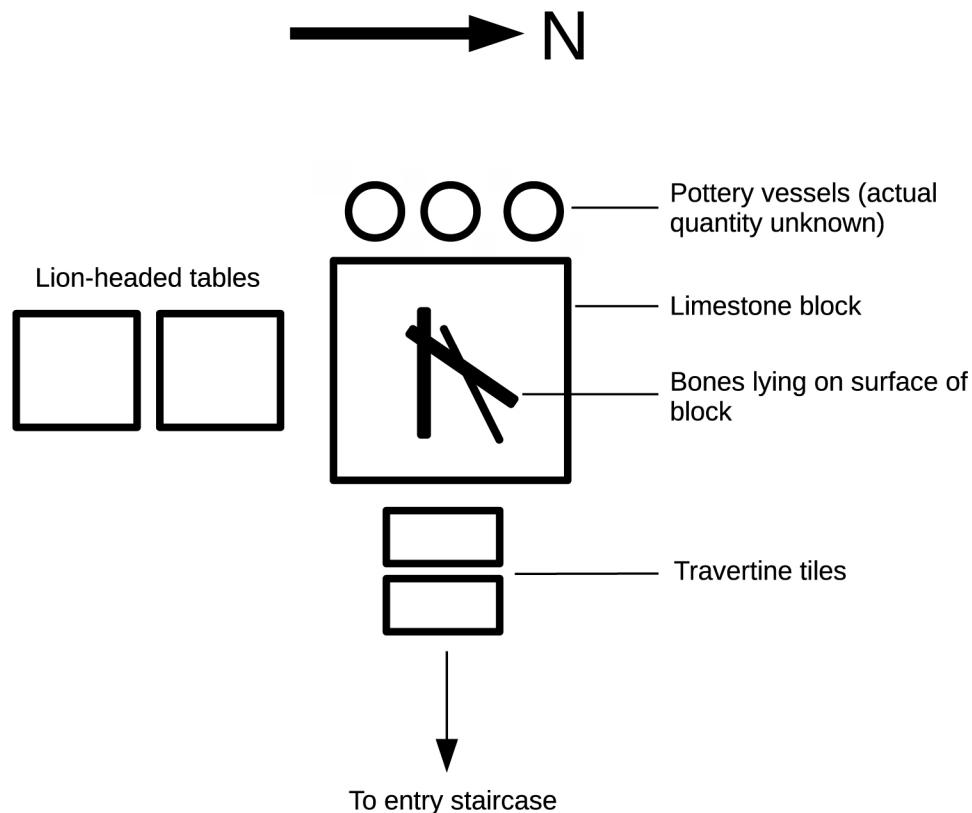
<sup>22</sup> Mariette (1889), p. 85.



**Fig. 3.** The first Saqqara table, now CG 1321 in Cairo (from Borchardt (1937), pl. 3).



**Fig. 4.** The second Saqqara table, now CG 1322 in Cairo (from Borchardt (1937), pl. 3).



**Fig. 5.** Reconstruction of in situ positions of the artefacts as found in Gallery C, Saqqara, interpreted from Mariette's description (drawing by T. Beuthe).

Bones found in both Gallery C and Memphis may be remnants of the embalming process, since intact Apis burials were not found to contain articulated mummies, but only packages of bones.<sup>23</sup>

At only 7 meters deep, the corridor and chambers of Gallery C are relatively shallow excavations.<sup>24</sup> The special layout of Gallery C was apparently designed for relative ease of accessibility, and embalming material was present in at least one of its corridors. Consequently, Gallery C likely represents an example of an underground component of a Saqqara embalming complex, whose superstructure remains unexcavated. The existence of such a superstructure can be surmised from a recently uncovered 26th Dynasty embalming complex at Saqqara. This complex consists of a superstructure and a shaft leading to an underground embalmers' installation.<sup>25</sup>

The general resemblance of many artefacts found in Gallery C to objects from the Memphite embalming precinct provides an indication that the Saqqara complex may have been in use prior to the establishment of the Memphite embalming complex in the 25th Dynasty. Three out of the four staircase entrances to Gallery C were found to be backfilled with rocks and sand when first uncovered by Mariette's team.<sup>26</sup> Consequently, the gallery entrances may have been deliberately backfilled after the embalming complex was abandoned.<sup>27</sup> A similar backfill of rocks and sand was

<sup>23</sup> Dodson (1999), pp. 63–64.

<sup>24</sup> Lauer (1939), p. 38.

<sup>25</sup> Hussein (2017).

<sup>26</sup> Mariette (1889), p. 83.

<sup>27</sup> The southernmost staircase was apparently not found until later excavations conducted by Firth. Its condition at the time of discovery was not described (Firth (1928), p. 82).

also found in the 26th Dynasty embalmer's shaft near the Unas pyramid,<sup>28</sup> providing evidence that such 'decommissioning' practices may have been common for embalmers' complexes in the 1<sup>st</sup> millennium BCE.

Thus, Saqqara Gallery C and the area above it may have constituted a 1<sup>st</sup> millennium BCE complex where the Apis bull was embalmed, prior to the establishment of the Memphite Apis embalming precinct circa the 25th Dynasty. Alternatively, there is also evidence to suggest the putative Saqqara superstructure and Gallery C substructure could have served to embalm other sacred creatures.

Gallery C and the structure overlying it would have been situated in convenient proximity to the Western Galleries, possibly enabling efficient transport of mummified animals to the Western Galleries for burial (see fig. 2). Evidence for long-term use and reuse of the Western Galleries can be inferred from documentary sources. The general appearance of the subterranean galleries, shown in fig. 6, seems to correspond to the layout of the recently excavated 2<sup>nd</sup> Dynasty royal grave of Ninetjer as well as the 2<sup>nd</sup> Dynasty complex of Hotepsekhemwy at Saqqara.<sup>29</sup> It has been suggested that the Western Galleries originally served as the burial complex of another 2<sup>nd</sup> Dynasty sovereign.<sup>30</sup> Evidence for the 2<sup>nd</sup> Dynasty date of the galleries may also be provided by the stone vessel fragments found in the south end of the galleries.<sup>31</sup> These vessels were said to be of inferior quality by Firth and Quibell,<sup>32</sup> but unfinished blanks and even raw material used in the fabrication of stone vessels were also found in the underground galleries of Ninetjer,<sup>33</sup> indicating that the presence of such objects may be normal in 2<sup>nd</sup> Dynasty royal burials at Saqqara. The vessels found in the south end of the Western Galleries were made of a variety of hard stones and 'alabaster' (likely travertine).<sup>34</sup> This description of the stone vessels found in the Western Galleries also corresponds approximately to the description of stone types used for vessels found in the Ninetjer galleries.<sup>35</sup>

In addition to the original sloped stairway entrance to the Western Galleries, several vertical shaft entrances are also attested for the complex (see the squares marked P<sub>5</sub> and P<sub>6</sub> in fig. 2 and those labelled 7, P', P<sub>4</sub> and P in fig. 6). Similar entries in the tomb of Ninetjer were created when the complex was reused in later periods.<sup>36</sup> Thus, the shaft entrances to the Western Galleries were likely also created to access the tunnels during this period of later use. Quibell and Firth briefly discussed the presence of stone vessels dumped in passages 'to the north' of these intrusive entrances, presumably by the individuals who created the intrusive shafts.<sup>37</sup> Again, this parallels the evidence from the tomb of Ninetjer, where stone vessels placed in the burial during the 2<sup>nd</sup> Dynasty were re-deposited in the central corridor of the tomb during a later period.<sup>38</sup>

Human and animal remains found in the Western Galleries also provide evidence for potential reuse of the complex in later period(s). A few human bones were uncovered in an unspecified sector of the Western Galleries.<sup>39</sup> These could be remains either of the original 2<sup>nd</sup> Dynasty royal burial, or of a later intrusive burial. The north end of the Western Galleries, located closer to what may be the original entrance staircase, labelled E by Lauer (see fig. 6), contained the bones of

<sup>28</sup> Hussein (2017).

<sup>29</sup> Lacher-Raschdorff (2014).

<sup>30</sup> Stadelmann (1991), p. 49; Dodson (2003), pp. 41–42.

<sup>31</sup> Lauer (1936), p. 181.

<sup>32</sup> Firth and Quibell (1935), pp. 17, 71.

<sup>33</sup> Lacher-Raschdorff (2014), pp. 91–92.

<sup>34</sup> Firth and Quibell (1935), p. 71.

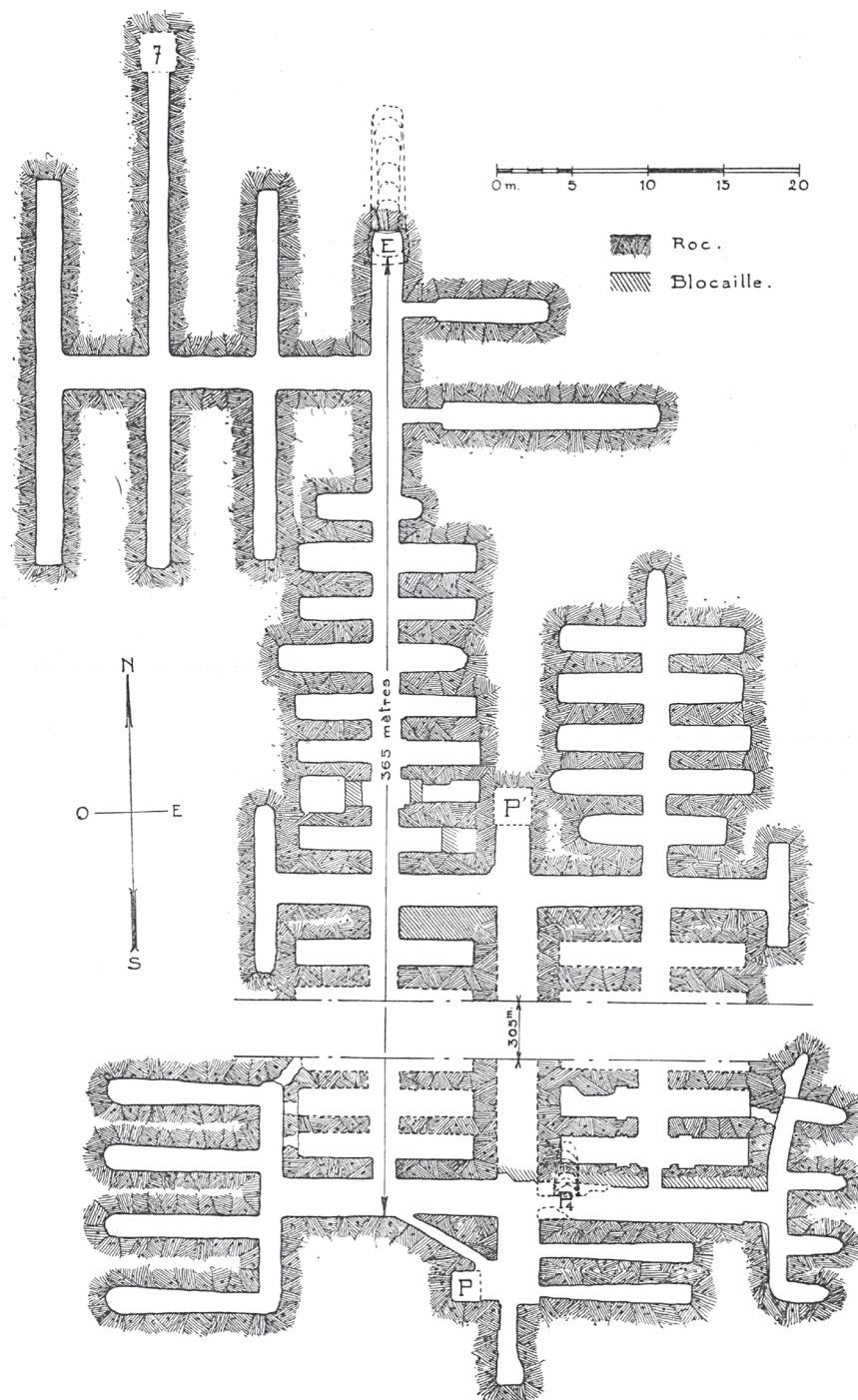
<sup>35</sup> Lacher-Raschdorff (2014), pp. 91–92.

<sup>36</sup> Lacher-Raschdorff (2011), pp. 545, 547.

<sup>37</sup> Firth and Quibell (1935), p. 17.

<sup>38</sup> Lacher-Raschdorff (2011), p. 542.

<sup>39</sup> Lauer (1936), p. 181, n. 1.



**Fig. 6.** Map of the explored sections of the Western Galleries in the Step Pyramid complex (from Lauer (1936), fig. 206).

numerous animals, including oxen, calves, donkeys, pigs, dogs, and crocodiles.<sup>40</sup> With the exception of the donkey remains, mummified remains or animal bundles with bones from the same species of animals mentioned by Lauer were also found ritually deposited in the ibis catacombs of Tuna el Gebel.<sup>41</sup> Consequently, the animal remains found near entrance E of the Western Galleries may originally have been placed in an animal catacomb that reused the Galleries as a burial space.<sup>42</sup> Thus, a genuine multi-use animal necropolis may have existed in the Western Galleries, and the destroyed embalmer's complex overlying Gallery C may have served this complex for an undetermined period of time.

From the evidence currently available, Gallery C in the Step Pyramid complex can now be considered an unusual example of an underground structure that formed part of an embalmer's workshop. This substructure was likely part of a complex where the Apis or other sacred animals were embalmed. It is possible to tentatively date this structure to the first half of the 1<sup>st</sup> millennium BCE. The Western Galleries may also have been re-used as an animal necropolis during this period.

## Bibliography

- Aston, B. G., Harrell, J. A., and Shaw, I. (2003), 'Stone', in P. Nicholson and I. Shaw (eds.), *Ancient Egyptian Materials and Technology*, Cairo: American University in Cairo Press, pp. 5-77.
- Bietak, M. and Reiser-Haslauer, E. (1982), *Das Grab des Anch-Hor, Oberschiffmeister der Gottesgemahlin Nitokris*, vol. II, UZKA 5, Wien: Verlag der Österreichischen Akademie der Wissenschaften.
- Borchardt, L. (1910), *Das Grabdenkmal des Königs Sabu-re*, vol. I, WVDOG 14, Leipzig: J. C. Hinrichs.
- Borchardt, L. (1937), *Denkmäler des Alten Reiches, (ausser den Statuen) im Museum von Kairo*, vol. I, CGC 1295-1541, Berlin: Reichsdruckerei.
- Davis, T.M. et al. (1912), *The tombs of Harmhab and Touatankhamonou*, London: Constable.
- Dodson, A. (1995), 'Of Bulls & Princes: The Early Years of the Serapeum at Sakkara', *KMT* 6.1, pp. 18-32.
- Dodson, A. (1999), 'The Canopic Equipment from the Serapeum of Memphis' in A. Leahy and J. Tait (eds.), *Studies on Ancient Egypt in Honour of H.S. Smith*, London: Egypt Exploration Society, pp. 59-75.
- Dodson, A. (2003), *The pyramids of ancient Egypt*, London: New Holland.
- Dodson, A. and Ikram, S. (2008), *The tomb in Ancient Egypt: royal and private sepulchres from the early dynastic period to the Romans*, London: Thames & Hudson.
- El Amir, M. (1948), 'The ΣΗΚΟΣ of Apis at Memphis: A Season of Excavations at Mit Rahinah in 1941', *JEA* 34, pp. 51-56.
- Firth, C. M. (1928), 'Excavations of the Service des Antiquités at Saqqara (October 1927–April 1928)', *ASAE* 28, pp. 81-88.
- Firth, C. M. and Quibell, J. E. (1935), *The Step Pyramid*, vol. 1, Cairo: Institut français d'archéologie orientale.
- Hussein, R. B. (Nov. 14, 2017), *Inside the Tombs of Saqqara: The Ancient Egyptian Burial Site Revealed*, <https://www.youtube.com/watch?v=ng3OP57Bdc0> [13 July 2019].
- Ikram, S. (2017), 'Typhonic bones: a ritual deposit from Saqqara?' in S. Jones, W. van Neer, and A. Ervynck (eds.), *Behaviour behind bones: the zooarchaeology of ritual, religion, status, and identity*, Oxford: Oxbow Books, pp. 41-46.
- Jones, M. (1990), 'The Temple of Apis in Memphis', *JEA* 76, pp. 141–147.
- Jones, M. and Jones, A. M. (1982), 'The Apis House Project at Mit Rahinah First Season, 1982', *JARCE* 19, pp. 51-58.
- Kessler, D. and Nur el-Din, A. H. (2005), 'Tuna al-Gebel: millions of ibises and other animals' in S. Ikram (ed.), *Divine Creatures: Animal Mummies in Ancient Egypt*, Cairo: American University in Cairo Press, pp. 120-163.

<sup>40</sup> Lauer (1936), p. 181, n. 1.

<sup>41</sup> Kessler and Nur el-Din (2005), pp. 152-153.

<sup>42</sup> Donkey remains were also found in a 3<sup>rd</sup> Dynasty corridor dug into the moat surrounding the Step Pyramid (Ikram (2017)). Thus the donkey bones in the Western Galleries could also date to the 2<sup>nd</sup> or 3<sup>rd</sup> Dynasties and not to the later 1<sup>st</sup> millennium reuse of these galleries.

- Lacher-Raschdorff, C. (2011), ‘The tomb of king Ninetjer and its reuse in later periods’ in M. Bárta, F. Coppens, and J. Krejčí (eds.), *Abusir and Saqqara in the year 2010*, Prague: Czech institute of Egyptology, Faculty of Arts, Charles University in Prague, pp. 537-550.
- Lacher-Raschdorff, C. M. (2014), *Das Grab des Königs Ninetjer in Saqqara: architektonische Entwicklung frühzeitlicher Grabanlagen in Ägypten*, AVDAIK 125, Wiesbaden: Harrassowitz.
- Lauer, J.-P. (1936), *La pyramide à degrés*, vol. I, Cairo: Institut français d’archéologie orientale.
- Lauer, J.-P. (1939), *La pyramide à degrés*, vol. III, Cairo: Institut français d’archéologie orientale.
- Mariette, A. (1882), *Le Sérapeum de Memphis*, Paris: F. Vieweg.
- Mariette, A. (1889), *Les mastabas de l’ancien empire*, Paris: F. Vieweg.
- Reader, C. (2017), ‘An early dynastic ritual landscape at North Saqqara: An inheritance from Abydos?’, *JEA* 103, pp. 71-81.
- El-Shahawy, A. and Atiya, F. (2005), *The Egyptian Museum in Cairo*, Cairo: Farid Atiya Press.
- Stadelmann, R. (1991), *Die ägyptischen Pyramiden: vom Ziegelbau zum Weltwunder*, Mainz: Philipp von Zabern.



# Moving heaven and earth for Khufu: Were the Trial Passages at Giza components of a rudimentary stellar observatory?

David Ian Lightbody<sup>1</sup>

## *Abstract:*

*This article describes a digital archaeological experiment to test a new hypothesis that explains the purpose and unusual form of the so-called Trial Passages at Giza. The enigmatic connected passages are carved into the bedrock on the east side of the Great Pyramid of Khufu and have been interpreted in various ways over the decades since they were first cleared. Based on a new analysis of their design, it is proposed here that they could serve very well as a place from which to observe the northern stars. Prolonged and accurate measurement of the stars of the circumpolar region of the northern sky could have been made from inside the main inclined passage, which rises from south to north. Accurate location of the Northern Celestial Pole (NCP) during these observations could have facilitated the accurate cardinal alignment of sides of the Great Pyramid. Other details of the architecture support this interpretation, and are set out here for consideration.*

## Background history of the Trial Passages

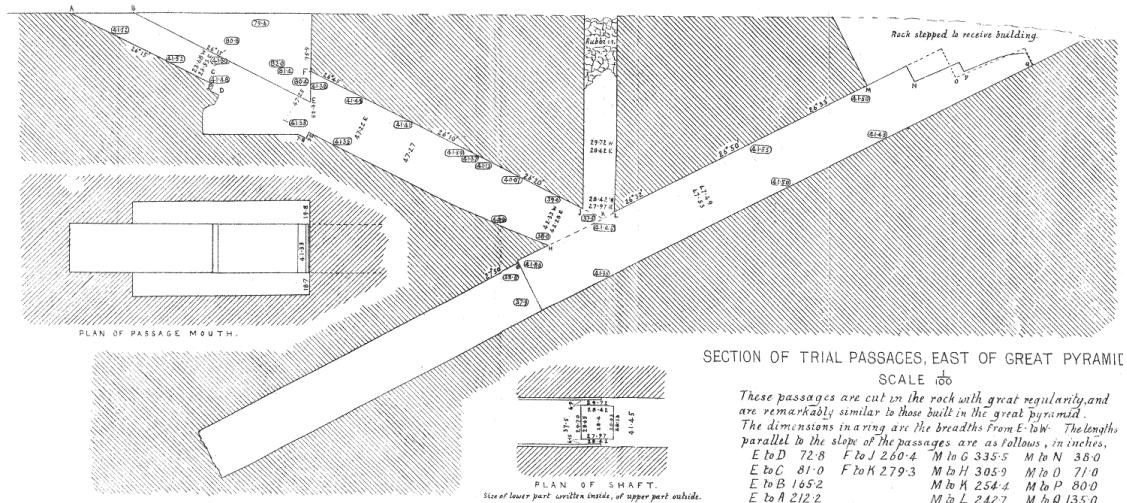
Visitors to the Giza Plateau today may notice three rectangular openings in the bedrock 87.5 m east<sup>2</sup> of the Great Pyramid of Khufu (Appendix 1). They are now closed off with metal gates and surrounded by railings, but when accessed they lead into an enigmatic set of sloping passages with rectangular sections often referred to as the Trial Passages. To date there remains a lack of consensus and clarity over their original purpose. All of the archaeologists who have surveyed them over the years concluded that they were built around the time the Great Pyramid was built, and several have noted the similarity in form between these passages and the descending and ascending passages of the Great Pyramid itself.<sup>3</sup> The inclinations of both sets of passages are all similar<sup>4</sup> and they are of similar width (2 cubits or 1.05 m), and all of them are aligned on a north-south axis. Several different hypotheses have been put forwards over the years since the Trial Passages were first cleared in an attempt to explain them, and they have been accurately measured and described.

1 Many thanks to reviewers Chris O’Kane, Alexander Puchkov, and Franck Monnier, whose feedback has improved this article significantly. Thanks also to Jon Bodsworth for providing photographs. This paper is dedicated to the late Glen Dash who sadly passed away while it was being completed. He was able to read the first draft and his feedback was extremely valuable. His own hypothesis, Dash (2017), on this subject matter was published in volume two of the JAEA: [www.egyptian-architecture.com/JAEA2/JAEA2\\_Dash](http://www.egyptian-architecture.com/JAEA2/JAEA2_Dash).

2 Petrie (1990), appendix 107.

3 Maragioglio and Rinaldi (1965), Tav 9; Maragioglio and Rinaldi (1965), pp. 189-90; Petrie (1883), pp. 50-51 and Pl. IIIb; Lehner (1985), pp. 45-50; Greenlees (1925); Vyse (1840), Vol. 1, pp. 189-90; Vol. 2 Appendix, p. 30.

4 26.5°, 50%, 1:2, or a seked-like slope of 14 palms using the ancient Egyptian system.



**Fig. 1.** Petrie's diagram presenting the data from his 1882/3 survey of the Trial Passages at Giza (north is to the right) (Petrie (1883), plate 3b).

The set of connected tunnels incorporates three separate openings onto the surface. The tunnels were excavated from the bedrock, which consists of nummulitic limestone at that location. The system is located to the north side of the causeway running between Khufu's mortuary temple and the valley temple that was originally built down below on the Nile floodplain, and which is now lost. Together, the shafts stretch approximately 23 m in length horizontally in a north south orientation, and reach down to a depth of approximately 10 m. The explorer Howard Vyse and later the Egyptologist Flinders Petrie surveyed and drew plans of these passages in the 19th century (Figure 1) revealing a layout that Petrie believed to be some sort of replica or trial version of the internal passages within the Great Pyramid. Parts of the configuration of the Trial Passages do resemble the Great Pyramid's descending passage where it meets the ascending passage. This junction with the upper shafts in the Great Pyramid still contains Aswan granite plugging blocks and so it was suggested that the Trial Passages were designed to test that block closing system. A narrowing of the ascending passage at that location corresponds with a narrowing of the southern Trial Passage at the equivalent location, and it has been proposed that this detail was deliberately designed to block the plugging stones at those positions. It is clear, however, that there are no such granite blocks installed in the Trial Passages.<sup>5</sup>

The most obvious difference is the tall vertical shaft in the Trial Passages, square in section, that rises above the junction between the two inclined passages. It has no equivalent in Khufu's pyramid. French scholar Franck Monnier considers it possible that the Trial Passages were a prototype to test the closing system in the ascending passage. This used a line of blocks intended to plug the access route into the monument at the junction of the two main passages, and in his hypothesis the vertical shaft in the Trial Passages may then have provided access to allow observation of the point where the first test closing blocks would become stuck in the narrowing corridors. Again, it must be noted that there are no plugging blocks in situ in the Trial Passages and no fragments have been found.

5 Other details of the design of the Trial Passages such as the sides of the southern access passage also resemble the bottom of the Grand Gallery with its side benches. There is no parallel in the Trial Passages for the 'service shaft' found opening onto the side of the Grand Gallery, however, and the section that supposedly equates to the horizontal corridor leading to the Queen's Chamber, in the southern Trial Passage, is only very short.

Other scholars have suggested that the Trial Passages were intended to be shafts leading into a smaller pyramid, perhaps a scaled down version of the Great Pyramid that was to be built at that location, or which was built there and was then cleared off the surface at a later date. No traces of foundations for a superstructure have ever been found, and no burial chamber has been excavated in the area. The sections and inclinations are, nevertheless, similar to those of the Great Pyramid.

The possibility remains that the passages had a different purpose, or perhaps another purpose. Giza surveyors Glen Dash and Flinders Petrie already noted that the inclinations of the north facing passages in the Great Pyramid could have been associated with efforts to observe the northern stars. Dash has suggested an observation device that could have been incorporated into those shafts to aid orientation of the architecture.

In the new hypothesis set out here, it is suggested that the Trial Passages were in fact designed to carry out accurate observations of the circumpolar stars in advance of the construction of the Great Pyramid, and that observation devices of the type described by Dash were installed within them. The Trial Passages were designed and intended to be used to establish an accurate, astronomy-based, north-south alignment for the construction of the Great Pyramid of pharaoh Khufu.

## Introduction to the new hypothesis

Many scholars have addressed the mechanisms and methods through which the ancient Egyptians were able to orient the sides of the Great Pyramid<sup>6</sup> to the cardinal directions (N-S-E-W) with great accuracy.<sup>7</sup> Egyptologist I.E.S. Edwards noted that no equipment or records showing how it was done have ever been recovered,<sup>8</sup> but geometric surveys of the sides and edges of the monument show that they originally deviated by, on average, less than 1/15<sup>th</sup> of a single degree from the cardinal directions when the casing stones were in place.<sup>9</sup> Although very precise, the visual precision of this alignment is within human naked eye capabilities.<sup>10</sup> Several authors have proposed methods that could have been used to achieve this using the stars that revolve around the Northern Celestial Pole as targets,<sup>11</sup> while others have proposed methods based on shadows cast by the sun.<sup>12</sup> In this article, I postulate that the alignment procedures carried out at Giza made use of the Trial Passages to the east of the Great Pyramid to observe the stars around the NCP over a prolonged period of time. The observations were then used to establish an accurate north-south surveying reference line for the Giza plateau. If valid, this new hypothesis lends support to arguments contending that the stars were used in the architectural orientation procedures at Giza.

The reason the ancient Egyptian architects wanted to align the pharaonic tombs in this way was to raise the status of the pharaoh (who would be entombed there) above all his compatriots by

<sup>6</sup> Belmonte (2001).

<sup>7</sup> Dash (2015b).

<sup>8</sup> Edwards (1979), pp. 117-118, 254-262.

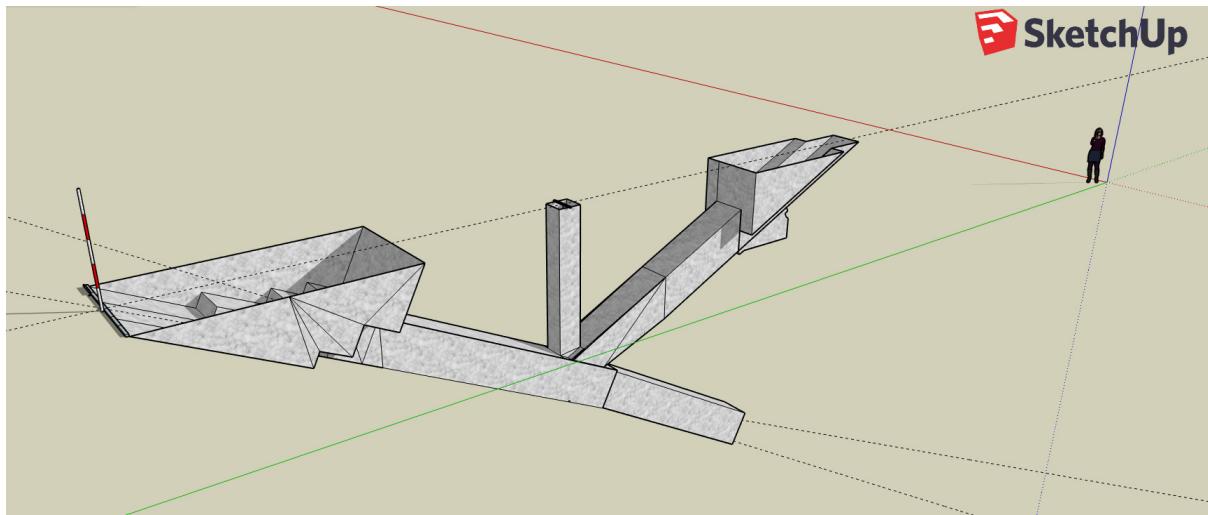
<sup>9</sup> Petrie (1883), p. 125; Lightbody and Monnier (2019), p. 82; Dash (2015b), p. 11; Cole (1925). Dash's 2015 survey showed that the average deviation of the casing was 3°54" +/-44" west of true north. This corresponds well with Petrie's 1882/3 findings of "about 4" arcminutes, also stated more precisely as 3°43" +/-6" west of true north.

<sup>10</sup> The ancient Egyptians did not have telescopic optical technology, nevertheless, a 20-20 vision human being observing with the naked eye can differentiate details separated by, at best, approximately 1 arcminute. By way of comparison, the diameter of the full moon covers approximately 31 arcminutes of the sky, while the solar disk is very slightly larger, varying from 31 1/2 to 32 1/2 arcminutes in diameter. 1/15<sup>th</sup> of a degree is 4 arcminutes.

<sup>11</sup> Petrie (1883); Edwards (1979). Petrie proposed a tall wall to the north supporting a long plumb line; Edwards envisaged a circular wall over which the circumpolar star would rise and set. The direction to true north would then bisect these points. No evidence of such structures has been recovered.

<sup>12</sup> Dash (2015a).

associating him and his monument with the eternal heavens above, as closely as possible. This architectural propaganda was part of the typical legitimization program that surrounded the reign of any pharaoh. The political and theological aspects are discussed more fully elsewhere,<sup>13</sup> but the technical methods used to achieve the accurate alignments are addressed in the discussion below.



**Fig. 2.** General arrangement of the Trial Passages as a 3D model, looking south east. There are three entrances into the lower passages, via two sloped passages and one vertical shaft. The indicator pole on the left is hypothetical and would have been used as a vertical north alignment marker. It is shown as 5 cubits in height (2.62 m). The experiments showed that 3 cubits (1.57 m) would have been adequate (David Lightbody).

The cardinal alignment of ancient Egyptian monuments is closely related to a number of technical subject areas that have been studied extensively by Egyptologists over the years. Many published papers have been devoted to sky-based timekeeping methods, including those relating to sundials,<sup>14</sup> calendars,<sup>15</sup> and astronomy.<sup>16</sup> The extents and details of ancient Egyptian knowledge of the stellar constellations and their daily and annual movements have also been extensively discussed. With respect to the architecture on the ground, the issue of accurate alignment relates to surveying methods,<sup>17</sup> metrology, and the stretching of the cord ritual, which is attested during the Old Kingdom and even as far back as the Early Dynastic Period.<sup>18</sup>

More specifically, discussions of the astronomical methods employed at Giza have usually revolved<sup>19</sup> around the constellations close to the Northern Celestial Pole (NCP),<sup>20</sup> and how these were used

<sup>13</sup> Baines and Yoffee (1998). This kind of technical knowledge could be described as high culture and was part of the legitimization program supporting the pharaonic hierarchy. Wilkinson (2001), p. 257.

<sup>14</sup> Khurana and Symons (2016); Salmas (2013); Salmas (2014).

<sup>15</sup> Robins (1995); Parker (1950).

<sup>16</sup> Chatley (1940); Lull and Belmonte (2009); Neugebauer and Parker (1960).

<sup>17</sup> Dash (2015b); Petrie (1883).

<sup>18</sup> Greenwell (2005), pp. 15-16; Belmonte, Polo, and Miranda (2009); Arnold (1991).

<sup>19</sup> Spence (2000), pp. 250-51; Edwards (1979); Lightbody and Monnier (2019), p. 156.

<sup>20</sup> The north and south celestial poles (NCP and SCP) are the two imaginary points in the sky where the Earth's axis of rotation, indefinitely extended, intersects the apparently visible celestial sphere that forms the night sky. From Egypt, only the north celestial pole is visible. In the northern hemisphere, the NCP remain fixed in the sky as the Earth spins on its axis and all other stars appear to rotate around it, completing one circuit per day (strictly, per sidereal day). The celestial poles are also the poles of the celestial equatorial coordinate system, meaning they have declinations of +90 degrees and -90 degrees (for the north

to determine the NCP's location in the northern sky and by extension the direction of true north on the ground. The NCP is not marked by any particular visible astronomical object today, and was not so marked during the Old Kingdom. Today it is most closely orbited by the star Polaris ( $\alpha$  Ursae Minoris), which currently rotates more than half a degree distant from the NCP on a daily basis.<sup>21</sup> The much slower wobble of the earth's axis, which describes a circle around part of the northern sky thanks to a phenomenon known as axial precession<sup>22</sup>, means that the closest bright star circling the NCP at the time the Great Pyramid was built was Thuban ( $\alpha$  Draconis).<sup>23</sup> At that time in approximately 2,590 B.C.<sup>24</sup> the orbit of Thuban was almost 1.5 degrees (81 arcminutes of the night sky) distant from the NCP. To achieve high precision alignments based on that object, it was, therefore, necessary to use some systematic observation and measurement procedure to determine the position of the NCP from the star's daily circling motion (or in conjunction with the motion of other circumpolar stars). Based on the architectural surveys, the ancient Egyptians were able to achieve that task with an accuracy of better than 1/15<sup>th</sup> of a single degree. Precisely how they managed to do that is still under discussion.<sup>25</sup>

All of these subjects are complex, challenging, currently lack clarity, and current theories provide few definitive answers. In response to that complexity, the content of this article remains doggedly focused on presenting a basic new hypothesis related to the architecture of the Trial Passages, with the intention only to demonstrate the practical feasibility of a procedure that could be carried out within them, and to establish and describe a possible sequence of tasks that would have constituted such a procedure.<sup>26</sup>

## Introduction to the experimental method

### *3D modelling environment*

In order to investigate the geometry of the Trial Passages structure in detail, a 3D model of them was built using the 3D CAD software Google/Trimble's Sketchup version 2019-06-21.<sup>27</sup> (Figure 2). This 3D modelling environment enables rapid prototyping and rendering of 3 dimensional designs,

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and south celestial poles, respectively). Monnier (2017), pp. 198-200.

21 Approximately 39 arcminutes distant.

22 The period of the wobble is approximately 26,000 years.

23 The closest of the stars of less than 4 magnitude, which are relatively easy to observe. The star iota Draconis (magnitude 4.55) was at that time closer to the Northern Celestial Pole, but would have been very dim.

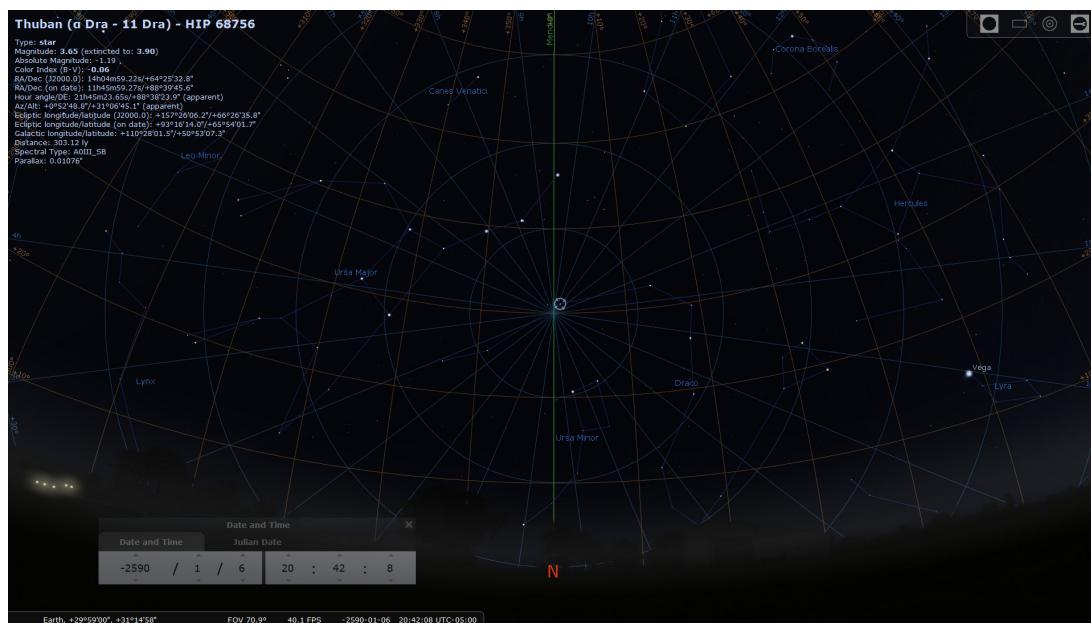
24 Bronk Ramsey *et al.* (2010), p. 1556.

25 Dorner (1981), pp. 167-168; Arnold (2003).

26 Haack (1984). Haack was the first to note that a linear regression line could be traced through some of the plotted points showing the cardinal alignment errors of Old Kingdom pyramids vs time. The slope of the resulting line represents a drift of around 20 arcseconds per year and Haack suggested this was the result of precessional drift on key star rising points on the horizon. This relationship does, however, require that the orientations of certain pyramids, including Djoser's, Khafre's, and Sahure's, are treated as outliers or are inverted (clockwise to counter-clockwise or vice-versa) to fit the line. While such a linear relationship may exist, the dataset supporting it is not particularly robust. Spence later suggested that the drift was due to precessional movement of stars around the NCP. As the direction of precessional drift for any particular star around the NCP depends on the observation date and time of day, Spence suggested that it was the vertical alignments of particular pairs of stars as they rotated around the NCP, at particular times, that were chosen and used to establish the azimuth of the NCP. Those vertical alignments then drifted over time due to precession. Dash later suggested that the errors were not due to precession at all, but were the by-product of an equinoctial solar alignment method, where the sun moved from east to west, but also drifted very slightly north or south through the day due to the change in seasons taking place, even within the time-frame of a single day. Again, the dataset supporting that hypothesis has some outliers that must be excluded or flipped before the model will fit the solar shadow data. The trends and errors in the dataset can equally be explained by an increasing level of construction accuracy leading up to Khufu's reign, followed by a decreasing level of accuracy as the Old Kingdom began to decentralize and slowly headed toward eventual disintegration. This is the hypothesis adopted in the current article.

27 <https://www.sketchup.com/>

and allows perspective views of, and from, structures to be simulated. The dimensions used to build the model were based on a detailed survey of the passages carried out by Flinders Petrie in 1882-3.<sup>28</sup> The digital model was built below the horizontal plane of the virtual environment as the passage system is below the ground at Giza. The dimensions and drawing produced by Petrie proved to be adequate so that a complete model of the passages could be created. An additional piece of data extracted from Petrie's survey was the orientation of the main axis of the passages, which he found to be 14° 43" east of north, or 14.72 arcminutes.<sup>29</sup> This was an important characteristic to consider in the new study as it was initially assumed that a large deviation from north could indicate that the passages may not have been useful for observation of the NCP. The view area may not have encompassed the east and west elongations of Thuban, and this aspect was to be explored. In fact, although less accurate than the alignment of Khufu's pyramid, this alignment value for the main structure of the Trial Passages equates to less than ¼ of a degree of deviation from true north.



**Fig. 3.** Stellarium screen shot showing the software configured to represent the constellations visible from Giza in 2,590 B.C. Thuban is highlighted near the NCP in the center, and its astronomical data-set is shown top left. The green line represents the celestial meridian (David Lightbody).

#### Digital planetarium data

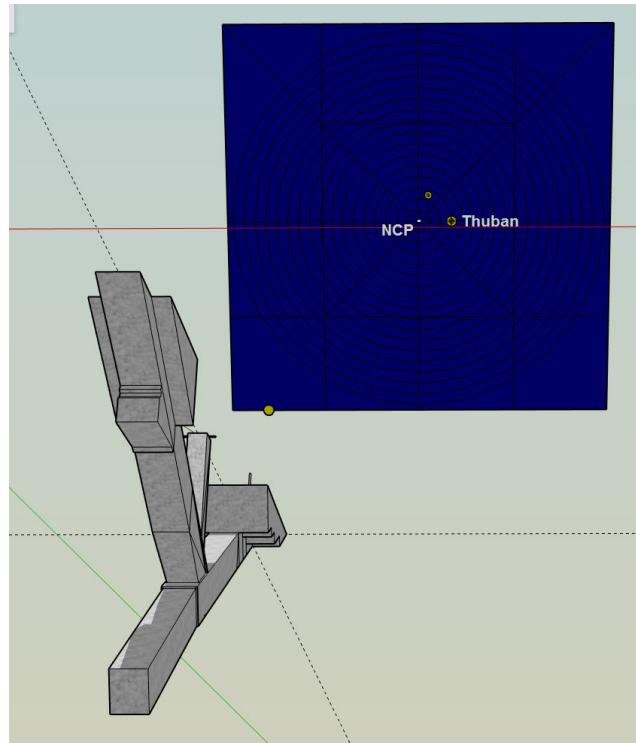
To determine which stars would have been visible from the passages when looking north at the time the Great Pyramid was built, the Stellarium 0.13.3 digital planetarium software was used.<sup>30</sup> The skyscape visible from Giza (Figure 3) was simulated by setting the location to that of Giza and by backtracking the system date to 2,590 B.C.

Once the ancient star positions at various times of the year in 2,590 B.C. were established and noted, the data was used to create a sub-section of the visible night sky incorporating a circle 8.5 degrees in radius around the NCP. This contained the whole area of sky visible from within the lower passages that was to be studied during the experiments. A representation of this area of

<sup>28</sup> Petrie (1883), plate 3b.

<sup>29</sup> Petrie (1883), p. 48.

<sup>30</sup> <https://stellarium.org/>



**Fig. 4.** View from the south east looking north of the Trial Passages looking up at the NCP and star square that is built into the model. This can be rotated to represent the correct time and date (model and image by David Lightbody).

sky was then built into the 3D CAD model environment in the form of a flat square of night sky visible to the north. The stars could not be represented or positioned effectively at infinity, as the model would have been far too large for the software to manage, so the square was positioned at 1,000 m distance from the shafts<sup>31</sup> on a direct line running north from the passages. A connecting line running from the passage entrance to the center of the square was inclined at 29.9792° N, which equates to the latitude of Giza, so that it was aimed directly at the NCP.<sup>32</sup> The star square was then inclined so that it was perpendicular to the line and so faced directly down at the shafts. Concentric circles were drawn around the NCP onto the star square at ½ degree intervals, which represented the visible angular distance of each circle from the NCP when observed from Giza.<sup>33</sup> The star Thuban, at a declination of 88°39', rotates just under 1 ½ degrees from the NCP. It therefore rotates very close to the third concentric circle on the star square and is shown there on

<sup>31</sup> A slight error is introduced to the modelling due to the fact that 1000 m is not infinity (or at least a much larger distance to the real stars). Given that an observer within the passages could not move east or west of the center line by more than +/- 0.5 m, the parallax error across this distance compared to reality equates to only 1/35<sup>th</sup> of a degree at most. This is very small, but must be noted as significant when dealing with a procedure that achieved a real-world accuracy of 1/15<sup>th</sup> of a degree. Future models could simulate the star square at even greater distances, which could reduce these errors, but the current model allowed full exploration of the general method outlined below, aiming primarily to establish that the outer limits of the sky area visible from the passages contained the relevant stellar motions. The geometric calculations below were carried out with the stars essentially at infinity.

<sup>32</sup> The NCP is the same angle above the northern horizon as the latitude of the location it is viewed from, and in fact this angle defines the latitude of the location.

<sup>33</sup> The distance between each circle was set as 8.72 m. which equates to 0.5 degrees of a circle of radius 1000 m. This introduces a slight error that increases towards the outer edges of the circle, as the star section is represented as being a flat plane rather than a spherical surface concentric to the shafts. Again, this slight error is significant within the context of the experiment, but not significant to the specific method discussion and conclusions.

the diagram (Figure 4). The star Iota Draconis is also shown on the star square, however, in reality it was hardly visible to the naked eye, and while it was slightly closer to the NCP than Thuban there seems little reason to assume that it would have been used in preference to the brighter star Thuban.

Finally, the whole star square was offset to the west by just under a  $\frac{1}{4}$  of a degree, as Petrie found that the main axis of the passages deviates to the east of north by this amount.<sup>34</sup> This means that the view line to the north looking out from the passages along the center line of the architecture actually passes half way between the NCP and the first concentric circle on the star square, to the right/east side of the NCP as seen from Giza.

Once the virtual architectural model and the stellar sky simulation were established, the view from within the passages to the north could be simulated and experienced (Figure 6).

### The Trial Passages as an NCP observation location

In the new hypothesis the three openings onto the surface are interpreted as a southern access tunnel, a central vertical plumb bob shaft, and a star observation tunnel. After climbing down the southern access tunnel, the observer would position themselves down in the southern end of the observation tunnel, to the south of the plumb bob and the junction between the two inclined passages. With feet down to the south, they would then look north towards Thuban and the NCP.

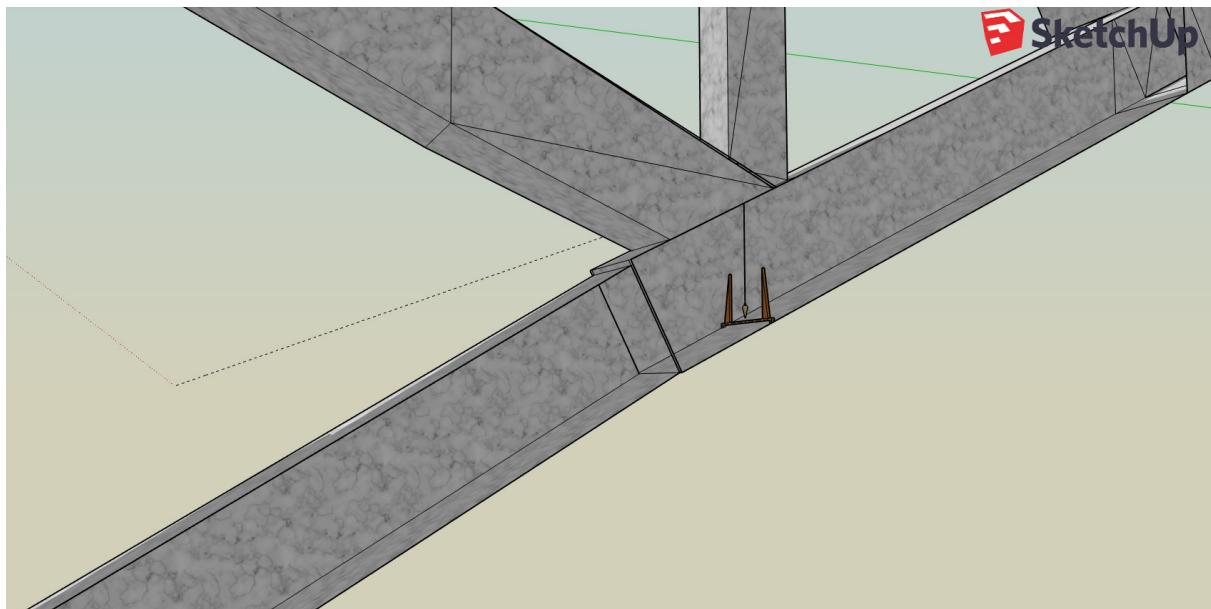
The purpose of observing the stars in this way was to establish a long straight line on the levelled ground running due true north-south. Once defined, its orientation could be translated laterally across the ground using basic geometric surveying methods so that the sides of the monument could be set-out, aligned, and built according to this orientation. The land surveying methods used to translate the reference line orientation laterally are outside the scope of this present work.

In order to establish an accurate true north-south reference line, two points that are precisely due north-south of each other must first be accurately established on the levelled ground. If the NCP is to be used to establish the two initial points then the two points will initially be on a line sloping up towards the NCP. Two corresponding points must then be created on the horizontal ground by extrapolating the positions of the sloping points vertically down onto the horizontal plane. The further apart the pairs of points are in a north-south direction, the better accuracy can be achieved with the alignment, and so most hypotheses attempting to recreate the procedures have envisaged a short sighting device (*merkhet*) at the southern end accompanied by a very tall pole/obelisk/wall at the north end. The sight-line between the device and the tall structure will then be of significant length. The top of the envisaged northern structures would have been adorned with a pointer, a mark, or sight, or gnomon, and this would constitute the northern point of the sloped stellar sight-line pair. In order to accurately translate the point at top of the northern structure vertically down onto the horizontal ground plane, plumb lines must be used. In the case of measurements using a very tall northern structure that plumb line could be rather long. A long plumb line system will lose accuracy if the structure supporting it is not entirely stable over long durations or if there are any excessive air movements due to inclement weather, or due to solar heat induced thermals. People walking by or accidentally impacting the structure could cause further movement and loss of position. When operating at high levels of precision over prolonged periods the length of any such plumb line could have proved to be excessive.

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<sup>34</sup> Petrie (1883), p. 275.

One solution to this is to drop the southern end of the inclined north-south sight line down into the bedrock below the horizon (Figure 5), meaning that there is no plumb line required at all at the northern end. The plumb line will then be positioned at the southern end and can be hung down into the ground from a horizontal wooden support resting on the ground level bedrock. The bedrock containing the whole passage system will not move under most normal conditions. The plumb line will then be securely fixed to the bedrock and can be completely contained within a protective vertical shaft that is not susceptible to surface air movements or accidental displacement. It is suggested here that the vertical shaft in the Trial Passages was created and used for that very purpose.

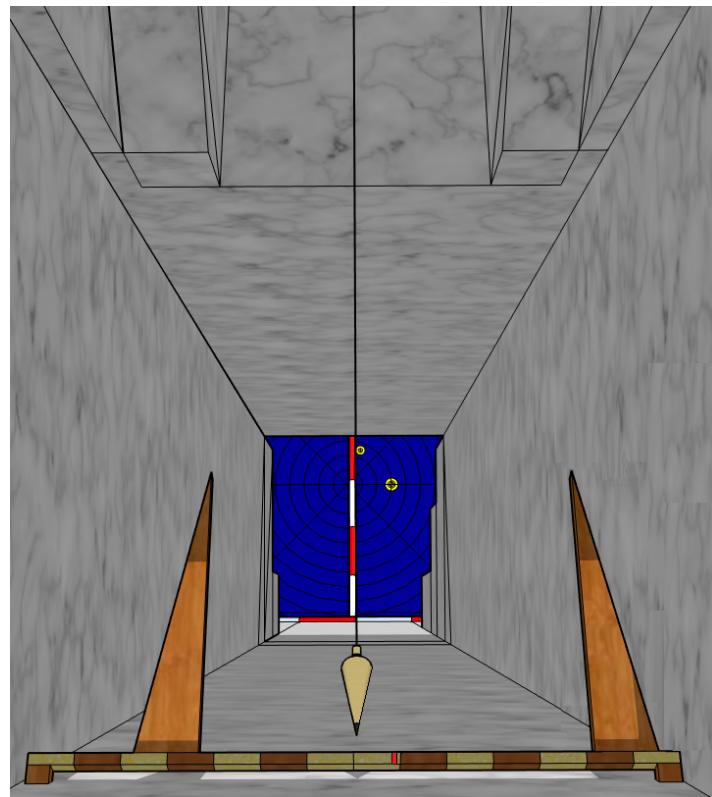


**Fig. 5.** Side view of the passages showing the observation location. An operator would enter by the southern shaft above left and climb down behind the alignment targets. A prostrate position would be assumed with legs down to the left, and head looking up to the right through the targets and past the plumb bob which hangs down the center shaft (model and image David Lightbody).

A calculation testing the initial hypothesis was carried out by the author in 2003. Based on the height, length, and average inclination of the Trial Passages, the initial calculations indicated that the vertical field of view to the north, from the bottom of the vertical shaft, would extend from around 26.5 to 33.5 degrees altitude (up-and-down) of the northern sky from Giza. The horizontal range of visible sky was of the same order (6 degrees, or 3 degrees to the east and west), and this would have allowed the motion of Thuban to be completely observed and described from the passages, given appropriate equipment.<sup>35</sup> The full motion of other circumpolar stars such as Kochab and Mizar were not visible. The exact form of the outer limits of the sky area visible from the shafts is complicated to define precisely due to the irregular form of the architecture at the northern end of the passages, and so in order to more accurately explore the details of the

<sup>35</sup> According to Petrie (1883), pp. 211-12. "The setting out of the orientation of the sides... ...would not be so difficult. If a pile of masonry some 50 feet high was built up with a vertical side from North to South, a plumb-line could be hung from its top, and observations could be made, to find the places on the ground from which the pole-star was seen to transit behind the line at the elongations, twelve hours apart. The mean of these positions would be due South of the plumb-line, and about 100 feet distant from it; on this scale 15" of angle would be about 1/10 inch, and therefore quite perceptible."

hypothetical setup, a 3-dimensional interactive model has now been built. The ancient viewing and measurement techniques used and the possible design of small hand tools and other equipment employed by an observer within the passages were also explored and tested (Figure 6).<sup>36</sup>

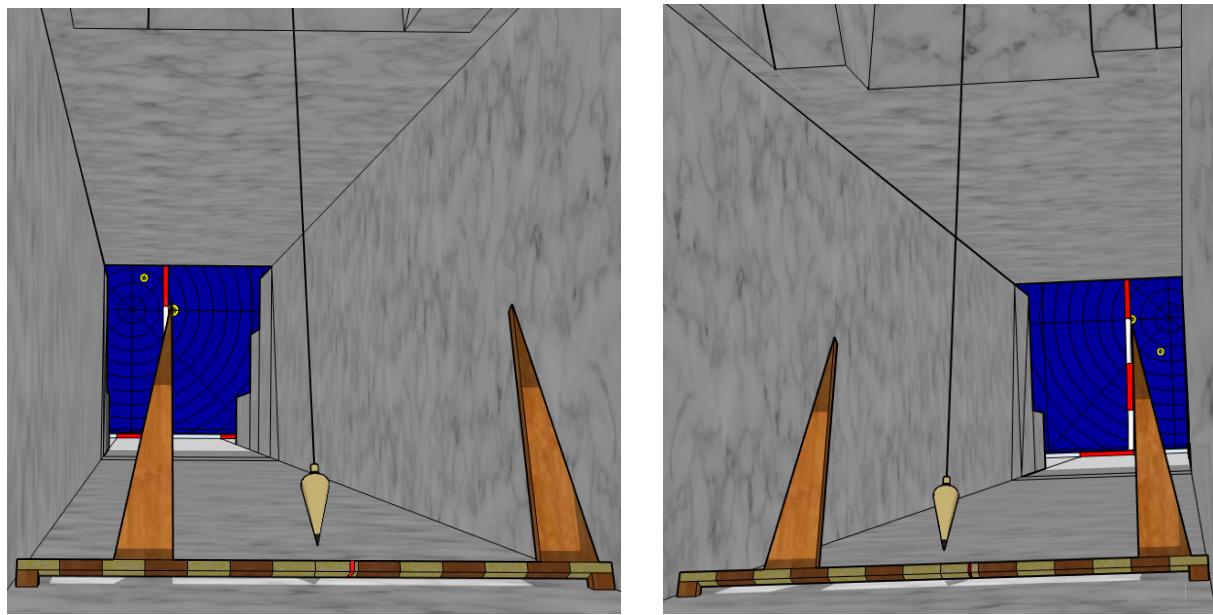


**Fig. 6.** General view from the lower southern shaft looking up at the NCP, which is the center of all the circles, through the targeting instrument, past the plumb line. The right side of the indicator pole on the surface is shown directly behind the plumb line. The NCP would be near the top of the third section of the pole from this position. The observer's eye would have to be slightly to the right of the plumb line to align accurately with the right side of the pole and the NCP, due to the architecture's  $\frac{1}{4}^\circ$  deviation from true north. The position is marked with a short vertical red line in the diagram.. Each section of the pole is 1 cubit in height, so the pole would need to be only 3 cubits (approx. 1.5 m) in height to be used for this procedure. Each target is shown as 1 cubit tall and two horizontal cubits are used as a track (model and image by David Lightbody).

### Observation method and equipment

To view a northern pole star in alignment with a plumb bob line suspended down the vertical shaft, the observer in the passages would have to be positioned to the south of the plumb bob's location, which is at the intersection of the three passages. In fact, there is adequate space at the junction of the two southern shafts so that an observer could climb down into the southern passages and enter the southern descending section without interfering with the plumb bob's location

<sup>36</sup> While this paper focuses on a method for establishing an accurate sky location for the NCP, it might be worth taking into consideration what other stars and astronomical objects would have been observable from the bottom of the southern and vertical zenith shafts. This could open up the subject for further discussion and allow the circumpolar stars to be considered with respect to the asterisms and decans overhead and near or on the ecliptic.



**Fig. 7.** View from the lower shaft observation position of the moveable targets set up to align with the east (left) and west (right) elongations of Thuban. The diagrams show each target aligned with the east/right side of the indicator pole, and then with the star Thuban. This eliminates errors due to the thickness of the pole. The plumb bob does not have to be positioned exactly half way between the two targets. A red mark can be put at the midpoint between the targets on the cubit. This is where the sight-line aligns with the NCP. The red mark is shown above and in figure 6. Once the offset (in this case to the east by almost 1 palm) from the plumb bob is measured on the cubits and known, the plumb line can be used to translate the horizontal position of this offset point vertically, up to the surface ground level. A similar pair of cubits can be set up around the plumb line on the surface and the near 1 palm offset measured out east from the top of the line to define the position of point (P2) on the ground. Alternatively, the plumb line could actually be moved 1 palm east, until it was suspended directly over the red mark. (P2) would then be at the top of the plumb line at ground level (model and images David Lightbody).

or any targeting equipment that might have been set up close to it. The observer could then assume a prostrate body position, with legs stretched down to the south, lying on their front with head and eyes facing up to the north. The southern end of the shaft is slightly more inclined than the northern section, and this may have been designed to allow the observer to maintain body, head, and eyes below the level of the sighting equipment. The optimum observation position may not have been directly behind the plumb bob but further back down the shaft. A meter or more gap between eye and sighting targets would allow the observer to more easily focus near-simultaneously on three objects: a close target near the plumb bob's location, a mid-range vertical pole up on the surface at the north entrance, and the distant northern star. The three targets could then be precisely aligned. Once the eastern-most and western-most positions of Thuban through the year were established, the mid-point could be measured out. This point is marked in figure 6 as a thin red vertical line on the horizontal cubits. This point is of primary significance and its position must be translated up to the surface using the vertical plumb bob line to define the southern point of the main N-S alignment line (P2). The slight offset is discussed below. This procedure is broadly in accordance with the method that Petrie described, although the passages are sub-surface. It does not rely on any simultaneous transits of stars or more complex astronomical methods that are subject to the effects of precession.<sup>37</sup>

37 Several such hypotheses have been proposed over the years that outline such methods, but this paper is limited to proposing

The design of the small adjustable equipment used to carry out these measurements is based on elements described by Petrie and Dash and others. The system consists of two moveable targets below ground that are aligned with a vertical object at ground level near the northern entrance. The vertical indicator on the surface there could be a short suspended plumb line, or more realistically, a short solid pole that had been set up vertically using a plumb line. A thin plumb line would be difficult to see from the lower shafts in darkness, and so a white painted straight pole or similar is envisaged in the current simulation. In the model it is shown as a red and white pole with separations at 1-cubit vertical intervals. It is hereafter referred to as the vertical indicator pole. The point at the base of the pole would define the northern end of the main N-S alignment line (P1).

Each moveable target (the vertical triangles) down below is then moved laterally to align its vertical inside edge with the side of the vertical indicator pole at the surface and with the eastern or western-most 'elongation' of Thuban respectively (on its circuit around the NCP) through the year or night (Figure 7). The midpoint between the targets then defines the precise horizontal position that looks directly up past the side of the indicator pole at the NCP. The choice of side used is arbitrary, but in the current simulation the right, east side of the pole is used.

## Geometric analysis

The first calculation to perform was to evaluate if the width of the tunnel was adequate to contain the full east-west travel of the two targets used for observing Thuban. Using data derived from the model, it was seen that the distance from either sight's inside edge up to the indicator pole at the north entrance (towards the point where the star appears to the observer) is approximately 13.54 m. At this distance from the indicator pole, the full 162 arcminutes<sup>38</sup> horizontal sweep between the two elongations of Thuban as it circles around the NCP would translate down to a 64 cm gap between the two moveable targets when they were both set up in alignment with the elongations. This equals 32 cm on each side of a central plum bob and main axis line, if the passages themselves were perfectly aligned to true north.

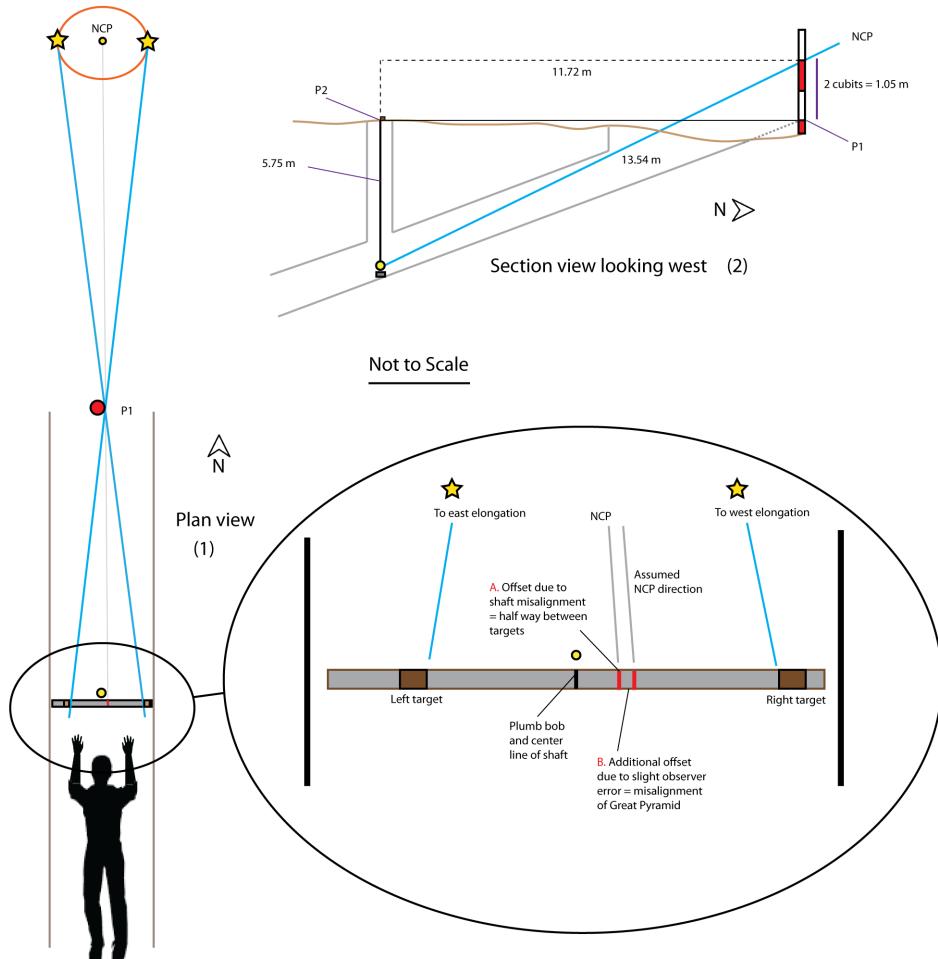
Working backwards from the measured survey data, however, a more precise position can be calculated for where the observer would have placed the midpoint marker between the two sights (Figure 8). To obtain the position, an offset to the east must be factored in due to the 14.72 arcminutes ( $0.245^\circ$ ) misalignment of the architecture to the east of true north, as measured by Petrie (A in Figure 8). Finally, a small offset should be factored in stemming from the small error of the Great Pyramid's final orientation, assuming that this error was derived from small instrument observation errors made in the Trial Passages (B in Figure 8). The passage misalignment value is, therefore, added to the pyramid's average misalignment error of  $1/15^{\text{th}}$  of a degree ( $0.067^\circ$ ) to find the position that the operator would originally have assumed was aligned with the NCP and true north. The two misalignment values are azimuth angles expressed on the horizontal plane, and not on a plane inclined up to the NCP so the linear offsets produced by these angles must, therefore, first be calculated for position P1 on the horizontal plane at the top of the plumb line, at the horizontal distance from the sighting pole to P1 of 11.72 m (again derived from the model).<sup>39</sup> This offset error value can then be translated vertically back down to the cubits at a ratio of 1:1.

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a Thuban-based method rather than comparing and evaluating all of the different methods proposed by Spence (2000) and others. See also Dash (2013), p. 9.

<sup>38</sup> 81 arcminutes  $\times 2 = 2$  degrees 42 arcminutes.

<sup>39</sup> The respective angles of  $0.245^\circ$  and  $0.067^\circ$  give a total of  $0.312^\circ$ . At a distance of 11.72 m, this gives a total offset of 6.38 cm (5.01 cm + 1.37 cm).



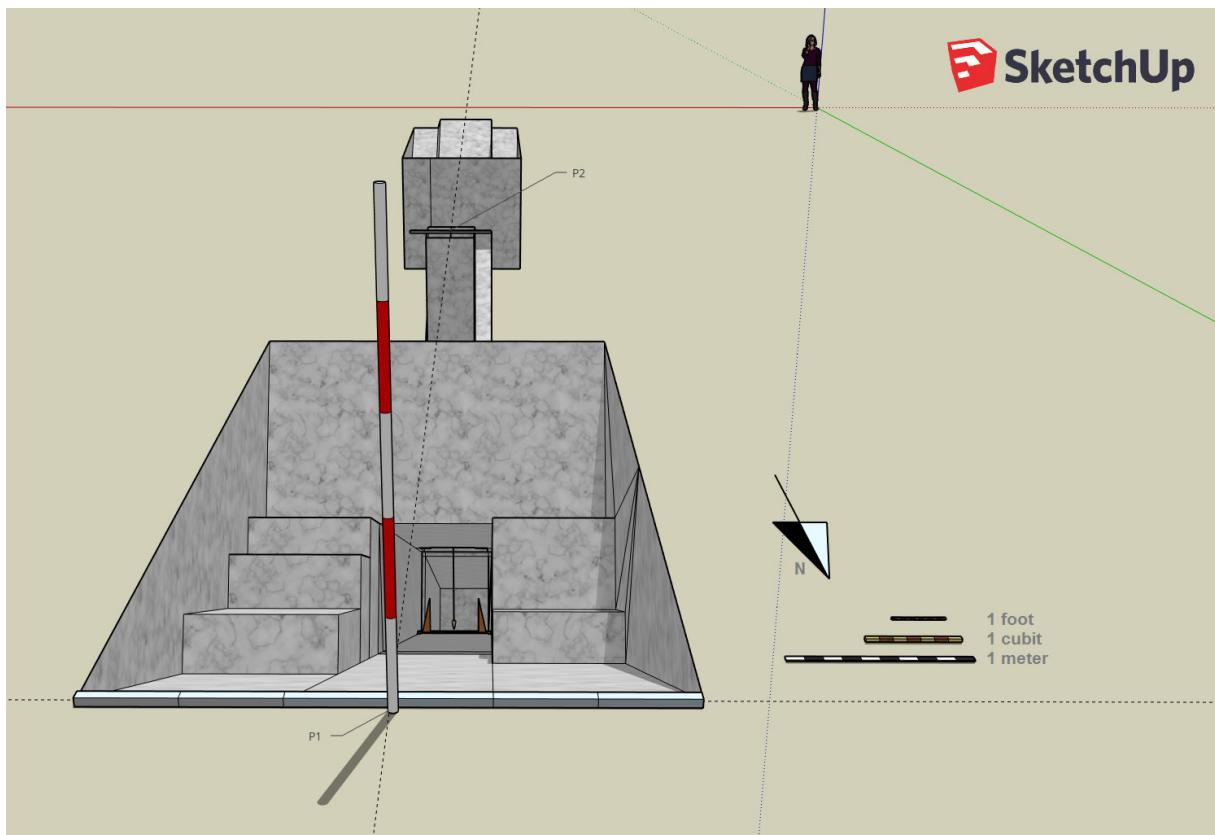
**Fig. 8.** Plan view (1) of observer in position looking north at the NCP through the targeting instrument and past the plumb bob. Enlarged view of target track shows positions of sight lines to NCP, and to elongations of Thuban, including more precise offsets (A and B) due to architectural and other/operator errors. Section view (2) shows the vertical geometry of the system and how the indicator pole would correspond to irregular surface topography, which deviates from the model (image David Lightbody).

The resulting offset of 6.38 cm to the east would mean that there was a distance of 38.38 cm between the plumb line/center of the passage to the target on the east side, and a distance of only 25.62 cm between the plumb line/center of the passage and the target on the west side. The assumed center point between the two targets, which is marked on the cubit in red, is 6.38 cm or almost 1 palm to the east of the plumb bob and the center line of the passages, and it is shown in the diagrams (Figures 6 and 7).

The standard-sized Old Kingdom rock-cut passage is typically 2 cubits wide, equating to 1.05 m or 52.35 cm on each side of the center line. This corresponds accurately with Petrie's measured value of 41.35 inches total width = 1.05 m, leaving 14 cm free at the east side of the passage. The thickness of the vertical target on that side would then have to fit within this free space, and some clearance would also be required between the wall and the operator's head to ensure a clear sight past the target's edge to the north. In conclusion, the full east-west range of shaft movements required to observe the full east-west range of Thuban's movements is just within the scope of the passages,

when using the proposed arrangement and the associated survey data. Two cubit-rods are used in the model to track the east-west axis of the targeting devices and to measure the observed offsets.

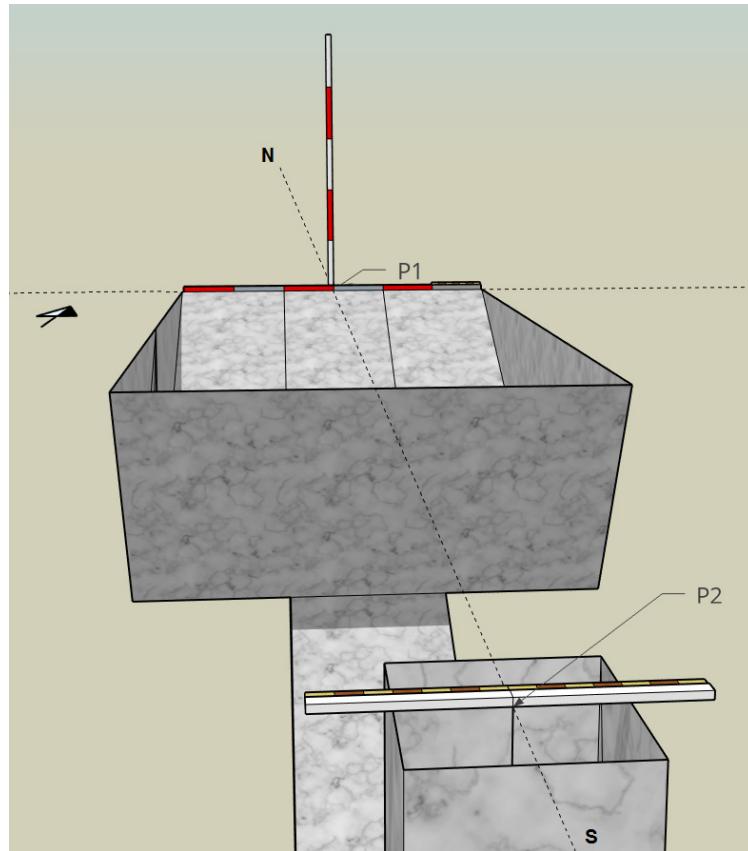
The construction sequence envisaged here is that a fairly rapid alignment to north was carried out before the passages were cut into the bedrock. According to Petrie, the resulting misalignment of the Trial Passages was approximately  $\frac{1}{4}$  of a degree east of true north. The Trial Passages were then used to establish a more accurate orientation line for the Great Pyramid itself. The final N-S line would have been extrapolated and translated laterally to set out the east edge of Khufu's monument. The Great Pyramid's resulting misalignment was between  $1/15^{\text{th}}$  and  $1/16^{\text{th}}$  of a single degree, so that the level of accuracy achieved by using this two-step method was increased by a factor of 4.



**Fig. 9.** View looking south down the north shaft of the Trial Passages. The two moveable targets and the bottom of the plumb line are visible within the shafts. The vertical indicator pole is shown at the end of the north entrance. It is displaced slightly to the west so that its east side is in line with the central axis of the passages. Points P1 and P2 determine the desired north-south alignment line (model and image David Lightbody).

### Occulting the star

One important procedure that would have ensured the real-life high precision of the method would have been to use only one side of the vertical indicator pole erected on the surface to align with the star (Figure 9). The observer in the passages down below could judge the position of the star by moving their head left and right and by observing through only one eye the point at which the star occulted behind the pole. The star would disappear from view at the exact moment the pole's edge and star were aligned with the observer's eye. The inside edge of the adjustable target-



**Fig. 10.** The final alignment line. Once the observations were completed and the plumb bob was positioned over the central point between the targets, points P1 and P2 would accurately define the horizontal line aimed at true north. Alternatively, if the plumb bob was slightly off center down below, the differential could be accurately noted and then marked out on the surface using the cubit scales depicted. In this case, point P2 would then be almost 1 palm to the east side of the top of the plumb line (model and image David Lightbody).

sight down below could then be positioned carefully in between the observer's eye and the pole, to align all three with the distant star. The moveable sights were close to the observer's view point, thus facilitating fine adjustments and producing an accurate alignment. On the other hand, an alternative setup with a single static indicator below and two moving targets on the surface would have required an additional operator up above and would have complicated the system, so it is likely that the surface level pole was static once embedded in place. In the virtual model, the pole was set so that its east edge is aligned with the north-south axis or center line of the architectural model. This would have been unnecessary in reality as the resultant north south line would in fact have been defined by the exact position of the eastern side of the pole, and so it was not necessary to very precisely position the pole initially. On the other hand, the pole had to remain very precisely vertical and stay firmly set in place once positioned there. Observations may have taken several months so that the full motion of Thuban could be observed and measured and so the pole would have required some degree of physical protection from accidental displacement. In the model, it is assumed that the eastern edge of the pole where it entered the ground surface defined the point (P1) that was the north end of the main and final north-south alignment.<sup>40</sup>

**40** One final point of note regarding the precision of the method is that, as the pole and the sights in the model were both erected vertically, it was not necessary for the observer to maintain or mark a constant head and eye observation height. The distance

During the virtual experiments, it was noted that the surface pole could theoretically be moved east or west up by to half a meter, and yet still be visible from the entire lower shaft observation position. This means that the horizontal view of the almost 3-degree horizontal range of Thuban to be measured by the instrument could be adjusted by up to +/- 2 degrees if necessary, by adjusting the pole's location,<sup>41</sup> for example in the event of a significant misalignment of the shafts during construction. The offset pole could still be used to observe and align with both elongations using the targets on the instrument below. This strengthens the case indicating that the initial orientation of the Trial Passages did not have to be very precise in order for them to be used to carry out very precise measurements. That was an unexpected result but it shows the strength of carrying out experimental archaeology. The approach has consistently proved to be effective and informative and tools and models can now be made in physical reality and/or in a more sophisticated virtual environment to further explore the set up.<sup>42</sup>

The final task to be accomplished once the pole and targets were aligned would be to transfer the vertical location of the center point between the two targets vertically up to the surface level (Figure 10). The plumb line was used for this purpose and it would have to be completely still during this procedure. This would establish point (P2), being the southern end of the main alignment at ground level. Both points, (P1) (N) and (P2) (S), that defined the final alignment would then have been accurately marked on the horizontal surface plane (Figure 10).

A note must be included here regarding the ground level around the passages. Rather than being carefully levelled like the pavement area around the Great Pyramid was, Petrie showed on his section drawing that the exposed bedrock surface around the passages is irregular and falls away to the north end. The ground there is clearly lower and is broken up, and so the reality of the structure deviates significantly from the ideal model tested above. Figure 8, however, shows how the alignment process could work even if the indicator pole were embedded below the ideal horizontal ground level. In essence, the geometric system would function just as it does in the ideal model, although the horizontal final alignment line would be elevated above the bedrock in places. A new topographical survey of the area could provide more data allowing more in-depth analysis, but as Petrie mentions there was already structure removed from the area around the northern passage entrance by the time he surveyed it in 1882/3, it could be difficult to reconstruct the structure and surface in its original form for this location.

## **Observations referencing the wider dataset and historical context**

It is informative to place the cardinal alignment data for the Great Pyramid within the wider dataset derived from pyramids built during the third through sixth dynasties.<sup>43</sup> With the Thuban-based alignment procedure described above, precession is not a factor, so the various values of casing alignment errors should be compared in order to identify other possible causal factors.

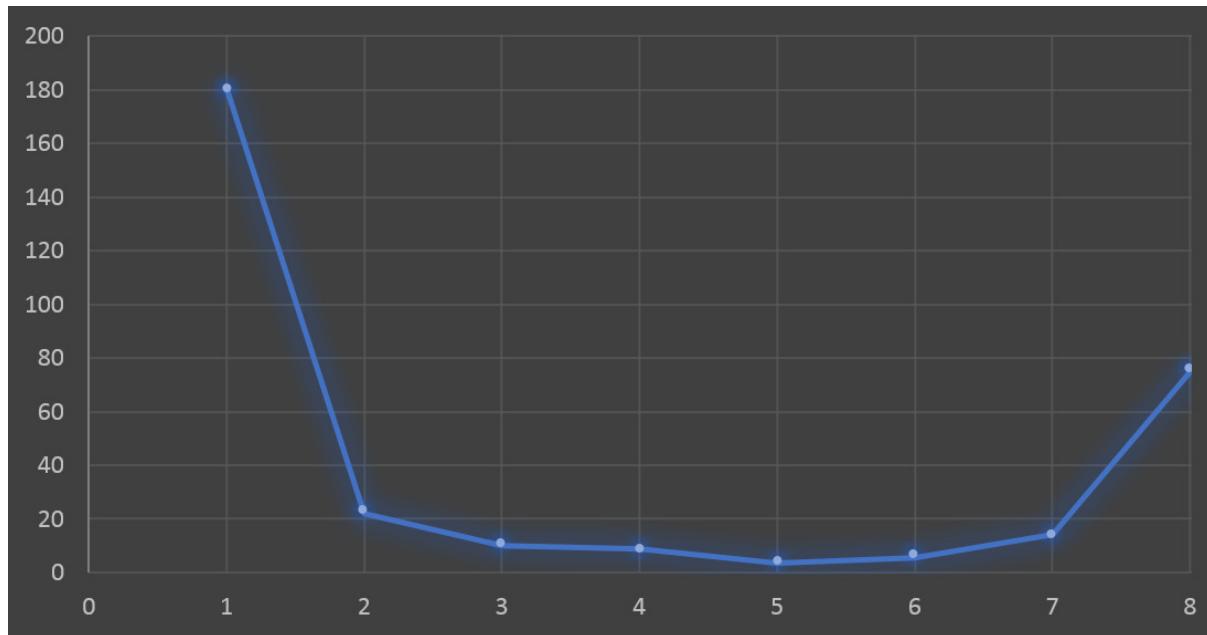
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between the inside edge of the sight and the east-side edge of the pole remained constant for any eye height, as they are parallel and the sight line connecting them was at a constant angle for any observer eye height.

<sup>41</sup> At 13.54 m distance, 2 degrees equates to 47 cm.

<sup>42</sup> It should be noted, however, that the closer the main axis of the shafts was to True north in the first place, the more accurate the final results would be, as the horizontal E-W axis of the targeting instrument track down below would be more symmetrically aligned with the surface pole and the NCP.

<sup>43</sup> Other Egyptian pyramids do not have similar “mini-observatories” nearby. It may be proposed that they used above-ground measurement techniques, which may go some way towards explaining their lower levels of accuracy and precision. Additionally, the second and third great pyramids at Giza may have used the same line as a reference, or the west side of Khufu’s monument.



**Fig. 11.** Errors in orientation to true north and variation through time (absolute values in arcminutes). 1. Djoser, 2. Meidum (passage), 3. Bent, 4. Red, 5. Khufu, 6. Khafre, 7. Menkaure, 8. Average of Sahure and Neferirkare. Data derived from Haack (1984) and Dash's working paper on the Simultaneous Transit method (2015). For Sahure (Spence 2000) gives 23° west of north and Jaromir Krejci (unpublished) approximately 20° west of north.

Figure 11 shows a plot of absolute values of pyramid alignment errors through time.<sup>44</sup> The pattern of change corresponds well with conclusions drawn from other aspects of the monumental architecture of the period, and wider historical information about the Old Kingdom.<sup>45</sup> The trends and errors in the dataset can be explained by an increasing level of construction quality and accuracy leading up to Khufu's reign, followed by a decreasing level of quality and accuracy, as the Old Kingdom began to decentralize, and slowly headed toward eventual disintegration. The pattern also corresponds inversely with the magnitude of the construction projects. As the pyramids got larger, their alignments became more precise.

Another significant observation is that the descending passages in pyramids were apparently even more accurately aligned to north than their outer casings. Dash noted that it would be easier to align the sloping descending passages directly to the northern stars than it would be to set out a horizontal line using a system with tall plumb lines, such as is proposed here. The latter method would then have been used to define the alignments of the horizontal sides of the monuments only. In Khufu's case the east side would have been defined first, and it is the most accurately oriented side. This methodological difference can explain the qualitative difference in accuracy levels between descending passages and outer casing alignments.

<sup>44</sup> Without regards to the sign of the rotational values; whether negative or positive.

<sup>45</sup> Dash (2015c), Figure 5.

## Iconographic sources

From the end of the First Intermediate Period onwards, an artistic convention developed that incorporated representations of the northern stars as well as important decanal stars and those near the ecliptic (most notably Orion and Sirius) on coffin lids. This was first included as an artistic theme on 11<sup>th</sup> dynasty coffins from Asyut.<sup>46</sup> During the New Kingdom, more elaborate versions of the scene were included in elite tomb artwork, most often on the vaulted ceilings of the burial chambers. These are referred to as astronomical ceilings, the most famous of which is that found on the ceiling of Senenmut's early 18<sup>th</sup> dynasty tomb at Deir-el Bahri. It is not the intention of this article to address those diagrams in detail, but it is worth noting that the scenes seem to represent a procedure through which the deceased would be able to orient to north, and perhaps the dates when this procedure should be carried out. This would allow the deceased to find the imperishable stars, despite the fact that their tomb was not oriented according the cardinal directions like the pyramids had been.

The scenes remain enigmatic, but some scholars have also suggested that the tall element at the center of the scene should be interpreted as a gnomon or sighting instrument.<sup>47</sup> A 19<sup>th</sup> dynasty scene from the Ramesseum is particularly interesting in this respect (Figure 12), as it seems to show deities holding marker posts and stretching cords up to the polar constellations. The part of the relief showing a motif named *Meskhetiu* is thought to refer to today's Ursa Major (Big Dipper, Plough, Great Bear) asterism, . This element is often shown in the form of a bull, a bull's foreleg, or a bull's hide and head.

As well as having the form of bull's foreleg it is believed that the constellation was perceived as being shaped like an adze (a woodworking tool), and that it may have been symbolically related to the adzes used in the funerary ritual known as the opening of the mouth ceremony. All of these ideas are associated with rebirth into the afterlife.

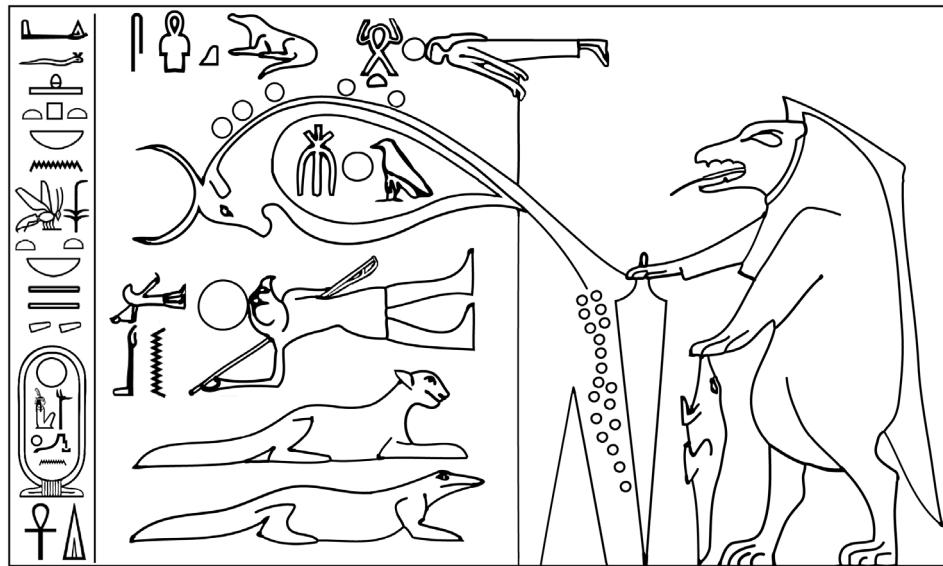
Thuban lies between the two Ursa asterisms in the sky and they may have been used as indicators to help identify which star in the sky was Thuban. An alignment of the two stars near the handle of the Big Dipper, pointing towards Ursa Minor, indeed runs past Thuban. When the Big Dipper was to the west of Thuban in the night sky then Thuban would have been very close to transiting the meridian and therefore close to true north. This could have provided a rudimentary method of accurately finding true north that may have been developed once the movements of the circumpolar stars had been studied, measured, and understood during the Old Kingdom. It is not the intention of this article, however, to study or analyze these diagrams in any more detail here, but it is worth being aware of them when considering the practical methods that might have been developed to find true north in the Memphite Necropolis during the Old Kingdom.

## Conclusions

The monumental Old Kingdom architecture of Giza continues to fascinate the global audience as well as archaeological experts. The precise cardinal alignment of Khufu's Great Pyramid is one of the most impressive aspects of its design and construction and it has remained challenging to explain how it was achieved. This study puts forwards a new hypothesis that the so-called Trial Passages east of the Great Pyramid were used in the alignment process.

<sup>46</sup> Coffin lids from Assiut, 11<sup>th</sup> Dynasty, Neugebauer and Parker (1960), Vol. I, plates 4-21.

<sup>47</sup> Lull (2009).



**Fig. 11.** Representations of the stars of the northern circumpolar region, as well as elements indicating an alignment procedure and associated equipment. From the Ramesseum (New Kingdom). The bull represents Meskhetiu, part of Ursa Major.

To test this hypothesis, experiments and calculations were carried out in conjunction with a virtual 3D model and planetarium software. These demonstrated that it is conceivable that a horizontal line on the surface could have been established that deviated by less than  $1/15^{\text{th}}$  of a single degree from true north, using the rudimentary method described and the rock-cut structure. It must be stressed, however, that it would have required an observer with excellent eyesight, a prolonged observation period perhaps stretching into several years, and very carefully handling of the different small components of the instrument to achieve this high level of precision.

The observations would have culminated with the positioning of two moveable targets, between which a mark would have been created that defined the east-west position of the point P2 on the surface. Any positional offset measured would have been translated to the surface using cubits and a long plumb line hanging down the central vertical shaft. The model showed that an offset of nearly 1 palm east from the centerline of the Trial Passage's architecture would have produced a final alignment equal to that observed in the survey of the Great Pyramid's base perimeter, once points (P1) and (P2) were connected.

Once the main alignment line was established, it would have been possible to accurately extend the line to the north and south with simple surveying techniques, but it would have been more complex to accurately displace the alignment east and west, for example to define the pyramid's east side which lay 87.5 m to the west. That task lies outside the scope of the current study, but it is worth noting that once the orientation of the NCP was established, it would also have been possible to note when Thuban crossed the meridian, directly above or below the NCP. If this information was quickly communicated across the work site, then any worker with a portable *merkhet* (a hand-held plumb bob and sight) would have been able to set up a local alignment to Thuban and the NCP that was extremely accurate. More elaborate devices might have allowed highly precise local alignments to be set up anywhere across the site at the given time. In that case, the local alignments were derived from the long duration measurements taken in the Trial Passages, but were not directly linked to them by physical terrestrial surveying measures.

There is almost no written or physical evidence of the methods used to achieve the alignment, and so the proposed arrangement described here in this article remains hypothetical. There is no suggesting that this interpretation is definitive in any way, but it should prove interesting food for thought for the many scholars who remain intrigued by the early developments in the exact sciences made at Giza. Future field work to study the architectural remains of the Trial Passages seems an unlikely scenario at present, but renewed interest in them may help initiate improved measures to preserve them for future generations, and a new topographical surface survey would be informative.

The results of this research project demonstrate that experimental archaeology has strengths as a research strategy. This research showed that archaeological experiments can be carried out in the virtual world just as they can be carried out in the real world. Increasingly sophisticated computers and virtual or enhanced reality environments will undoubtedly become more prominent research tools in the future. Just as non-destructive testing methods have certain advantages over more traditional and destructive archaeological methods, virtual archaeological research environments allow researchers to carry out work while avoiding many of the problems inherent with site-based archaeology. Travel costs, environmental damage, permit delays, and safety issues can all be avoided in the virtual world.

## Bibliography

- Arnold, D. (1991), *Building in Egypt: Pharaonic Stone Masonry*, Oxford: Oxford University Press.
- Arnold, D. (2003), *The Encyclopaedia of Ancient Egyptian Architecture*, New York: I.B. Taurus.
- Baines, J. and Yoffee, N. (1998), ‘Order, Legitimacy, and Wealth in Ancient Egypt and Mesopotamia’, in *Archaic States*, edited by G.M. Feinman and J. Marcus, Santa Fe: School of American Research Press.
- Belmonte, J.A. (2001), ‘On the Orientation of Old Kingdom Egyptian Pyramids’, *Journal for the History of Astronomy, Archaeoastronomy Supplement* 32, pp. S1-S20.
- Belmonte, J.A., Polo, M.A.M. and Miranda, N. (2009), ‘Unveiling Seshat: New Insights into the Stretching of the Cord Ceremony’, in J.A. Belmonte and M. Shaltout(eds.), *In Search of Cosmic Order: Selected Essays on Egyptian Archaeoastronomy*, Cairo: SCA Press.
- Bronk Ramsey, C., Dee, M.W. Rowland, J.M., Higham, T.F.G., Harris, S.A., Brock F. and Quiles, A. (2010), ‘Radiocarbon-Based Chronology for Dynastic Egypt’, *Science* 328, pp. 1554-1557.
- Chatley, H. (1940), ‘Egyptian Astronomy’, *The Journal of Egyptian Archaeology* 26, pp. 120-126.
- Cole, J.H. (1925), *The Determination of the Exact Size and Orientation of the Great Pyramid of Giza*, Paper no. 39, Cairo: Survey of Egypt.
- Dash, G. (2013), ‘How the Pyramid Builders May Have Found Their True North’, *AERAGRAM* 14, pp. 8-14.
- Dash, G. (2015a), ‘Did the Egyptians Use the Sun to Align the Pyramids?’, *AERAGRAM* 15-1 & 2, pp. 4-28.
- Dash, G. (2015b), ‘The Great Pyramid’s Footprint: Results from Our 2015 Survey’, *AERAGRAM* 16-2, pp. 8-14.
- Dash, G. (2015c), ‘Simultaneous Transit and Pyramid Alignments: Were the Egyptians’ Errors in Their Stars or in Themselves?’, *Glen Dash Foundation for Archaeological Research*, Vol. Revision of January 27.
- Dash, G. (2017), ‘Occam’s Egyptian Razor: The Equinox and the Alignment of the Pyramids’, *The Journal of Ancient Egyptian Architecture* 2, pp. 1-8.
- Dorner, J. (1981), *Die Absteckung Und Astronomische Orientierung Aegyptischer Pyramiden*, Innsbruck: Universitaet Innsbruck.
- Edwards, I.E.S. (1979), *The Pyramids of Egypt*, Middlesex: Penguin.
- Greenlees, D. (1925), ‘The So-Called “Trial Passages” of Petrie East of the Great Pyramid’, *Museum of Fine Arts, Boston, Giza Excavation Diary*, Vol. 4, p. 308.
- Greenwell, D. (2005), ‘Ancient Egyptian Temples: The Foundation Ceremony and Foundation Deposits’, *The Ostracon. The Journal of the Egyptian Study Society* 16-2, pp. 3-6.
- Haack, S.C. (1984), ‘The Astronomical Orientation of the Egyptian Pyramids’, *Journal for the History of Astronomy* 15, no. Archaeoastronomy Supplement, p. 119.

- Khurana, H. and Symons, S. (2016), 'A Catalogue of Ancient Egyptian Sundials', *Journal for the History of Astronomy* 47-4, pp. 375-85.
- Lehner, M. (1985), *The Pyramid Tomb of Hetep-Heres and the Satellite Pyramid of Khufu*, Mainz Am Rhein: DAIK and Verlag Phillip von Zabern.
- Lightbody, D. and Monnier, F. (2019), *The Great Pyramid: Haynes Operations Manual*, Sparkford: Haynes.
- Lull, J. (2009), 'A Possible Ancient Egyptian Astronomical Instrument for Positioning the Central Meridian', *Discussions in Egyptology* 46, pp. 47-56.
- Lull, J., and J.A. Belmonte (2009), 'The Constellations of Ancient Egypt' in *In Search of Cosmic Order, Selected Essays on Egyptian Archaeoastronomy*, edited by J.A. Belmonte and M. Shaltout, Cairo: SCA Press.
- Maragioglio, V. and Rinaldi, C.A. (1965), *L'architettura Delle Piramidi Menfite 4. La Grande Piramide Di Cheope Plates*, Vol. IV: Rapallo.
- Maragioglio, V. and Rinaldi, C.A. (1965), *L'architettura Delle Piramidi Menfite 4. La Grande Piramide Di Cheope Text*, Vol. IV: Rapallo.
- Monnier, F. (2017), *L'ère des géants*, Paris: Éditions de Boccard.
- Neugebauer, O. and Parker, R.A. (1960), *Egyptian Astronomical Texts. Four Volumes: I. The Early Decans; II. The Rameside Star Clocks; III. Decans, Planets, Constellations and Zodiacs (Text); III. Decans Planets, Constellations and Zodiacs (Plates)*, Providence: Brown University Press.
- Parker, R.A. (1950), *The Calendars of Ancient Egypt*, SAOC 26, Chicago: University of Chicago Press.
- Petrie, W.M.F. (1883), *The Pyramids and Temples of Gizeh - 1st Edition*, London: Field & Tuer.
- Petrie, W.M.F. (1990), *The Pyramids and Temples of Gizeh - 2nd Edition from 1885 Republished in a New and Revised Edition with an Update by Zahi Hawass*, London: Histories and Mysteries of Man Ltd.
- Robins, G (1995), 'Mathematics, Astronomy, and Calendars in Pharaonic Egypt', in J.M. Sasson, J.M. Baines, G. Beckman and K.S. Rubinson (eds.), *Civilizations of the Ancient Near East*, Vol. 3, London: Charles Schribner's Sons.
- Salmas, A.C. (2013), 'La Mesure du temps de la journée (I). Modules et fonctionnement des premières horloges à ombre', *BIFAO* 113, pp. 353-380.
- Salmas, A.C. (2014), 'La mesure du temps de la journée (II). Modules et fonctionnement des horloges à ombre tardives et des cadran solaires', *BIFAO* 114, pp. 419-46.
- Spence, K. (2000), 'Ancient Egyptian Chronology and the Astronomical Orientation of the Pyramids', *Nature* 408, pp. 320-324.
- Vyse, H. (1840), *Operations Carried on at the Pyramids of Gizeh in 1837: With an Account of a Voyage into Upper Egypt, and an Appendix*, London: J. Fraser.
- Wilkinson, T.A.H. (2001), *Early Dynastic Egypt*, London: Routledge.

The 3D model of the Trial Passages developed for this research project has been shared with colleagues on Sketchup 3D Warehouse (go to <https://3dwarehouse.sketchup.com/> and search for "Trial Passages by David Lightbody") so that other researchers can test, adapt, and use it as they see fit within their own virtual research environments. The author can be contacted at [davelightbody@hotmail.com](mailto:davelightbody@hotmail.com)

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## Appendix

### Photos I-VII

Photographs of the Trial Passages site from 2003:

I - General view to SW, II - S entrance, III - central shaft, IV - descending passage from N entrance, V, VI - N entrance, VII - General view from N (courtesy of Jon Bodsworth with permission).



I



II



III



IV



V



VI



VII



# La scène de traction du colosse de Djéhoutyhotep.

## Description, traduction et reconstitution

Franck Monnier

### *Abstract:*

*This article reports a project by the author to analyze the well-known scene showing the transportation of the colossus statue of Djebutyhotep displayed in his tomb at Dayr al-Barshā. As part of the analysis, the author created a full-color reconstruction of the original scene, and carried out a full review of the most up-to-date scholarship available on the subject matter. Finally, the article provides a full translation of the hieroglyphic texts accompanying the scene and interpretation regarding the transportation technique they describe.*

De nombreuses<sup>1</sup> civilisations et sociétés antiques ont cultivé un art lié au mégalithisme, qu'il fût appareillé ou monolithique.<sup>2</sup> Cependant, extrêmement rares sont les témoignages qu'elles nous ont légués pour exposer avec plus ou moins de détails les techniques mises en œuvre dans le déplacement de charges hors normes. Dans cette documentation très parcellaire, on compte la célèbre scène de traction d'un colosse peinte sur un mur de la tombe de Djéhoutyhotep, qui s'est trouvée reproduite et commentée d'innombrables fois.<sup>3</sup> Les relevés aux traits existants datent tous du 19<sup>e</sup> siècle et aucun n'avait offert de restituer l'intégralité des couleurs originales.<sup>4</sup>

L'objectif de cet article est tout d'abord de proposer pour la première fois une restitution complète de la fresque (pl. I).<sup>5</sup> Non pas qu'elle ait la prétention d'être définitive puisqu'une mission épigraphique est actuellement menée par l'université KU Leuven dans le cadre du Dayr al-Barshā Project. De nombreux détails seront certainement mis en lumière par ce programme, notamment sur le style et le rendu des hiéroglyphes, et conduiront à une mise au trait parfaitement fidèle qui, seule, pourra rendre justice à l'extraordinaire qualité de cette œuvre.

1 Nous adressons nos sincères remerciements à Marleen De Meyer qui a eu la gentillesse de nous communiquer les précieuses photographies reproduites dans cet article. Nous sommes également très reconnaissant envers Michel Dessoudeix, Daniel Malnati, Marleen De Meyer et Toon Sykora pour nous avoir aidé à améliorer et corriger son contenu. Toute erreur subsistante serait bien entendu de la seule responsabilité de l'auteur.

2 Nous utilisons ici la signification étendue du terme qui permet de qualifier une maçonnerie composée de blocs exceptionnellement volumineux ou les grands monolithes (colosses et obélisques).

3 Les références bibliographiques contenant les premières reproductions sont listées dans De Meyer et Willems (2016-2017), pp. 37-39.

4 John Gardner Wilkinson avait composé une aquarelle de la scène (elle est reproduite dans Málek et Baines (1981), pp. 126-127). Rapidement esquissée, celle-ci ne constitue pas à proprement parler une reproduction.

Certaines aquarelles détaillées avaient été exécutées mais jamais publiées. Certaines d'entre elles ont été mises en ligne sur le site du Griffith Institute [[http://www.griffith.ox.ac.uk/archive/GI-watercolours/Deir-el-Bersha/GI\\_wd\\_Deir\\_el\\_Bersha\\_Djehoutihotep\\_1.html](http://www.griffith.ox.ac.uk/archive/GI-watercolours/Deir-el-Bersha/GI_wd_Deir_el_Bersha_Djehoutihotep_1.html)] ; consulté le 02 décembre 2019]. Voir aussi De Meyer et Cortebeeck (2015).

5 À partir des photos prises par Major Hanbury Brown (Davies (1999), pp. 29-35), des relevés de P. E. Newberry (Newberry et Fraser (1895), pl. XIV-XV) et d'une photo récente que Marleen De Meyer nous a aimablement communiquée (fig. 2).

Dans l'attente de l'accomplissement de cette mission, nous avons analysé des détails de la scène et l'ensemble des textes qui l'accompagnent. Ce travail, accompagné d'une mise au point sur la traduction du récit, est ici exposé et suivi d'un ensemble de commentaires sur le procédé décrit par les artistes égyptiens.



**Fig. 1.** Entrée de la chapelle et de la tombe de Djéhoutyhotep  
(© Dayr al-Barshā Project, KU Leuven ; photo de Marleen De Meyer).



**Fig. 2.** Scène de traction du colosse dans la chapelle de Djéhoutyhotep  
© Dayr al-Barshā Project, KU Leuven ; photo de Marleen De Meyer).

## Description

Cette scène de traction d'un colosse figure dans la chapelle située au-dessus de la tombe du nomarque Djéhoutyhotep (12<sup>e</sup> dynastie, tombe n°2 (17L21/1)) à Deir el-Bersheh (ou Dayr al-Barshā<sup>6</sup>), sur le mur ouest de la pièce principale.<sup>7</sup> Cette représentation est la plus détaillée de ce type dans le répertoire iconographique égyptien.<sup>8</sup> De surcroît, elle est accompagnée de textes descriptifs qui offrent de précieux renseignements sur la méthode et la main-d'œuvre employées dans ce type d'opérations.

Les décors de la chapelle ont grandement souffert depuis leur découverte au 19<sup>e</sup> siècle. D'importants fragments ont été vandalisés et d'autres sont tombés en poussière suite à un tremblement de terre. Tous ces événements sont survenus avant que l'état des lieux ne soit dressé par l'égyptologue Percy E. Newberry.<sup>9</sup> Fort heureusement, les relevés de ce dernier purent bénéficier de l'existence d'une photographie amateur prise juste avant les dégradations par un certain Major Hanbury Brown.<sup>10</sup> La fresque est désormais très lacunaire et le texte accompagnant la traction du monolithe quasi intégralement détruit.

<sup>6</sup> Willems (2013), p. 188.

<sup>7</sup> Au sujet de la fouille et de la description de la tombe : Willems *et al.* (2009), pp. 377-342.

<sup>8</sup> Pour une bibliographie détaillée de la découverte et la description de la tombe, se diriger vers De Meyer et Willems (2016-2017), pp. 37-39.

<sup>9</sup> Newberry et Fraser (1895), pp. 2-5.

<sup>10</sup> Newberry et Fraser (1895), p. 5 ; Davies (1999), pp. 29-35.

La scène immortalise le déplacement d'une effigie colossale arborant les traits du propriétaire de la tombe, une faveur que ce dernier gagna auprès de son souverain, probablement Sésostris III, le dernier roi sous lequel officia le gouverneur.<sup>11</sup> L'évènement était sans doute exceptionnel, peut-être même sans précédent pour un dignitaire. Nul autre n'avait connu un tel privilège et, même pour un roi, ériger une statue d'une telle dimension était chose peu commune avant le Nouvel Empire.<sup>12</sup>

Le décor est planté dans le 15<sup>e</sup> nome de Haute-Égypte, le nome du Lièvre, à une dizaine de kilomètres au sud-est de la colline de la ville moderne d'El-Ashmounein, l'antique Hermopolis Magna.

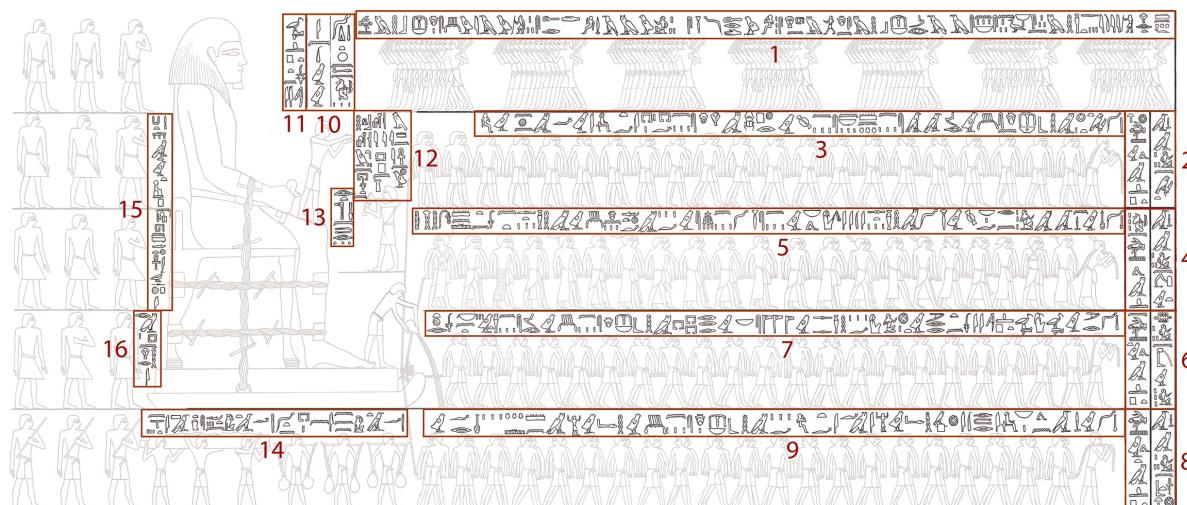
La précieuse charge, montée sur un traineau, est tractée par un corps de 172 jeunes soldats provenant des quatre coins de la région et rassemblés pour l'occasion. La peinture les montre répartis en huit files parallèles de 43 individus disposées sur quatre registres superposés. Le registre le plus élevé décrit des jeunes gens courant, agitant des tiges de palmiers, l'artiste ayant tenu à souligner la dynamique du peuple en liesse qui exprime son enthousiasme devant la majestueuse charge et son imposant convoi.

Un ‘chanteur-meneur’, posté debout sur les genoux de la statue, frappe dans ses mains. Il bat la cadence pour coordonner les mouvements des haleurs et assurer une vitesse constante.

Dans le registre inférieur, sous la statue, sont représentés deux groupes de trois serviteurs. Les premiers portent chacun deux cruches d'eau au moyen d'une palanche.<sup>13</sup> Les suivants portent ensemble sur leurs épaules un lourd madrier dont la face supérieure est grossièrement taillée.

## Traduction des textes

### *Légendes de la scène*



**Fig. 3.** Emplacement des légendes de la scène de traction du colosse de Djéhoutyhotep (Franck Monnier).

11 Il vécut sous Amenemhat II, Sésostris II puis Sésostris III (Newberry et Fraser (1895), p. 3).

12 Amenhemat III fut le commanditaire d'une paire de colosses en quartzite à Biahmou (Petrie (1889), pp. 53-56 ; Habachi (1941), pp. 721-732). D'autres pharaons du Moyen Empire ont sans doute aussi fait dresser de grandes effigies, mais celles-ci ont pour la plupart été réemployées au Nouvel Empire (Sourouzian (1988), pp. 229-254, pl. 62-75).

13 Simon-Boidot (1995), pp. 25-32.

- (1) ‘Le nome du Lièvre est en fête, son cœur est en joie, ses vieillards ont rajeuni, ses jeunes recrues se sont épanouies. Ses enfants jubilent, le cœur en fête, quand ils voient leur maître et le fils de leur maître, dans les faveurs du souverain, en train d’exécuter son monument.’

*Wnt m hb ib.s 3w(.w) b3ws hrd(.w) d3mw[.] sw3d(.w) hrdw.s hr nhm ib.sn m hb m33.sn nb.sn s3 nb.sn m hswt ity hr irt mnwf*

- (2-3) ‘Les jeunes recrues de l’ouest du nome du Lièvre sont venues en paix. Paroles dites : “L’Ouest est en fête ! Leur cœur est en joie quand ils voient les monuments de leurs seigneurs et l’héritier qui prospère parmi eux. Sa maison est la maison de son père lorsqu’il était un jeune enfant.”’

*d3mw n Imntt Wnt iw(.w) m htp dd-mdw Imntt m hb ib.sn 3w(.w) m33.sn mnw n nbw.sn iw<sup>c</sup> hpr m hri-ib.sn pr.f pr it.f iw.f m nhnw*

- (4-5) ‘De jeunes soldats du nome du Lièvre sont venus en paix. Paroles dites : “Il est bon pour les recrues que leur maître a formées ! L’héritier est prospère grâce aux faveurs du souverain, (son) maître ! Nous sommes venus et nous avons prospéré, ses enfants étant à sa suite. Notre cœur est en joie en raison des faveurs du Roi stable et durable.”’

*d3mw n h3wtiw n Wnt iw(.w) m htp dd-mdw nfrw n d3mw ir.n nb.f iw<sup>c</sup> w3d(.w) m hswt ity nb(f) iw.n sw3d.n msw.f m-ht.f ib.n 3w(.w) m hswt nt nsw mn w3h*

- (6-7) ‘Une phyle de prêtres-ouab du nome du Lièvre. Venir en paix. Paroles dites : “Aimé de Thot, Djéhoutyhotep, aimé du Roi, aimé de sa population et loué de tous ses dieux (de la ville). Les temples sont en fête, leur cœur en joie quand ils voient tes faveurs auprès du Roi (litt. ‘de par le Roi’).”’

*s3 n w<sup>c</sup>bw n Wnt iwt m htp dd-mdw mrw Dhwti Dhwti-htp mry nsw mrrw niwt.f hssw ntrw.s nbw r3w-prw m hb ib.sn 3w(.w) m3(3).sn hswt.k nt hr nsw*

- (8-9) ‘Les jeunes recrues de l’est du nome du Lièvre. Venir en paix. Paroles dites : “Mon maître est arrivé à Tjerti. Nemti s’est réjoui de lui. Ses ancêtres sont en fête, le cœur en joie, célébrant les beaux monuments.”’

*d3mw n Bbtt Wnt iwt m htp dd-mdw wd3.n nb.i r Trti Nmti h<sup>c</sup>.w im.fitw.f m hb ib.sn 3w(.w) h<sup>c</sup>.w m mnw[f] nfrw*

- (10) ‘Paroles dites : “battre la mesure pour la troupe par le chanteur-meneur.”’

*dd-mdw dit hn n m<sup>c</sup>s in mdww*

- (11) ‘Djéhoutyhotep, aimé du Roi !

*Dhwti-htp mry nsw*

- (12) ‘Le prêtre-ritualiste et scribe-des-formes (dessinateur) du palais royal qui a peint cette tombe décorée, Horimeniankhous.’

*hry-hbt ss kdwt n pr-nsw ssy pr pn pr(.w) Hr-imn-i-<sup>c</sup>nhw*

- (13) ‘Faire l’encensement.’

*irt sntr*

- (14) ‘Porter l'eau par (ceux) du domaine funéraire. Porter les madriers<sup>14</sup> de la voie de transport par (ceux) des autels.<sup>15</sup>’

*fȝt mw in pr-dt fȝt hwt n sȝ in hȝwt*

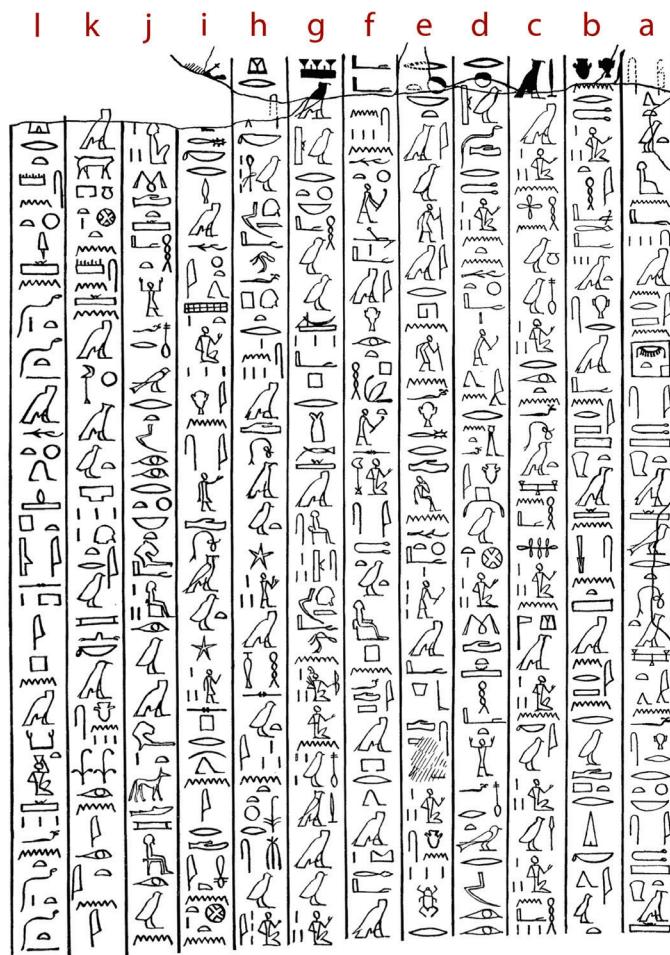
- (15) ‘Le directeur des travaux de cette statue, le scribe du coffre<sup>16</sup> Sépi, fils de Khéti-ankh.’

*hrp kȝt m twt pn sȝ hn Hti-ȝnh sȝ Spi*

- (16) ‘L'intendant Neheri.’

*(i)m(i)-r(ȝ) pr Nhri*

*Texte principal*



**Fig. 4.** Texte principal décrivant le déplacement du colosse de Djéhoutyhotep, situé à l'origine à gauche du colosse mais aujourd'hui disparu (Newberry et Fraser (1895), pl. XIV).

14 Littéralement ‘pièces de bois’.

15 Traduction imposée par le contexte et le terme employé *ȝȝwt* (voir note 19 ci-dessous).

16 Au sujet du ‘scribe du coffre’, voir Falk (2015), p. 85. Le scribe du coffre de la scène de Djéhoutyhotep est représenté avec des documents sous les bras dans une autre scène de la tombe (Newberry et Fraser (1895), pl. XXVII).

‘(a) Escorte d’une statue de 13 coudées (de haut) en pierre d’Hatnoub alors que la route qu’elle avait empruntée était périlleuse plus que toute chose, et qu’il était pénible (b) pour les hommes d’y déplacer des pierres de valeur en raison de la dureté des pierres sur le sol.<sup>17</sup> Je fis venir (c) une troupe de jeunes recrues pour lui aménager la route, avec des équipes d’ouvriers (tailleurs de pierres) des carrières. Les chefs qui étaient avec eux (d) étaient informés.

*šms twt n mh 13 m inr n hwt-nbw ist št3 wrt w3t it.n.f hr.s r ht nb(t) ist št3 hr ib n rm̄t ith 3tiw hr.s m-č inr št3 n snt(t) m inr n rwdt rdi.kw iwt d3mw n hwnw nfrw r irt n.f w3t hnč s3w n hrtyw-ntr n ikww hrpw hnčw rh.w*

Des hommes fortement armés dirent : ‘Nous sommes venus pour la déplacer !’. Mon cœur était en joie et les habitants, unis, étaient en liesse. C’était magnifique à voir plus que (e) toute chose. Il y avait un vieillard qui s’appuyait sur un enfant. Les forts étaient avec les faibles. Leur cœur s’était épanoui. (f) Leurs bras avaient gagné en force et chacun d’eux déployait la force de mille hommes.

*dd rm̄t nt nht-č i.n r int.fib.i 3w(.w) niwt dmd.t(i) hnč.t(i) nfr wrt m33 r ht nbt i3w im rhn.n.f hr hrd nhtw-č m-čb sdtiw ib.sn hpr(.w) wi.sn nht(.w) wč im hr irt pht s h3 (1000)*

Et cette statue (de forme) rectangulaire, sortie de la montagne, était (g) d’une qualité sans égale. Des bateaux avaient été équipés et remplis de choses précieuses, convoyés par ma troupe de soldats. Les jeunes recrues (h) disposées en rangs l’accompagnaient. Leurs voix louaient mes faveurs auprès du Roi. Mes enfants étaient (i) (...) et parés derrière moi. Les habitants de mon nom déclamaient des louanges après que j’atteignis le quai (?) de cette ville.<sup>18</sup> (j) [Les habitants] réunis étaient en liesse. C’était magnifique à voir plus que toute chose.

*ist twt pn ifd(.w) m pr m dw 3 m s3w r ht nb(t) hnčww pr(.w) mh(.w) m špssw tp-m3č n mšč.i n nfrw d3mw hr skw tp-m3č.f tpt-r3.sn m dw3wt m hswt.i nt hr nsw msw.i [...] hkr(.w) m-h̄t.i sp3-č tiw.i hr nis dw3wt spr.n.i r dmi n niwt tn [niwt] dmd.t(i) hnč.t(i) nfr wrt m33 r ht nbt*

Les gouverneurs ont pris leur fonction, les administrateurs ont été désignés (k) [...] à l’intérieur de cette ville. Ce sont des autels<sup>19</sup> sur le fleuve (càd ‘la rive du fleuve’) que j’ai établis. Leur cœur ne pouvait pas imaginer ce que j’ai accompli :

J’ai réalisé pour moi (l) une basse demeure du ka<sup>20</sup> (chapelle) aménagée solidement pour l’éternité, après avoir établi cette mienne tombe grâce à un travail d’éternité.’

*h3tiw-č ir:w m-h3t s3bw d3w-mr ir:w n [...] m-hnw niwt tn smn.n m h3wt tp itrw n k3 ib.sn nn ir:n.i irt.i n.i [hwt-k3] hrt smnh.ti n dt dt m-h̄t htp is.i pn m k3t.f nt dt dt*

17 Littéralement ‘en raison des pierres sur le sol de la voie consistant en pierres dures’.

18 *dmi* signifierait dans ce contexte ‘quai, port’ (Hannig (2003), p. 1476). Le déterminatif employé conforterait ce point de vue (lire Willems, Peeters et Verstraeten (2005), p. 174 (n. 10)).

19 Ce terme *h3wt* signifie ‘autels’ et sa présence ici peut sembler étrange. Les recherches et analyses effectuées par Harco Willems et son équipe ont pourtant démontré l’existence d’un lieu cultuel dédié aux gouverneurs sur la rive orientale du fleuve (Willems (2014a), pp. 198-208). On retrouve ce même terme dans la légende accompagnant les porteurs de madriers.

20 Un petit temple, une chapelle. La mention ‘Demeure du ka’ a disparu, mais une autre figurant ailleurs dans la tombe a permis de combler cette lacune (De Meyer et Willems (2016-2017), p. 53).

## Reconstitution de la technique de transport

Le responsable des opérations est mentionné derrière la statue. Il s'agit du scribe-du-coffre Sépi, fils de Khéti-ankh. Un intendant nommé Néhéri, qui tint probablement une part importante dans l'exécution du projet, a également eu le privilège de voir figurer son nom à sa suite.

La statue est décrite comme étant de 13 coudées (sous-entendu ‘haute de’), soit 6,80 mètres environ. Djéhoutyhotep y est représenté assis sur un siège à dossier muni de pieds en forme de pattes de lion. Elle est dite en ‘pierre d’Hatnoub’, c'est-à-dire en travertin.<sup>21</sup> Elle semble faire corps avec son socle. Le tout est solidement harnaché au moyen d'un cordage et monté sur un traineau dont les patins sont recourbés à l'avant et taillés en biseau à l'arrière.

### *La piste (caractéristiques, parcours et destination)*

Il est exprimé clairement que le madrier représenté sous le traineau (dit ‘pièces de bois de la voie de transport’) était destiné à être posé sur le chemin aménagé spécialement pour l’œuvre. Mais les détails manquent pour en définir l’usage précis. S’agit-il de pièces de traverses,<sup>22</sup> d’une cale d’arrêt,<sup>23</sup> d’éléments dentés ‘antidérapants’,<sup>24</sup> de rails d’une glissière ou encore d’un levier<sup>25</sup>? Toutes ces éventualités ont été émises faute de détails et sans guère d’arguments probants, il faut le souligner. Les nombreuses voies et rampes armées de traverses découvertes jusqu’à présent<sup>26</sup> nous orientent plus favorablement vers un aménagement de la route pour y faire glisser le bloc. Etant donné les quelques dizaines de kilomètres à abattre, il est inconcevable que la route fut pourvue de telles pièces sur tout son long. Un démontage progressif puis un repositionnement à l'avant était une nécessité. Ce madrier pourrait donc représenter des traverses ou tout ce qui sert d'une manière générale à faciliter le déplacement par glissement. Des bas-reliefs assyriens illustrent bien cette technique qui consistait à monter puis démonter la voie lors du passage d'une statue colossale<sup>27</sup> (fig. 5-6).

Il va sans dire que les deux groupes de trois individus ne renseignent en rien sur leur nombre. ‘Trois’, dans l’iconographie et l’écriture égyptiennes, étant la marque du pluriel,<sup>28</sup> le scribe en charge du décor a usé de cette convention pour utiliser l'espace disponible. Cet artiste, le ‘scribe des formes’<sup>29</sup> et prêtre-lecteur Horimeniankh, est d’ailleurs cité et représenté devant le colosse, accomplissant un geste d’encensement. Un autre personnage, anonyme cette fois, vide l’eau d’une jarre à l'avant du traineau. Ce thème iconographique relativement courant traduit un détail particulièrement important de la technique employée pour déplacer des blocs très lourds.<sup>30</sup> D’abord interprété par Newberry

21 Souvent incorrectement appelé albâtre ou calcite-albâtre (Shaw (2010), pp. 11-12).

22 Clarke et Engelbach (1930), p. 85.

23 Choisy (1904), p. 118, fig. 90. ; Goyon (1969), p. 33.

24 Badawy (1963), pp. 328-329.

25 Vandier (1943), pp. 187-190.

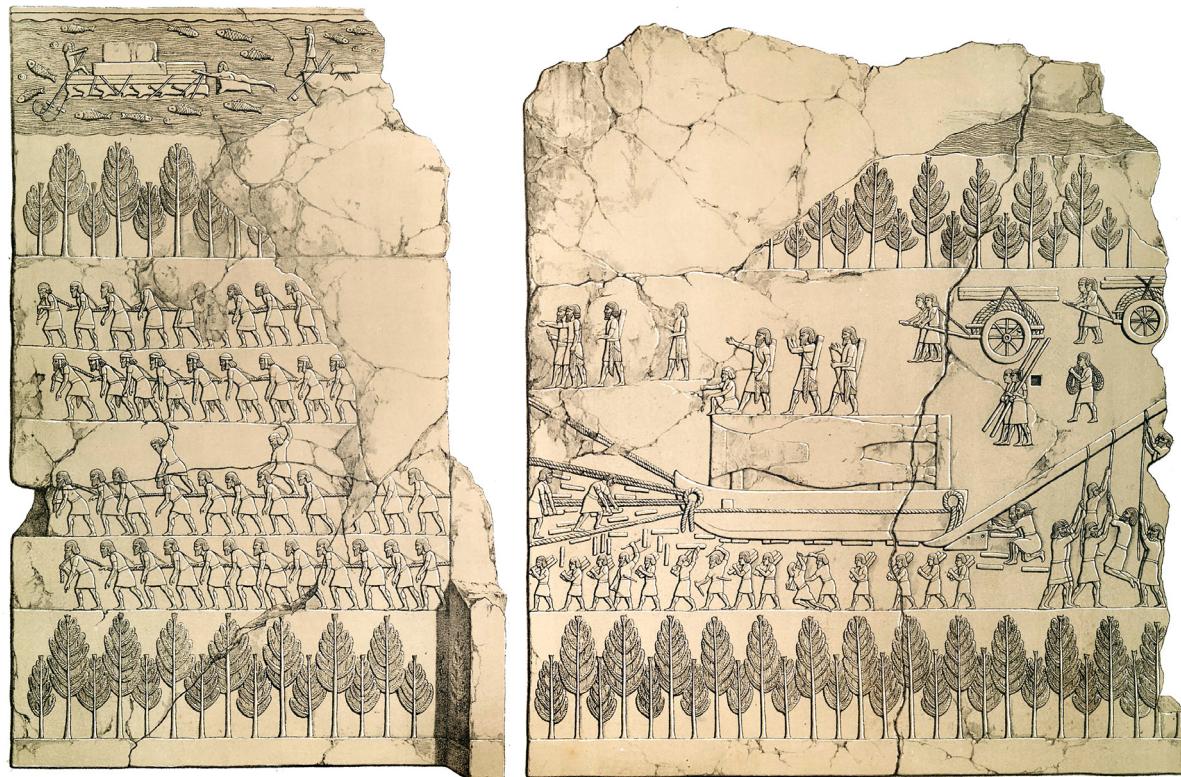
26 Arnold (1991), pp. 79-95 ; Monnier (2017), pp. 221-222. Voir plus récemment ces rails qui permettaient d'y faire glisser de gros blocs bouchons au Ouadi el-Jarf (Tallet, Marouard et Laisney (2012), pp. 406-407, fig. 13 et 15).

27 Davison (1961), pp. 11-16. Davison réfute avec raison l’opinion de Layard selon laquelle ces sculptures auraient été déplacées sur des rondins. Les taureaux avaient emprunté des terrains bien trop accidentés pour rendre cette technique opérante. De plus, l’ensemble des bas-reliefs montre bien que leur voie était recouverte d’une multitude de pièces de bois au profil plat (Layard (1853a), pl. 12, 15, 16 ; Layard (1853b), p. 111). La planche 12 de la référence ci-dessus montre plus clairement des pièces à peine ébranchées, de formes irrégulières, un détail qui a déjà été mis en évidence par Barney Harris (Harris (2018), p. 273).

28 Goyon *et al.* (2004), p. 204.

29 Au sujet des ‘scribes des formes’ (ou ‘des contours’) : Andreu-Lanoë (2013), introduction.

30 Delvaux (2018), pp. 50-51.



**Fig. 5.** Bas-relief assyrien décrivant le transport d'un taureau ailé au moyen d'un traineau glissant sur une piste recouverte de madriers (d'après Layard (1853a), pl. 13).



**Fig. 6.** Bas-relief assyrien décrivant le transport d'un taureau ailé en position verticale (d'après Layard (1853), pl. 16).

comme un acte rituel de purification,<sup>31</sup> il consistait en fait à humidifier la voie afin de réduire les frottements et ainsi diminuer les efforts à fournir. Le technicien qui en avait la responsabilité<sup>32</sup> était régulièrement ravitaillé par les porteurs d'eau représentés plus bas. Il n'était pas nécessaire d'opérer ainsi sur toute la surface de la route, – plutôt que faciliter la tâche des haleurs, cela l'aurait contrariée inévitablement – mais de seulement se focaliser sur les parties en contact.<sup>33</sup> L'adjonction de boue aurait augmenté considérablement l'effet recherché,<sup>34</sup> mais sur une surface restreinte seulement pour éviter de transformer toute la largeur de la voie en véritable glissière impraticable. Et encore cela n'est-il vraisemblable que lorsque le déplacement s'effectuait non loin du fleuve et non sur les pistes désertiques. L'usage d'huile parfois évoqué<sup>35</sup> est non seulement absolument infondé, mais improbable, ne serait-ce que par la quantité faramineuse qu'il aurait fallu produire pour en pourvoir les immenses chantiers de construction (grandes pyramides par exemple).

La légende indique que les porteurs d'eau et de madriers étaient successivement liés au 'domaine funéraire' et aux 'autels'. On peut s'étonner de l'implication de personnels attachés au service funéraire dans le transport fastidieux d'un colosse. Mais tout le texte met l'accent sur l'investissement des habitants de la région d'où qu'ils provenaient. L'entreprise, de par son ampleur, devait requérir toutes les forces disponibles pour être menée à bien. Plutôt qu'être forcé à la tâche, le peuple prenait part à cette action et acquérait la fierté de contribuer à son succès. La faveur acquise par leur gouverneur auprès du souverain l'était aussi pour eux-mêmes.

Le texte principal peint à gauche de la scène offre quelques informations sur le déroulement du transport, sans toutefois être assez clair et précis pour en extraire un scénario détaillé et une reconstitution précise. On y apprend notamment que le terrain n'était pas praticable et qu'il devait être retaillé par une équipe de carriers et de soldats appelés en renfort.

Absolument rien ne subsiste du colosse, si bien que d'aucuns estiment qu'il a pu ne jamais exister, tout au moins dans de telles proportions.<sup>36</sup>

Ne recourant pas à une telle extrémité, la plupart des commentateurs ont débattu de l'emplacement du colosse et de ce qu'il implique sur son trajet et la technique de transport. Khéménou, l'antique Hermopolis Magna sur la butte actuelle d'El-Ashmounéin,<sup>37</sup> se situe sur la rive ouest, de l'autre côté du fleuve au regard d'El-Bersheh, tandis que la nécropole se trouve à l'Est, du même côté que la carrière. Choisir l'une ou l'autre de ses destinations revient donc à envisager le recours à la flottaison ou bien à l'écartier. Dans le premier cas, il aurait fallu disposer d'une flotte spécialisée,<sup>38</sup> entraînant une complexification considérable des techniques à mettre en œuvre (embarquement,

<sup>31</sup> Newberry et Fraser (1895), p. 20. La question fait débat dans le milieu de la tribologie, une partie admettant l'hypothèse de la lubrification par l'eau comme possible (Dowson (1998), pp. 32-57), et les opposants la balayant d'un revers de la main (Nosonovsky (2007), pp. 45-46). Ces derniers ne se reposent cependant que sur la vision dépassée de Newberry. L'état de la documentation a permis d'établir qu'il s'agit bel et bien d'un geste technique (Delvaux (2018), pp. 50-51).

<sup>32</sup> Delvaux (2018), p. 51.

<sup>33</sup> Ayrinhac (2016), pp. 466-473.

<sup>34</sup> Une longue voie composée de traverses et recouverte de boue avait été découverte à Mirgissa en Nubie (Vila (1970), pp. 178-180). Il s'agissait d'une glissière permettant de halter les bateaux par voie de terre pour franchir la cataracte.

<sup>35</sup> Dernièrement Nosonovsky (Nosonovsky (2007)), qui repose son argumentation sur quelques passages tirés de la Bible, mais en ne considérant que très superficiellement la documentation égyptienne.

<sup>36</sup> Par exemple Pieke (2016), p. 101.

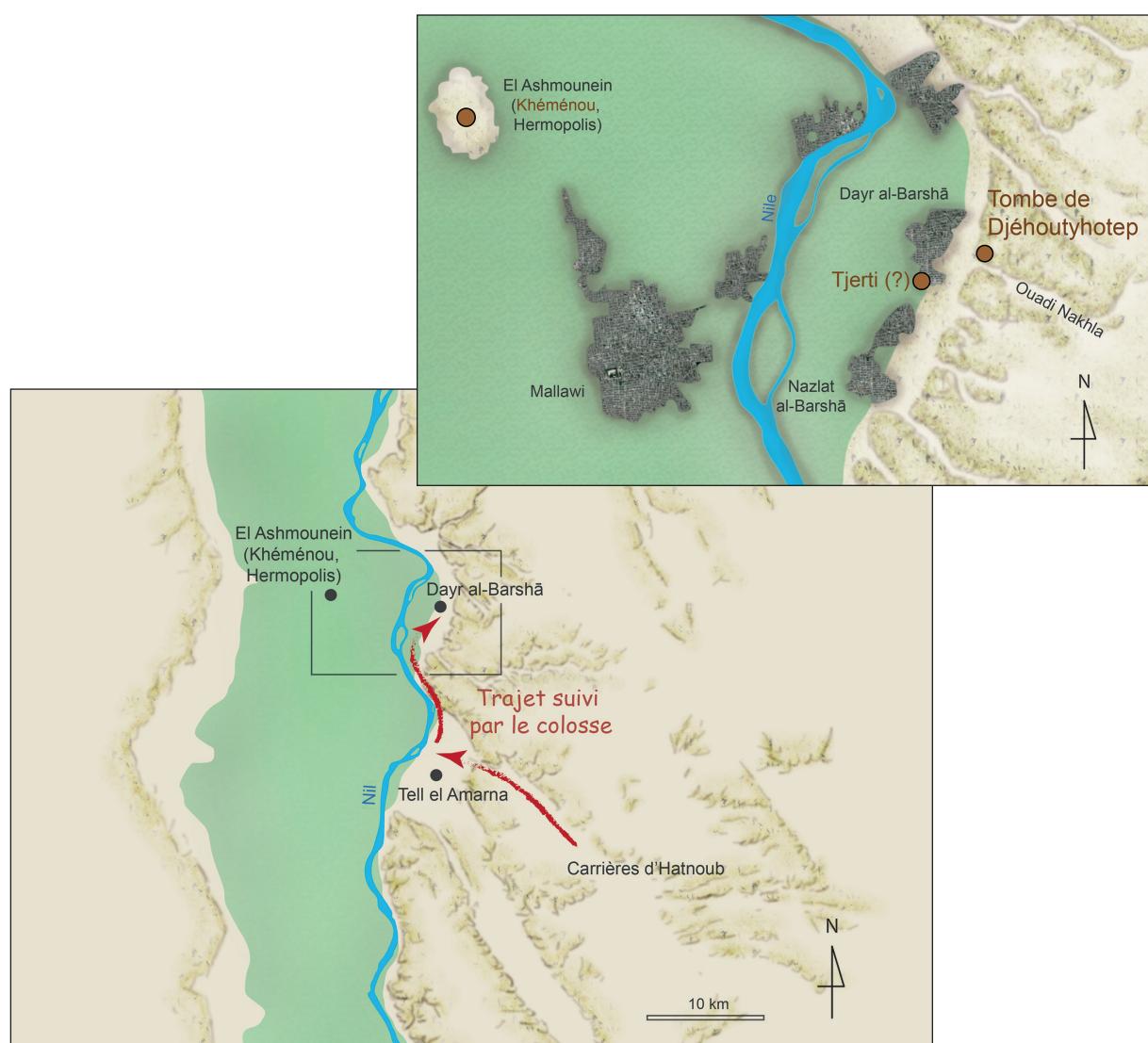
Cette prise de position peut paraître étrange. Selon Gabriele Pieke, l'image du nomarque aurait été démultipliée et l'événement dramatisé pour exalter son impact. Une telle mise en exergue est attestée par ailleurs, mais aucune à notre connaissance ne relate un événement si précis et si riche de détails ; elles se limitent à éléver la stature du personnage. Il faut bien admettre que la présente scène dépasse de loin un tel procédé.

<sup>37</sup> Newberry et Fraser (1895), p. 24. On trouvera une bibliographie à ce sujet dans De Meyer et Willems (2016-2017), p. 35.

<sup>38</sup> Willems, Peeters et Verstraeten (2005), p. 178.

débarquement, contrôle du chaland sur le fleuve), ainsi qu'une augmentation plus que substantielle du coût global des opérations. Dans cette optique, nous nous attendrions à voir cette étape primordiale représentée sur un mur de sa chapelle, mais rien n'y fait allusion. Les scènes et les textes de la tombe du gouverneur mentionnent bien des bateaux et leurs riches cargaisons,<sup>39</sup> mais rien d'autre qu'une succession d'embarcations ordinaires.

L'ensemble de la documentation milite en faveur d'une expédition totalement terrestre.<sup>40</sup> La légende du registre inférieure prête une parole aux jeunes soldats de l'Est du nome qui souligne que le convoi parvient à la ville de Tjerti (sans doute sa destination finale<sup>41</sup>), et non la ville Khéménou et son palais du gouverneur comme on l'a souvent cru.<sup>42</sup> Tjerti pourrait être identifiée au lieu-dit al-Tūd, un



**Fig. 7.** Illustration du trajet suivi par le colosse et son convoi entre les carrières d'Hatnoub et Dayr al-Barshā (en encadré : détails des environs de Dayr al-Barshā) (Franck Monnier).

<sup>39</sup> Newberry et Fraser (1895), pl. 12, 18.

<sup>40</sup> Willems, Peeters et Verstraeten (2005), pp. 173-189 ; Willems (2014b), pp. 106-109.

<sup>41</sup> Willems, Peeters et Verstraeten (2005), pp. 180-181.

<sup>42</sup> On trouvera une bibliographie à ce sujet dans De Meyer et Willems (2016-2017), p. 35.

quartier au sud de Deir el-Bersheh situé à 1500 mètres à l'ouest de la nécropole des gouverneurs,<sup>43</sup> à la marge de l'ancien lit du fleuve.<sup>44</sup> C'est d'ailleurs de ce côté du Nil que proviennent les protagonistes célébrant l'arrivée de la statue. Dans cette optique, le convoi se serait dirigé de la carrière, droit vers le Nil sur une quinzaine de kilomètres pour contourner les reliefs escarpés, puis aurait bifurqué vers le Nord, longeant la berge sur une distance égale pour rejoindre le port de Tjerti, et enfin atteindre un lieu de culte aux ancêtres, situé non loin en contrebas de la nécropole des dignitaires.<sup>45</sup> C'est durant la deuxième étape du parcours que l'escadrille aurait joué un rôle non négligeable, celui de ravitailler et d'assister les troupes qui progressaient péniblement le long de la berge.<sup>46</sup>

Les scènes et les textes de la chapelle de Djéhoutyhotep mettent l'accent sur l'édifice jouissant de ce joyau : la chapelle du Ka<sup>47</sup> (dite ‘basse’ dans le texte). Elle a pour nom : ‘L'amour de Djéhoutyhotep dans le nome du Lièvre est durable’ et ne doit pas être confondue avec la tombe proprement dite. Il est dit que des offrandes en provenance pourront être offertes à la statue tandis que celle-ci était encore en route.<sup>48</sup>

La carrière d'Hatnoub d'où a été extraite la statue se situe à une vingtaine de kilomètres au sud-est, dans le désert oriental.<sup>49</sup> Un réseau antique de routes reliées à ce lieu a été mis au jour aux environs de Deir el-Bersheh, à l'endroit de la nécropole du Moyen Empire, celle où se trouve la tombe de Djéhoutyhotep.<sup>50</sup> Il convient de souligner qu'outre une occurrence du toponyme Tjerti, les inscriptions font constamment allusion à la tombe dans le contexte de la scène. Il est donc fort probable que la statue siégeait non loin pour que les fidèles puissent rendre hommage à leur seigneur près de sa demeure d'éternité en y déposant des offrandes.

#### *Forme et position de la statue sur son traineau*

Le texte décrit la statue comme étant rectangulaire, laissant planer la possibilité d'un bloc seulement équarri lors de son transport.<sup>51</sup> Bien que cela puisse paraître curieux et en complète contradiction avec la scène qui l'illustre, cette option n'en demeure pas moins vraisemblable dans une certaine mesure. Une statue dépeinte achevée et décorée n'entraîne pas obligatoirement qu'elle ait effectivement affiché cette apparence tout le long de son trajet.<sup>52</sup> Il s'agit, plus qu'une convention artistique, de représenter le dignitaire (ou le pharaon dans d'autres cas semblables) dans une stature idéale et non sous un jour défavorable. Ce point de vue est conforté par le soin du détail dont le scribe a fait preuve. Les traits du visage, la chevelure ainsi que la barbe sont peints, et on peut penser que ces touches de finitions n'étaient posées qu'en tout dernier lieu, lorsque la statue était arrivée à bon port puis débarrassée de ses liens. Le qualificatif de ‘rectangulaire’ n'implique pas obligatoirement une forme strictement parallélépipédique, géométriquement parlant. Nous serions donc enclin à penser qu'avant d'atteindre Tjerti, le colosse n'était que grossièrement ébauché afin qu'aucun éclat ni dommage ne vienne entacher la surface du monument.

43 Willems (2013), pp. 188-192, taf. XXIX ; Willems, Peeters et Verstraeten (2005), pp. 173-189.

44 Willems (2014b), p. 108-109.

45 Willems (2014b), p. 107.

46 Willems (2014b), p. 107.

47 Newberry et Fraser (1895), pl. 11 et 16 ; Willems (2014b), pp. 107-108.

Une analyse récente a permis d'établir ce fait (De Meyer et Willems (2016-2017), pp. 34-56).

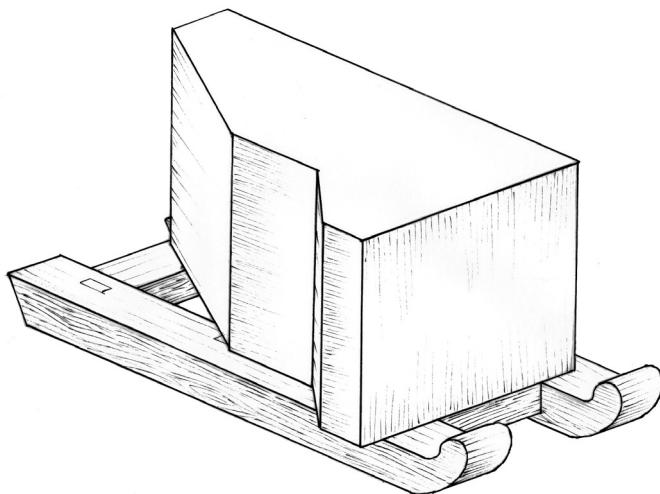
48 De Meyer et Willems (2016-2017), p. 54.

49 Shaw (2010), pp. 1-9.

50 De Laet et al. (2015), pp. 286-300.

51 Willems, Peeters et Verstraeten (2005), p. 174.

52 Newberry et Fraser (1895), p. 25.



**Fig. 8.** Position et forme supposées du monolithe durant la majorité de son parcours (Franck Monnier).

Quant au transport, un déplacement du bloc dans une position verticale durant la majeure partie du trajet est improbable. Du point de vue pratique, déplacer une énorme charge est toujours plus aisée lorsque celle-ci est étendue sur son long (fig. 8). Agir à l'encontre de ce principe vous confronte à des balancements latéraux, risque inutile et surtout insensé lorsqu'il s'agit de franchir des dénivélés et des passages tortueux.

À l'approche de son lieu de destination, deux hypothèses sont envisageables. Soit le monolithe fut toujours acheminé sur son flanc puis érigé à la toute fin des opérations, soit on le redressa pour lui apporter les touches finales afin qu'il effectue la fin de son périple de la manière la plus solennelle.

L'étape représentée sur le mur de la tombe participe davantage d'une parade, de réjouissances durant lesquelles la foule honore son nomarque. Le colosse est accueilli par des fumigations d'encens et les acclamations de la population. Le contexte nous incite à penser que la statue ait effectivement été redressée, peut-être même ravalée pour être parée des traits les plus fins.<sup>53</sup> Les dernières centaines de mètres à parcourir durent davantage tenir d'une procession très festive, rituelle même, le long de laquelle vinrent se masser tous les habitants de la région, afin de participer à un événement que personne n'avait jamais pu contempler jusqu'alors. Comme l'enseignent les scènes de la tombe, des offrandes en provenance de la chapelle d'accueil étaient déjà présentées à la gigantesque effigie.<sup>54</sup> Dans un tel contexte, tout devait être parfait, en premier lieu l'image que Djéhoutyhotep souhaitait renvoyer de lui-même. Des fumigations d'encens embaumait l'air et les louanges pleuvaient. C'est dans une telle atmosphère que les dispositifs et le convoi, soigneusement et méthodiquement mis en place, mirent un point final à l'aventure. La statue, cette fois dressée, aurait avancé lentement et sûrement jusque sur son piédestal. Les traverses du traineau auraient été progressivement ôtées de manière à ce que les patins latéraux avancent de part et d'autre du socle, et ce, jusqu'à ce que la statue y repose.

53 Là encore, le parallèle avec les scènes assyriennes n'est pas dénué d'intérêt puisque l'une d'entre elles montre qu'une fois sculpté, le taureauachevait sa course en position debout (fig. 6).

54 De Meyer et Willems (2016-2017), p. 54.

Un tel scénario n'est plus concevable lorsqu'il s'agit de déplacer et mettre en place des colosses de 750 tonnes,<sup>55</sup> ces derniers exigeant rampes et plans inclinés pour assurer la pose finale.<sup>56</sup> Les dimensions et la masse du colosse de Djéhoutyhotep, certes hors du commun mais toujours 'raisonnables', ne constituaient pas encore un obstacle au type de manœuvres décrit dans ce scénario.

#### *Le nombre de baleurs*

D'une hauteur de 6,80 mètres, le bloc de la statue de Djéhoutyhotep devait peser aux alentours de 80 tonnes et dans les 70 tonnes une fois sculpté.<sup>57</sup>

La fresque montre le colosse tracté par 172 hommes, ce qui amène à une répartition uniforme des efforts à exercer. Si l'on prend la scène au pied de la lettre, c'est-à-dire avec le nombre exact d'individus, chacun d'entre eux devait être à même de déplacer 407 kg. Une étude récente entreprise par Simon Delvaux à partir d'une série de documents égyptiens a révélé que le nombre d'ouvriers représentés respectait globalement une règle de proportionnalité, établit qu'une charge déplacée de 340 kg par personne constituait un ratio moyen, une norme traduisant peut-être une réalité de terrain au-delà de la simple convention artistique.<sup>58</sup> Des expériences grandeur nature menées par l'archéologue Henri Chevrier au temple de Karnak l'ont conduit à constater qu'un homme seul, dans des conditions optimales et sur terrain plat, pouvait mouvoir 1000 kg.<sup>59</sup> Nous sommes loin de ce cas de figure qui constitue une valeur limite finalement rarement applicable dans des conditions réelles. Ces valeurs paraissent représenter un véritable défi physique et pourraient amener à imaginer que les ouvriers ne soient pas tous représentés. Il est fort possible que cette valeur très précise de 172 n'est que la conséquence d'une composition équilibrée sur quatre registres. Il est néanmoins raisonnable de la considérer proche de la réalité. Étant donné l'implication des habitants de la région, rien ne s'opposait à ce que des renforts intervinssent durant les étapes les plus difficiles du parcours, augmentant plus ou moins sensiblement cet effectif.<sup>60</sup>

Une nouvelle comparaison avec les bas-reliefs assyriens est riche d'enseignement.<sup>61</sup> Les taureaux ailés androcéphales pesaient une trentaine de tonnes.<sup>62</sup> Leur déplacement était également assuré par la traction au moyen de quatre cordes disposées côté à côté, et les manœuvres représentés (des forçats<sup>63</sup>) se comptaient toujours entre 50 et 60.<sup>64</sup> On parvient dès lors à un ratio compris entre 500 et 600 kg par personne, une valeur supérieure aux cas égyptiens, mais finalement relativement

<sup>55</sup> Les colosses de Memnon et du Ramesseum par exemple.

<sup>56</sup> Arnold (1991), pp. 66-70. Nous sommes d'avis que le procédé de mise en place d'un colosse monumental était identique à celui d'un obélisque.

<sup>57</sup> Percy E. Newberry avait estimé une masse de 58 tonnes (Newberry et Fraser (1895), p. 23) et cette valeur fut constamment reproduite par la suite. Plus récemment, celle-ci a été corrigée et revue à la hausse : 80 tonnes (Willems, Peeters et Verstraeten (2005), pp. 173-174 (n. 6)). Les calculs de Simon Ayrinhac ont abouti à une valeur de 70 tonnes (avec une marge d'erreur de plus ou moins 5 tonnes) (Ayrinhac (2016), pp. 470-471). On lira également également Michel (2019). Nos propres estimations ont abouti à cet ordre de valeurs : près de 80 tonnes pour le bloc ébauché et 70 tonnes une fois sculpté aux traits du dignitaire.

<sup>58</sup> Delvaux (2018), pp. 52-53.

<sup>59</sup> Chevrier (1970), p. 20.

<sup>60</sup> On lira également les réflexions de Marianne Michel au sujet du nombre d'ouvriers employés dans la traction des monolithes (Michel (2019)).

<sup>61</sup> Non pas que nous envisageons un lien direct, les événements étant bien trop distants chronologiquement et géographiquement. Mais les documents peuvent s'avérer être complémentaires dans une certaine mesure, l'Égypte et l'Assyrie ayant développé des capacités technologiques semblables.

<sup>62</sup> Danrey (2004), p. 320.

<sup>63</sup> Des soldats assyriens n'hésitent pas à les rosser pour qu'ils s'emploient au maximum.

<sup>64</sup> Layard (1853a), pl. 12, 15, 16 ; Layard (1853b), p. 111.

On peut accorder de l'importance à cette valeur puisque le transport d'autres monuments plus massifs (obélisque et bloc de pierre) a exigé une multitude d'ouvriers que les artistes ont pris le soin de représenter en bien plus grand nombre (Layard (1853a), pl. 10-11).

proximes, dont la différence peut s'expliquer par les conditions de travail plus rigoureuses imposées aux captifs assyriens.

Dans tous les cas, dont celui qui nous occupe ici, il ne s'agissait pas pour chacun de soulever des masses de 400 à 600 kg, mais de les déplacer. L'effort minimal à exercer est proportionnel à la résistance aux frottements du traineau en contact avec le sol. La lubrification par l'eau rendait l'opération humainement réalisable. Une étude récente de tribologie n'a pu aboutir à une conclusion ferme sur les caractéristiques de ce déplacement, en raison du nombre trop important de variables.<sup>65</sup> Comme son auteur, nous sommes convaincu que seule l'archéologie expérimentale est à même d'éclaircir un peu plus la question, notamment les détails relatifs aux matériaux employés pour diminuer les frottements, ou encore la manière de coordonner les efforts de la troupe. Cette équivoque n'est aucunement une remise en cause de la faisabilité d'une telle entreprise. De nombreux documents sont là pour attester que les monolithes égyptiens étaient déplacés par d'immenses corps ouvriers, par exemple le papyrus Anastasi I,<sup>66</sup> ou encore les inscriptions du Ouadi Hammamat qui évoquent jusqu'à 2000 individus employés simultanément dans ce type d'opérations.<sup>67</sup>

### *La ligature*

La fixation au traineau est assurée par des anneaux métalliques (sans doute en cuivre). Les cordes sont mises sous tension en tordant des torons avec de solides tiges de bois selon la technique dite 'du tourniquet espagnol'.<sup>68</sup> En guise de protection, des pièces de cuir (ou en fibres végétales ?) sont calées entre elles et les arêtes du bloc. Dans l'hypothèse où la statue est achevée lors de son transport, il faut éviter de l'écorner, d'en émousser les bords et les angles.<sup>69</sup> Si le bloc n'est qu'équarri, ces protections doivent éviter le cisaillement des cordes.<sup>70</sup>

D'un point de vue technique et pratique, le cordage tel qu'il est représenté est déconcertant. Il a déjà été remarqué que la corde fixant la statue au traineau, serrée sur les cuisses, ne pouvait tenir dans une telle position sans risquer de glisser vers l'avant.<sup>71</sup> En outre, les cordes représentées à l'horizontale ne paraissent d'aucune utilité, si ce n'est d'accentuer un peu plus seulement la tension de cette corde verticale.<sup>72</sup> Cela nous semblerait être une mesure maladroite pour un tel usage. Reginald Engelbach a proposé une solution montrant qu'il n'était nul besoin que ces liens fassent un tour complet.<sup>73</sup> Disposés sur un seul côté, ils pouvaient faire office de tirants perpendiculaires pour présenter l'avantage de retenir la fixation principale tout en la maintenant dans une tension maximale.<sup>74</sup> Il nous paraît en outre évident qu'une telle charge ait nécessité une ligature un peu plus élaborée pour éviter tout glissement ou basculement en arrière, ne serait-ce qu'avec une attache au niveau des pieds. Nous avons déjà souligné ailleurs que le souci d'exactitude n'était pas une préoccupation de l'artiste égyptien, qui réinterprétait bien souvent à travers son propre prisme le sujet représenté<sup>75</sup> (le décorateur n'était pas un responsable de travaux, et la fresque n'avait pas vocation à dresser un bilan technique). Nous devons donc composer avec certaines imprécisions et lacunes inhérentes à ce genre de représentations.

<sup>65</sup> Ayrinhac (2016), pp. 469-470.

<sup>66</sup> Gardiner (1911), I.14.8-16.5, pp. 33-34 ; Fischer-Elfert (1986), pp. 143-147 ; Monnier (2020).

<sup>67</sup> Farout (1994), pp. 143-172.

<sup>68</sup> Joosse (2002), pp. 67-70.

<sup>69</sup> Badawy (1963), p. 325 ; Goyon *et al.* (2004), p. 204.

<sup>70</sup> Delvaux (2018), p. 47.

<sup>71</sup> Joosse (2002), p. 70.

<sup>72</sup> Joosse (2002), p. 69.

<sup>73</sup> Engelbach fit une maquette qu'Henri Chevrier reproduisit plus tard dans son article : Chevrier (1970), pl. 1.

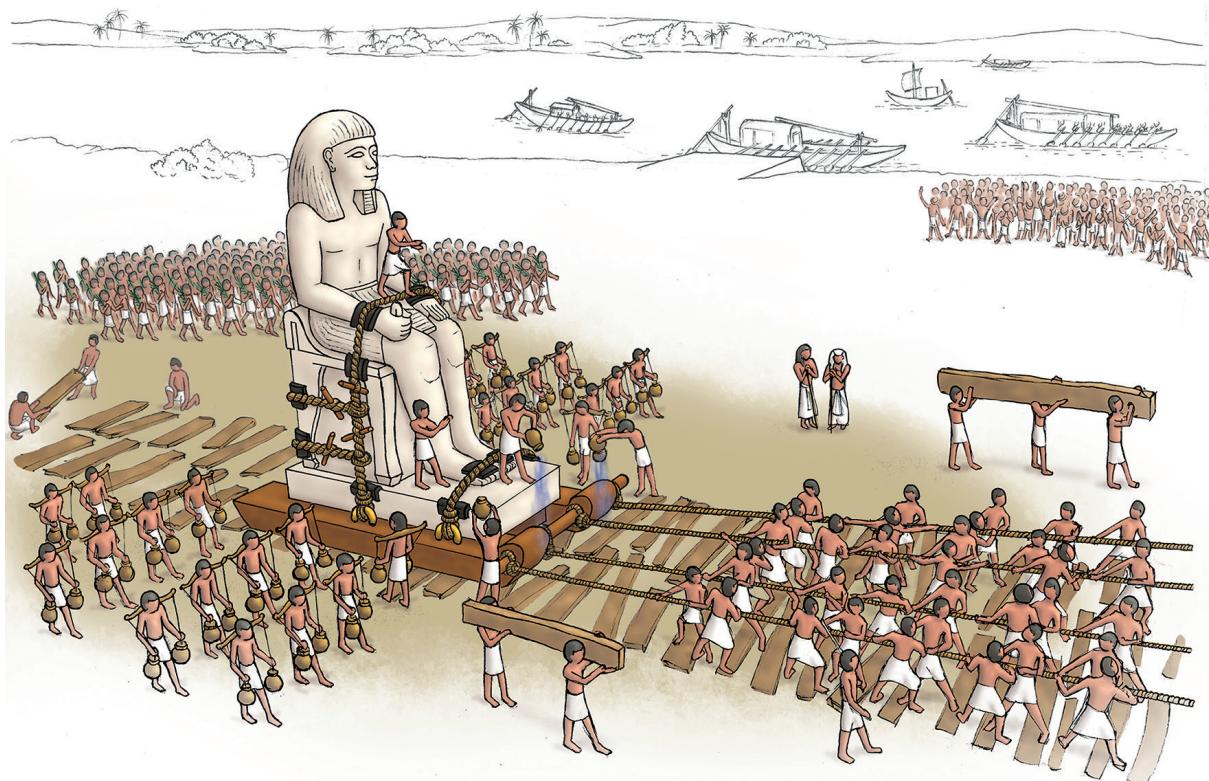
<sup>74</sup> *Ibidem.*

<sup>75</sup> Voir par exemple les représentations de tours de siège (Monnier (2012-2013), pp. 125-138).

## Conclusion

En matière de témoignages égyptiens sur la construction, la scène du colosse de Djéhoutyhotep est d'une rare prolixité. Alliant texte et image, elle nous renseigne sur le responsable des opérations (Sépi, fils de Khéti-ankh), l'origine du monolithe (les carrières d'Hatnoub), sur sa destination (Tjerti), sa taille, et sur la manière dont les sujets du nomarque le déplacèrent sur plusieurs dizaines de kilomètres. Il ne semble pas que le transport fluvial ait été retenu pour soulager les efforts de la troupe. Le nomarque avait une main d'œuvre abondante et rien ne suggère qu'il ait eu la possibilité de disposer d'une flotte spécialisée.

Le traineau était mu par glissement à la force des bras. Leur nombre était fixé en fonction de la charge à déplacer et des difficultés rencontrées. À cet égard, l'artiste (Horimeniankh) semble s'être montré fidèle à une convention puisque les 172 hommes de sa fresque traduisent une masse moyenne déplacée de 400 kg/personne environ, une valeur très proche de ce que l'ensemble de la documentation révèle. Ce ratio ne traduit en rien une réalité rigoureusement mécanique puisque les efforts à exercer se calculent en fonction des frottements, de l'éventuelle pente de la voie, des points d'appuis des ouvriers, de leurs poids, de leur condition physique, etc. Il s'agit d'un problème très complexe dont nous ignorons la plupart des paramètres, mais que l'on pourrait éclairer au terme d'une série d'expériences effectuées en conditions réelles. Cette épreuve du terrain qui nous fait défaut aujourd'hui permit aux Égyptiens de répondre aux défis posés, et probablement d'établir des règles simples telles que ce ratio.



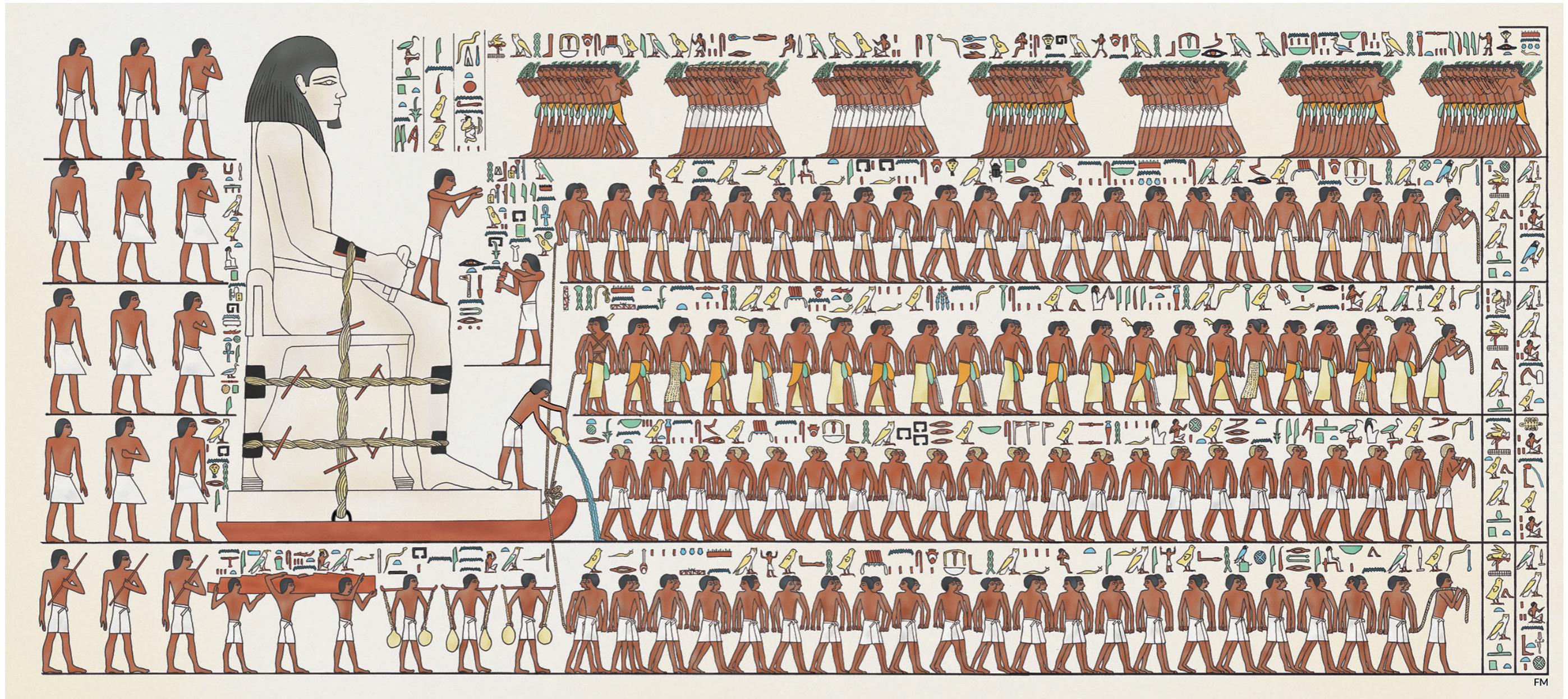
**Fig. 9.** Reconstitution de la traction du colosse de Djéhoutyhotep à l'approche de sa destination (dessin de l'auteur sur la base d'une maquette élaborée par Reginald Engelbach) (© Franck Monnier).

Il n'y a aucune raison de douter que la statue ait été dressée à la verticale sur son traîneau, tout du moins à l'approche de son but, la majeure partie du trajet l'ayant obligée plus probablement à rester sur son flanc. Des bas-reliefs assyriens montrent l'alternance des positions avec cette technique de déplacement. Ceux-ci montrent aussi comment la voie, composée de madriers, était montée puis démontée au fil du cheminement. C'est probablement ce type de traverses qui est représenté en dessous du colosse de Djéhoutyhotep, et non d'hypothétiques cales d'arrêt dont l'emploi demeure malgré tout plausible.

## Bibliographie

- Andreu-Lanoë, G. (2013), *L'art du contour. Le dessin dans l'Égypte ancienne*, Musée du Louvre (Paris) et Musées royaux d'art et d'histoire (Bruxelles), introduction.
- Arnold, D. (1991), *Building in Egypt. Pharaonic Stone Masonry*, New-York/Oxford.
- Ayrinhac, S. (2016), 'The Transportation of the Djehutihotep Statue Revisited', *Tribology Online* 11:3, pp. 466-473.
- Badawy, A. (1963), 'The transport of the colossus of Djehutihotep', *Mitteilungen des Instituts für Orientforschung* VIII, pp. 326-332.
- Chevrier, H. (1970), 'Technique de la construction dans l'ancienne Égypte. II. Problèmes posés par les obélisques', *RdE* 22, pp. 15-39.
- Choisy, A. (1904), *L'art de bâtir chez les Égyptiens*, Paris.
- Clarke, S. et Engelbach, R. (1930), *Ancient Egyptian Construction and Architecture*, Londres.
- Danrey, V. (2004), 'Le taureau ailé androcéphale dans la sculpture monumentale néo-assyrienne : Inventaire et réflexions sur un thème iconographique', dans O. Pelon (éd.), *Studia Aegeo-Anatolica* 39, Lyon, pp. 309-349.
- Davies, W. V. (1999), 'Djehutyhotep's colossus inscription and Major Brown's photograph', dans W. V. Davies (éd.), *Studies in Egyptian Antiquities: A Tribute to T. G. H. James*, BM Occasional Paper 123, pp. 29-35.
- Davison, C. St. C. (1961), 'Transporting Sixty-Ton statues in early Assyria and Egypt', *Technology and Culture* 2:1, pp. 11-16.
- Delvaux, S. (2018), 'L'enseignement de la documentation iconographique de l'Ancien et du Moyen Empire quant à l'utilisation du traîneau', *JAEA* 3, pp. 45-63.
- Dowson, D. (1998), *History of Tribology*, (2<sup>e</sup> éd.), Londres.
- Falk, D. A. (2015), *Ritual processional furniture: A material and religious phenomenon in Egypt*, Thèse de doctorat, Université de Liverpool.
- Farout, D. (1994), 'La carrière du *wḥmw* Ameny et l'organisation des expéditions au Ouadi Hammamat au Moyen Empire', *BIFAO* 94, pp. 143-172.
- Fischer-Elfert, H.-W. (1986), *Die Satirische Streitschrift des Papyrus Anastasi I. Übersetzung und Kommentar*, Wiesbaden.
- Gardiner, A. H. (1911), *Egyptian Hieratic Texts, Part I*, Leipzig, 1911.
- Goyon, J.-Cl., Golvin, J.-Cl., Simon-Boidot, Cl. et Martinet, G. (2004), *La construction pharaonique, du Moyen Empire à l'époque gréco-romaine*, Paris.
- Habachi, L. (1941), 'The Monument of Biyahmū', *ASAE* 40, pp. 721-732.
- Hannig, R. (2003), *Ägyptisches Wörterbuch I. Altes Reich und Erste Zwischenzeit*, Mainz am Rhein.
- Harris, B. (2018), 'Roll me a great stone : a brief historiography of megalithic construction and the genesis of the roller hypothesis', *Oxford Journal of Archaeology* 37(3), pp. 267-281.
- Joosse, A. (2002), 'Spanish lashings in Ancient Egypt ?', *KMT* 13-1, pp. 67-70.
- De Laet, V., van Loon, G., Van der Perre, A., Deliever, I. et Willems, H. (2015), 'Integrated remote sensing investigations of ancient quarries and road systems in the Greater Dayr al-Barshā Region, Middle Egypt : a study of logistics', *Journal of Archaeological Science* 55, pp. 286-300.
- Layard, A. H. (1853a), *A second series of the Monuments of Nineveh: including bas-reliefs from the palace of Sennacherib and bronzes from the ruins of Nimroud*, Londres.
- Layard, A. H. (1853b), *Discoveries in the Ruins of Nineveh and Babylon*, Londres.

- Mâlek, J. et Baines, J. (1981), *Atlas de l'Égypte ancienne*, Paris, pp. 126-127.
- De Meyer, M. et Cortebeeck, K. (2015), *Djehoutihotep. 100 jaar opgravingen in Egypte / Djehoutihotep. 100 ans de fouilles en Égypte*, Leuven, 2015.
- De Meyer, M. et Willems, H. (2016-2017), 'The Regional Supply Chain of Djehutihotep's Ka-Chapel in Tjerty', dans G. Andreu-Lanoë et F. Morfoisse (éd.), *Sésostris III et la fin du Moyen Empire. Actes du colloque des 12-13 décembre 2014 Louvre-Lens et Palais des Beaux-Arts de Lille*, CRIPÉL 31, pp. 33-56.
- Michel, M. (2019), 'Forces de traction en Égypte ancienne, exemples de blocs, statues assises et obélisques', dans *La pierre comme porteur de messages du chantier de construction et de la vie du bâtiment. Actes du XXIe Colloque International de Glyptographie (du 8 au 14 juillet 2018, Amay, Belgique)*, Bruxelles, pp. 319-334.
- Monnier, F. (2012-2013), 'Proposition de reconstitution d'une tour de siège de la XIe dynastie', JSSEA 39, pp. 125-138.
- Monnier, F. (2017), *L'ère des géants. Une description détaillée des grandes pyramides d'Égypte*, Paris, 2017.
- Monnier, F. (2020), 'L'obélisque géant décrit sur le papyrus Anastasi I. Révision du problème', *Les Cahiers Caraïbes d'Égyptologie* 24-25 (en préparation).
- Newberry, P.E. et Fraser, G. W. (1895), *El-Bersheb, part I : the Tomb of Tehuti-hetep*, 3rd Memoir of the Egypt Exploration Fund, Londres.
- Nosonovsky, M. (2007), 'Oil as a Lubricant in the Ancient Middle East', *Tribology Online* 2:2, pp. 44-49.
- Petrie, W. F. (1889), *Hawara, Biahmu and Arsinoe*, Londres.
- Pieke, G. (2016), 'Playing with traditions. The decoration of Djehutyhotep II's tomb at Deir el-Bersha reconsidered', dans L. Hudáková, P. Jánosi et Andrea Kahlbacher (éd.), *Change and Innovation in Middle Kingdom Art*, MKS 4, Londres, pp. 95-115.
- Shaw, I. (2010), *Hatnub : Quarrying travertine in Ancient Egypt*, Londres.
- Simon-Boidot, Cl. (1995), 'Accessoires de porteurs d'eau', *Bulletin du Cercle Lyonnais d'Égyptologie Victor Loret* 9, pp. 25-32.
- Sourouzian, H. (1988), 'Standing royal colossi of the Middle Kingdom reused by Ramesses II', MDAIK 44, pp. 229-254, pl. 62-75.
- Tallet, P., Marouard, G. et Laisney, D. (2012), 'Un port de la IV<sup>e</sup> dynastie au Ouadi el-Jarf (mer Rouge)', BIFAO 112, pp. 399-346.
- Vandier, J. (1943), 'Note sur le transport du colosse d'El Bersheh', *Chronique d'Égypte* 36, pp. 185-191.
- Vila, A. (1970), 'Les vestiges de la plaine', dans J. Vercoutter, *Mirgissa I*, Paris, pp. 178-180.
- Willems, H., Peeters, C. et Verstraeten, G. (2005), 'Where Did Djehutihotep Erect His Colossal Statue?', ZÄS 132, pp. 173-189.
- Willems, H. et al. (2009), 'Report of the 2004-2005 Campaigns of the Belgian Mission to Dayr al-Barshā', MDAIK 65, p. 377-342.
- Willems, H. (2013), 'A Note on the Ancient Name of Dayr al-Barshā', ZÄS 140, pp. 188-207.
- Willems, H. (2014a), 'Les tombes de particuliers, à travers l'exemple de Deir el-Bersha', dans Fl. Morfoisse et G. Andreu-Lanoë (éd.), *Sésostris III, pharaon de légende*, Lille, pp. 198-208.
- Willems, H. (2014b), *Historical and Archaeological Aspects of Egyptian Funerary Culture. Religious Ideas and Ritual Practice in Middle Kingdom Elite Cemeteries*, Leiden-Boston.



**Pl. 1.** Reconstitution de la scène de traction du colosse dans la chapelle de Djéhoutyhotep  
(© Franck Monnier).



# L'extraction des blocs en calcaire à l'Ancien Empire

## Une expérimentation au ouadi el-Jarf

Franck Burgos & Emmanuel Laroze<sup>1</sup>

*Abstract:*

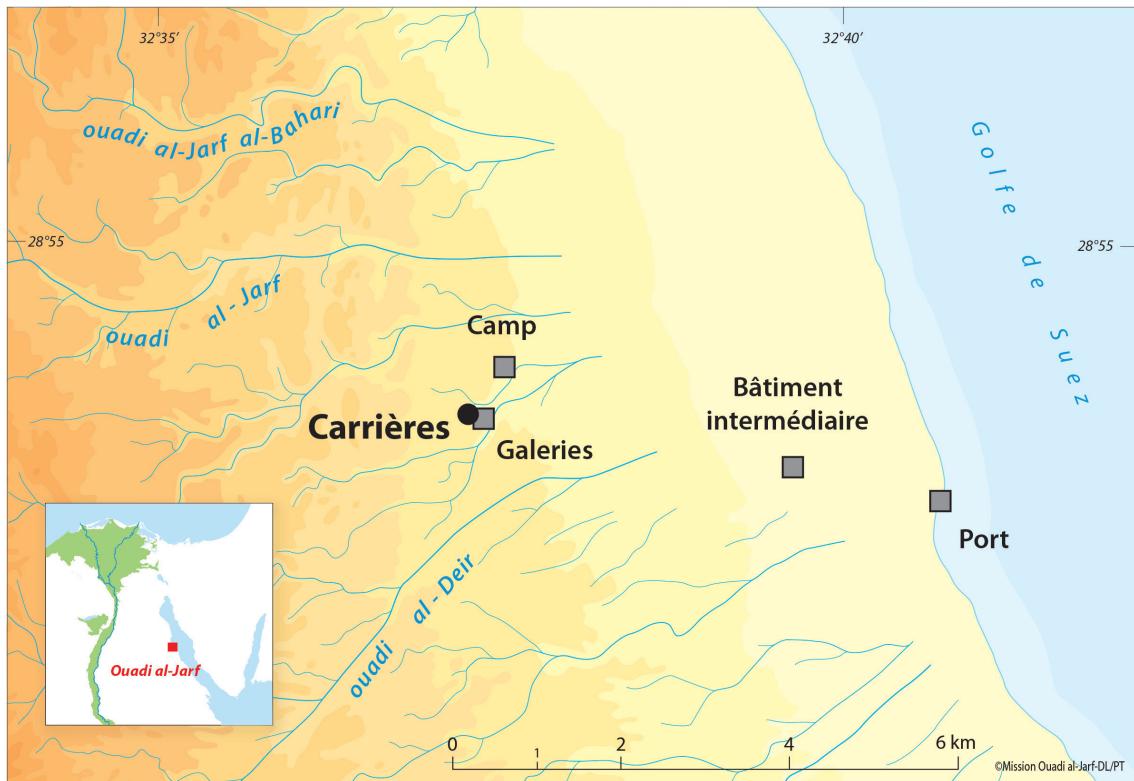
*This article addresses the techniques used for the extraction of limestone blocks from quarries during the Old Kingdom. The study draws on the latest research conducted at the Wadi al-Jarf harbor complex, located on the western shore of the Gulf of Suez. Approximately one hundred extracted blocks have been discovered there in an unfinished state, along with tools such as ropes, wooden hammers, and pieces of copper chisels. The items found in and around the quarry have led to a better understanding of the methods used by the ancient stonecutters, to produce large-sized blocks. To study the processes in more detail, an experiment was carried out to extract a one cubic meter stone using replicas of the ancient tools found at the site, and to test new hypothetical reconstructions of the steps followed in the process. The information collected and the experience gained has yielded new understanding of the organization of labor and has resulted in cutting performance rates being estimated for the first time. Information about the use of water to soften the stone during cutting of extraction trenches has also been brought to light.*

La mission archéologique du ouadi el-Jarf s'intéresse à un complexe portuaire de la IV<sup>e</sup> dynastie (-2670 à -2450 av. J.-C.) installé dans une zone désertique sur la rive occidentale du golf de Suez.<sup>2</sup> Depuis 2011, date de la première campagne, les fouilles qui y sont conduites annuellement ont mis au jour de nombreuses constructions inédites. Si les premières installations sont datées de Snéfrou, le site sera essentiellement aménagé par son fils, Chéops. Son occupation demeurera cependant brève puisque à la mort de celui-ci, il sera immédiatement abandonné. Oublié pendant plusieurs millénaires, l'endroit n'a connu aucune réoccupation ultérieure. Ainsi, les vestiges sont demeurés dans un état de conservation remarquable. La découverte d'un lot exceptionnel de papyrus en 2014 a révélé que ces installations étaient très directement liées au chantier de la grande pyramide.<sup>3</sup> Cette documentation écrite nous informe en effet que les équipes qui œuvraient sur ce site travaillaient une partie de l'année à l'approvisionnement par voie fluviale du plateau de Gizeh en matériaux de construction. Autrement dit, les hommes qui ont travaillé dans le complexe du ouadi el-Jarf étaient composés de marins, mais aussi de spécialistes du bâti. Parmi les installations les plus remarquables, on distingue sur le littoral une jetée en L d'environ 200 m x 200 m et un immense bâtiment 'intermédiaire' en peigne de plus de 2000 m<sup>2</sup>. Les vestiges les plus intéressants pour notre étude relative aux techniques de taille de pierre se situent plus loin à l'ouest, à environ 3 km, où

<sup>1</sup> Franck Burgos (tailleur de pierre, CNRS) et Emmanuel Laroze (architecte, CNRS) sont rattachés au laboratoire Orient et Méditerranée (Umr 8167). Sauf mention contraire toutes les illustrations sont signées des auteurs.

<sup>2</sup> La mission du ouadi el-Jarf est dirigée par Pierre Tallet. Nous tenons à le remercier pour le soutien qu'il apporte à nos travaux ainsi que pour la grande liberté qu'il nous accorde dans leur conduite. Pour l'histoire de la découverte et la présentation du site voir Tallet, Marouard et Laisney (2012), pp. 399-446.

<sup>3</sup> Tallet (2017) ; Tallet (2014) pp. 25-49.

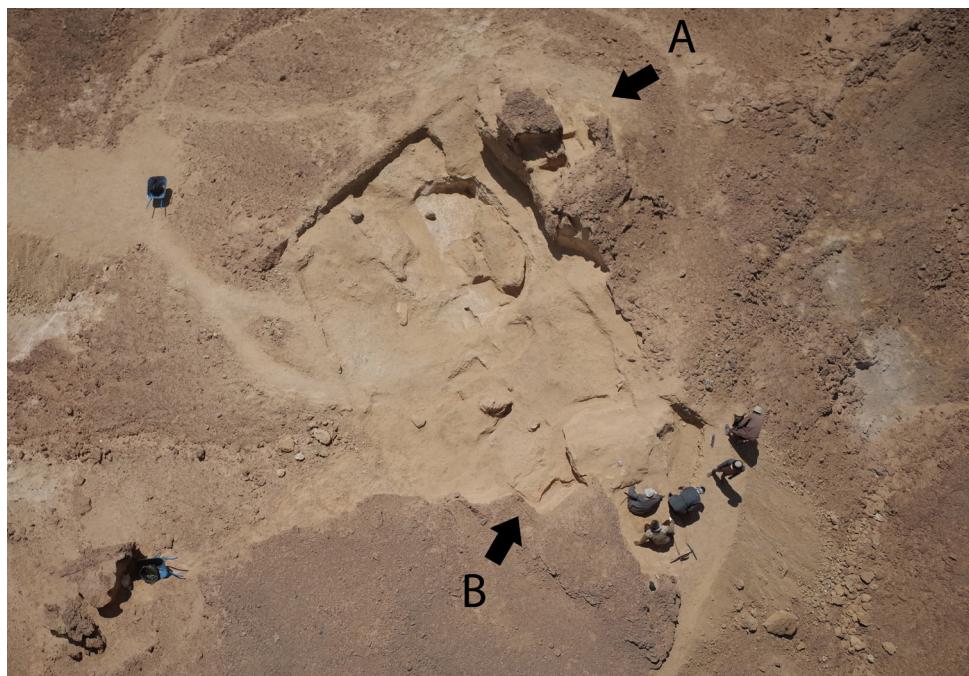


**Fig. 1.** Plan d'ensemble du site du ouadi el-Jarf (Laisney, CNRS).



**Fig. 2.** Le système de fermeture constitué de gros blocs devant l'entrée des galeries G5 et G6.

émergent les premiers escarpements du massif calcaire. Là, se trouve un ensemble de magasins composé d'une trentaine de galeries creusées dans la roche qui servaient à abriter des bateaux et du matériel expéditionnaire (fig. 1). Celles-ci étaient obstruées par des systèmes de fermeture étanche et particulièrement robuste constitués de très gros blocs.



**Fig. 3.** Vue aérienne de la carrière au terme des dégagements. A) bloc abandonné en cours d'extraction, B) empreinte d'un bloc extrait.

Rien qu'autour de l'éminence rocheuse du secteur 1 qui compte 17 galeries, ce sont 135 blocs de fermeture qui ont été inventoriés. Ces gros blocs aux dimensions variables ont en moyenne un volume de  $3 \text{ m}^3$  et un poids de 5,8 t.<sup>4</sup> Si certains d'entre eux ont été altérés ou déplacés pour pouvoir sortir le matériel des galeries, ils sont demeurés en grande majorité dans leur position d'origine (fig. 2). La plupart sont dans un état brut de carrière, c'est-à-dire qu'ils n'ont pas été retaillés pour une installation particulière. Ceux-là conservent en effet sur leurs faces des traces d'outils, des fractures ou des ressauts caractéristiques de leur extraction. La carrière d'où ces blocs proviennent a par ailleurs été découverte en 2017 (fig. 3). L'observation des différentes empreintes, ainsi que celle d'un bloc resté en cours d'extraction, nous renseignent sur les procédés utilisés et l'organisation des équipes. Enfin, de nombreux outils ayant servi aux travaux – maillets, enclumes, percuteurs, pointes de broches en cuivre, cordes – ont été retrouvés. Leur confrontation avec les traces qu'ils ont laissées sur la pierre permet d'affiner nos interprétations. La richesse des informations livrées par le site et leur authenticité – rappelons qu'il n'existe aucune ambiguïté quant à la datation des traces ou du matériel retrouvé puisqu'il n'y a jamais eu de réoccupation – offrent des conditions exceptionnelles pour l'étude des techniques de construction de cette période. Dans ce contexte, il nous a paru intéressant de comparer nos observations et nos interprétations avec des mises en situation concrètes. Nous avons par conséquent entrepris l'extraction d'un bloc d'environ  $1 \text{ m}^3$  selon les méthodes antiques. Par ce travail expérimental, il s'agissait de retrouver les gestes et les postures des carriers, mais aussi de mettre en lumière des difficultés voire les impossibilités qu'ils pouvaient

4 Leur poids est cependant assez variable puisqu'il s'échelonne entre 2 et 15 tonnes.

rencontrer pour certaines opérations. En utilisant des outils en cuivre comparables à ceux retrouvés sur le site, nous avons pu tester leur résistance ainsi que leur efficience par rapport au calcaire local. Finalement, nous avons cherché à évaluer le temps et les effectifs nécessaires aux différentes tâches.

### Les techniques d'extraction à l'Ancien Empire

Nos connaissances sur l'extraction des blocs de calcaire à l'Ancien Empire sont limitées et sont essentiellement attachées au plateau de Gizeh où de nombreux gisements sont encore visibles. Sur le côté nord-ouest de la pyramide de Khéphren<sup>5</sup> (fig. 4) mais aussi à proximité de l'angle nord-ouest de la pyramide de Mykérinos, les fonds de tranchées qui dessinent une sorte de damier nous renseignent sur la méthode pratiquée à cette époque par les carriers. La chambre inachevée de la grande pyramide met en œuvre les mêmes techniques.<sup>6</sup> L'extraction s'effectuait en deux temps : le dégagement des faces verticales, puis le décollement le long de la face inférieure horizontale du bloc. Le calcaire est une roche sédimentaire, si bien qu'il existe un sens de clivage qui assure une cohésion plus forte dans un sens que dans l'autre. Les deux opérations mettaient donc en œuvre deux techniques différentes : la taille de tranchées dans le sens vertical et la *rupture par extension* dans l'autre sens, c'est-à-dire celui parallèle aux lits de la pierre.<sup>7</sup>



**Fig. 4.** Les fonds de tranchées d'extraction dans l'angle nord-ouest de la pyramide de Khéphren à Gizeh.

<sup>5</sup> Vyse (1840), pp. 159-160 ; Arnold (1991), pp. 31-32, fig. 2.4 ; Clarke et Engelbach (1930), pp. 16-17, fig. 13 ; Isler (2001), p. 222, fig. 10.1 ; Hölscher (1912), pp. 33-34, fig. 19. Certains auteurs pensent toutefois que cette carrière maintes fois citée en exemple pourrait dater du Moyen-Empire: Goyon *et al.* (2004), pp. 149-150, fig. 158.

<sup>6</sup> Lehner et Hawass (2017), pp. 425-426.

<sup>7</sup> Noël (1968), pp. 310-311.



**Fig. 5.** Évolution de la technique du havage de l'Ancien Empire à nos jours : le développement d'outils de plus en plus longs et résistants a permis d'optimiser le creusement des tranchées qui se sont progressivement réduites en largeur. 1) Le ciseau et le maillet à l'Ancien Empire, 2) le pic de carrier (ou escoude) à la Période Romaine, 3) l'aiguille en acier durant la période moderne. Cette évolution met en lumière une réduction progressive des déchets de taille.

Le carrier attaquait la roche avec un ciseau en cuivre,<sup>8</sup> un maillet en bois et probablement des outils lithiques.<sup>9</sup> Le creusement des tranchées – appelé aussi havage – s'effectuait de haut en bas, l'outil posé perpendiculairement aux lits sédimentaires de la pierre. Le carrier tenait l'outil au niveau de ses pieds et travaillait donc en règle générale en position accroupie. Les tranchées verticales devaient être suffisamment larges pour qu'il puisse y travailler au fur et à mesure qu'il descendait à l'intérieur.<sup>10</sup> La largeur de la tranchée était inhérente à l'outil utilisé. Les capacités technologiques à l'Ancien Empire ne permettaient pas, semble-t-il, de produire de grandes pièces métalliques. Le ciseau, petit outil en cuivre, ne dépassait pas une vingtaine de centimètres et se tenait en main. La partie active était une sorte de prolongement de la main, qui était située à quelques centimètres de celle-ci seulement. Pour manipuler l'outil, le carrier devait donc l'accompagner dans la tranchée. Il est intéressant à ce propos de souligner que l'amélioration des performances de l'extraction au cours du temps, conditionnée par l'évolution des outils et de leur résistance, s'est accompagnée d'une diminution progressive de la largeur des tranchées (fig. 5). Avec des outils emmanchés qui seront lancés, comme les pics de carrier ou des escoudes, voire avec des ciseaux plus longs, les tranchées se réduiront à quelques centimètres seulement. De nos jours, cet espace ne mesure plus que quelques millimètres seulement, la largeur nécessaire pour que circulent des fils hélicoïdaux ou des haveuses (disques tranchants). À l'Ancien Empire, la nécessité de travailler à l'intérieur de la tranchée impliquait que celle-ci mesure plus d'une

<sup>8</sup> Plusieurs exemplaires de cet outil de l'Ancien Empire, appelé aussi bédane, ont été retrouvés. Voir par exemple l'exemplaire découvert dans une carrière de diorite de Khéops publié dans Goyon (1977). Il est inutile de préciser qu'il s'agissait d'outils précieux et onéreux car leur fabrication mettait en œuvre une technologie avancée et une chaîne de production complexe (extraction du minerai, réduction, forge, etc...). À propos du cuivre, voir Odler (2016); Lucas (1927), pp. 162-170.

<sup>9</sup> Voir pour la dolérite Kelany, Harrell et Brown (2010), pp. 127-148.

<sup>10</sup> Ce type de tranchée large s'appelle un enjarrot. Voir Abdul Massih et Bessac (2009), p. 62; Noël (1968), p. 149. Cette technique élémentaire était utilisée sur d'autres terrains que l'Égypte, voir par exemple Bessac (2007b), p. 197 et fig. 1 ; Bessac (2014), p. 157.

cinquantaine de centimètres. Cette valeur était incompressible. Compte tenu de ce paramètre, les carriers avaient donc intérêt à détacher des blocs volumineux.<sup>11</sup> Autrement dit, plus ceux-ci étaient gros, plus leur taille était économique. Cette optimisation était toutefois contrariée par la question du transport dont la difficulté augmente avec le poids de la charge. Le dimensionnement optimum d'un bloc était donc contraint par ces deux facteurs.



**Fig. 6.** Bloc de fermeture posé en délit devant l'entrée d'une galerie. Les carriers ont de toute évidence exploité la strate marneuse (située ici à gauche) pour détacher facilement le bloc de son substrat.

La technique employée pour le détachement proprement dit, c'est-à-dire la séparation du bloc du banc rocheux selon un plan horizontal, est en revanche beaucoup moins bien connue. Cette opération devait en tout cas être la plus délicate à réaliser, en particulier en l'absence d'outils en acier. Les coins éclateurs prouveront plus tard leur grande efficacité pour cette opération. Mais en l'absence de traces manifestes de ces outils sur les gisements de l'Ancien Empire, il faut considérer qu'ils n'étaient pas encore utilisés à cette époque. La seule technique qui ait été avancée est celle de Reisner qui consistait à placer une grande pièce de bois à la base d'une des faces du bloc et à

**11** Deux exemples permettent évaluer cette différence de rentabilité pour un bloc isolé : avec des tranchées de 0,5 m de large et 1 m de hauteur, il faut creuser 3m<sup>3</sup> de roche pour dégager un bloc d'un 1 m de côté quand il faut tailler 5 m<sup>3</sup> de pierre pour extraire un bloc de 2 m de côté. La géométrie du bloc pouvait aussi avoir une incidence sur l'économie de la taille. Sur ce sujet voir Monnier, F., 'Le mégalithisme appareillé dans les pyramides de l'Ancien Empire' (en préparation).

l'arroser abondamment.<sup>12</sup> La force latérale exercée par le bois trempé aurait alors fait éclater la pierre, désolidarisant le bloc de son banc. Quoi qu'il en soit, de nombreux chercheurs s'accordent à dire que les carriers de l'Ancien Empire ont dans la mesure du possible exploité les propriétés géologiques du calcaire pour cette opération délicate. Celui-ci étant une roche sédimentaire, il est composé d'une succession de couches plus ou moins bien solidaires les unes des autres. Les strates argileuses, plutôt meubles, qui partagent certains bancs plus durs devaient donc être particulièrement recherchées car, une fois atteintes par les tranchées verticales, le bloc avait alors une faible adhérence avec la roche et pouvait par conséquent être retiré facilement. À ouadi el-Jarf, de nombreux blocs présentent sur une de leurs faces cette couche marneuse ou friable, signe qu'ils ont été détachés de cette manière (fig. 6).<sup>13</sup> Pour résumer, le procédé de l'extraction d'un bloc consistait à creuser des tranchées verticales depuis une plateforme et à fracturer la face inférieure. Ce principe demeurera à peu de choses près le même durant toute la civilisation égyptienne.<sup>14</sup>

### **La carrière du ouadi el-Jarf : interprétation et matériel exhumé**

En 2017, nous avons eu la chance de découvrir à ouadi el-Jarf une carrière d'où ont été extraits des blocs servant à la fermeture des galeries. Elle se situe à environ 400 m à l'ouest de la principale concentration des magasins antiques. Sa position dominante par rapport au site a certainement facilité l'évacuation des blocs. La carrière a été partiellement dégagée l'année suivante durant deux semaines. Cette zone d'extraction se remarque par une sorte de dépression délimitée par deux fronts de taille situés sur ses côtés ouest et nord. Elle se distingue d'autre part par la présence de trois diaclases parallèles au front nord. Celles-ci ont de toute évidence été déterminantes dans le choix de cette zone d'exploitation puisque ces particularités géologiques facilitent l'extraction. En effet, elles permettent de faire l'économie du creusement d'une tranchée sur un côté d'un bloc. C'est d'ailleurs le long d'une de ces diaclases dans la partie nord qu'on observe une intéressante empreinte d'extraction. Là, on constate que deux tranchées verticales seulement, perpendiculaires l'une à l'autre, ont été nécessaires pour détacher le bloc (fig. 3B et fig. 7). On remarque d'autre part que le fond de celles-ci est deux fois moins large qu'en partie supérieure. C'est probablement par souci d'économie que les carriers ont ainsi réduit la largeur de la tranchée : la base du bloc étant atteinte et délimitée, il était en effet inutile d'enlever le reste. De l'ensemble des traces conservées on comprend la méthode d'extraction. Une fois que le bloc a été désolidarisé de la roche sur ses 4 côtés, les carriers ont creusé en dessous afin de le détacher complètement de son banc.

Non loin de là, au sud-ouest de la zone dégagée, se trouve un bloc qui a été abandonné en cours d'extraction (fig. 3A et fig. 8). Bien qu'il ait été partiellement rongé par le vent et le sable, on distingue encore très nettement deux tranchées. Au fond de celles-ci, on observe plusieurs petites 'plateformes' d'environ 0,50 m x 0,50 m qui s'étagent à des hauteurs différentes. Chacune d'elles devait correspondre à un espace de travail. En fait, un homme devait avoir la charge de deux d'entre elles contiguës et devait les décaisser en alternance. Avec une telle organisation, on comprend que plusieurs carriers pouvaient travailler là simultanément.<sup>15</sup> Divers outils lithiques, qui s'apparentent souvent à de gros galets, ont été trouvés dans cette zone d'extraction. La présence de vert de gris sur certaines pierres nous montre qu'elles ont été au contact du cuivre. Il s'agit là d'enclumes et de percuteurs qui servaient à

<sup>12</sup> Reisner (1931), p. 69 ; Goyon *et al.* (2004), p. 147 ; Arnold (1991), p. 33.

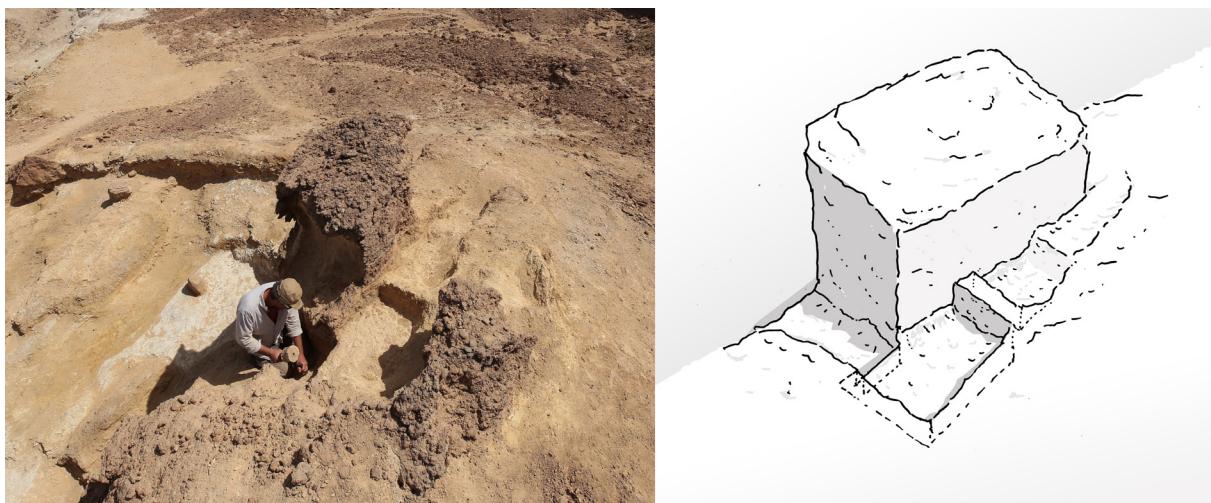
<sup>13</sup> À Gizeh, Georges Goyon explique à ce propos que l'irrégularité des assises de la grande pyramide serait liée à l'exploitation des bancs de carrière, Goyon (1978), pp. 405-413. Voir aussi sur le même sujet l'article plus ancien de Tarrell et Petrie (1925), pp. 36-39.

<sup>14</sup> Harrell et Storemyr (2015), pp. 19, 32, fig. 25.

<sup>15</sup> L'organisation et les dimensions de ces espaces de travail sont tout à fait comparables à ceux visibles dans le fond des tranchées d'extraction des obélisques en granit à Assouan. Voir par exemple la restitution dans Goyon *et al.* (2004), p. 164, fig. 180 et 181.



**Fig. 7.** Empreinte d'extraction d'un grand bloc dans la carrière du ouadi el-Jarf.



**Fig. 8.** Bloc abandonné en cours d'extraction au ouadi el-Jarf. Deux tranchées perpendiculaires sont encore bien conservées. Dans le fond de celles-ci, on observe des sortes de caissons d'environ  $0,50 \times 0,50$  m s'étageant à différentes hauteurs qui correspondent à des postes de travail.

rabattre le tranchant de l'outil. Ce procédé, qui devait être effectué fréquemment, permettait d'affûter la partie active de l'outil. Les plus gros cailloux devaient quant à eux servir de cale pour maintenir temporairement des blocs en hauteur ou pour que des leviers puissent y prendre appui, voire pour sécuriser des tranchées horizontales lorsqu'il s'agissait de travailler en sape. Quelques débris de bois, dont un reste de maillet usagé, ont aussi été découverts. La grande quantité de tessons de céramique qui jonchaient le sol témoigne d'un important besoin en stockage – on pense à l'eau bien entendu – dans cette zone. Celle-ci n'a été fouillée que partiellement lors d'une saison mais nous avons été surpris de ne pas trouver beaucoup d'éclats de taille qui caractérisent normalement les espaces où on travaille la pierre. En revanche, nous avons dégagé une grande quantité de substrat sableux. Nous comprendrons plus tard, grâce à l'expérimentation, qu'il s'agissait là des résidus de l'extraction. L'observation des traces laissées sur la pierre à ouadi el-Jarf et les instruments qui ont été retrouvés sur place permettent de restituer la ‘caisse à outils’ du carriera qui était somme toute rudimentaire (fig. 9) :

- Maillets en bois d'acacia.<sup>16</sup>

Cette essence de bois a la particularité d'être très dure et résistante. Les ressources de ce matériau ont par ailleurs toujours été très abondantes sur le territoire égyptien, ce qui était une réelle opportunité pour les tailleurs de pierre qui en faisaient une grande consommation. Les ‘copeaux’ ou les déchets de bois qu'on trouve en abondance sur le site indiquent que les maillets étaient soumis à rude épreuve et que leur altération nécessitait de les remplacer fréquemment.

- Outilage lithique.

Des galets en pierre dure servaient de marteaux et d'enclumes.

- Cordages.

Retrouvées en grandes quantités sur le site, les cordes servaient au déplacement des blocs mais aussi à solidariser des pièces entre elles. Celles qui étaient utilisées par les carriers devaient être à 3 brins et mesurer 3 cm de diamètre minimum comme l'indiquent les nombreuses empreintes laissées par celles-ci sur les angles des blocs (fig. 10). L'étude de Claire Newton a montré que celles-ci étaient faites, soit de lanières de tiges de papyrus (*Cyperus papyrus*), soit de tiges feuillées de halfa (*Desmostachya bipinnata* et/ou *Imperata cylindrica*).<sup>17</sup>

- Ciseaux en cuivre.

Il s'agissait d'outils précieux et durables. La dureté et l'affûtage de leur partie active était entretenue par un battage à froid à l'aide d'une pierre et d'une enclume. Seules quelques pointes brisées ont été retrouvées sur le site.

- Leviers et cales en bois.

Bien que nous n'ayons pas retrouvé d'exemplaires de ces outils à Jarf, ces instruments étaient indispensables pour la manipulation, le calage ou le décollement des blocs. Les mortaises taillées sur certains blocs pour les manipuler montrent que les leviers avaient des sections de 10 à 15 cm de côté.

Nos observations nous ont conduits à restituer une technique d'extraction convaincante qui paraît dans ses grandes lignes être conforme aux interprétations faites sur d'autres sites. Il restait à confronter notre état de la connaissance avec la pratique pour tenter d'apporter des informations quantitatives (délais, effectifs, usure des outils, etc) mais aussi d'ordre pratique (posture des ouvriers, pénibilité, compréhension de l'environnement de travail, etc).

<sup>16</sup> Claire Newton a pu identifier qu'il s'agissait majoritairement d'Acacia, probablement d'une ou plusieurs espèces disponibles localement (rapport d'étude archéobotanique de fin de mission, 2019, p. 15). Actuellement, les acacias les plus fréquents dans le désert côtier de la mer Rouge sont les deux sous-espèces d'*Acacia tortilis* (Forssk.), Hayne (*A. tortilis* subsp. *tortilis* et *A. tortilis* subsp. *raddiana*) et *A. ehrenbergiana* Hayne.

<sup>17</sup> *Ibidem*, p. 29.

## Mise en place de l'expérimentation : le choix de la zone d'extraction et la fabrication des outils

L'expérimentation a été conduite durant les campagnes de 2018 et 2019 et s'est concrétisée par l'extraction de deux blocs d'environ 1 m<sup>3</sup> chacun. La zone qui a été choisie se situe à environ 50 m au sud-ouest de la carrière antique. Cette proximité présentait plusieurs avantages. Outre son intérêt pour des questions d'accessibilité et de logistique, la facilité pour aller et venir entre les deux espaces était utile pour étudier et comparer les traces d'exactions. L'affleurement rocheux que nous avions choisi respectait également les critères requis : pierre tendre à légèrement ferme, une accessibilité tant pour le travail que pour l'évacuation des blocs par la suite, un banc homogène d'environ 1,5 m avec la présence d'une faille apportait une économie de travail. Les quatre ciseaux utilisés pour l'expérience ont été forgés en France à partir de segments de 22 cm de longueur et de 25 mm de diamètre de tube plein en cuivre (fig. 11). Le cuivre est un métal tendre qui a la particularité de durcir quand on le forge. Ce changement de propriété sous l'effet de sa déformation plastique s'appelle l'écrouissage. Comme il est ductile, il peut supporter un écrouissage important. Au cours de cette opération il convient toutefois à ne pas dépasser sa limite d'élasticité au risque d'obtenir un métal déstructuré. Pour la mise en forme des ciseaux plusieurs méthodes ont été testées :

- Méthode 1 : Le métal a été chauffé à la forge et mis en forme à chaud. Après refroidissement total, le cuivre a de nouveau été battu dans l'espoir de le durcir. Cette méthode n'a pas fonctionné, car la mise en forme du ciseau était trop avancée à la forge pour pouvoir être écrouie ensuite. Lors d'un essai sur une pierre ferme, la partie active du ciseau s'est écrasée et pliée.
- Méthode 2 : Le ciseau a été entièrement forgé à froid, sur l'enclume. Cela n'a pas fonctionné car la limite ductile du cuivre – le métal a commencé à se déstructurer – a été atteinte avant que le ciseau ne prenne sa forme définitive. Lors de l'essai sur la pierre, le ciseau s'est fendu en petites lamelles feuillettées.
- Méthode 3 : la forme du ciseau a été dégrossie à chaud sur la forge, en prenant soin de laisser suffisamment de métal à étirer pour obtenir un écrouissage à froid correct. Cette méthode s'est avérée fructueuse lors de l'essai sur la pierre ferme. L'outil, percuté sans retenue par le maillet, a bien attaqué la pierre sans s'abîmer.

Les outils que nous avons fabriqués sont légèrement plus gros que ceux qui ont été retrouvés au ouadi el-Jarf. La largeur de notre tranchant est approximativement de 1,6 cm tandis que les traces d'outils visibles sur les blocs antiques sont plutôt comprises dans une fourchette de 1 à 1,3 cm.<sup>18</sup> La forme de nos ciseaux est celle qui vient la plus naturellement sous la forge. C'est pour cette raison qu'elle est identique à celle des ciseaux en cuivre antiques.<sup>19</sup> Le cuivre qui a servi à forger nos outils n'est évidemment pas le même que celui produit durant l'antiquité. Mais il ne fait aucun doute que les anciens forgerons égyptiens avaient acquis une grande maîtrise pour la fabrication de leurs outils. Ils savaient rendre ce métal suffisamment dur – grâce à la forge mais aussi par leur composition avec l'ajout d'arsenic par exemple – et résistant pour tailler de la pierre tendre à légèrement ferme. De tels outils ne pouvaient pas être utilisés pour des pierres dures comme la calcite, le marbre, le quartzite, le schiste ou le granit. Les maillets ont, quant à eux, été tournés en Égypte dans un bois vert qui résiste bien aux impacts. Leur diamètre était d'environ 22 cm. Des essais avec des maillets

<sup>18</sup> Nous avons retrouvé quelques têtes d'outils : objets 282 et 283.

<sup>19</sup> Voir par exemple celui retrouvé par Lauer à Saqqara : Lauer (1936), p. 232, fig. 234. Le même outil est restitué dans Goyon et al. (2004) p. 379, fig. 489. Voir également, la planche XXII dans Petrie (1917), et les outils en cuivre exhumés dans Reisner et Fisher (1914), p. 251 et pl. XI, III, n°18. Les outils en bronze plus récents auront aussi la même forme.



**Fig. 9.** La ‘caisse à outils’ des carriers du ouadi el-Jarf : maillet en bois, pic en pierre, corde et ciseau en cuivre (ici pointe brisée). Matériel retrouvé en fouille sur le site (G. Pollin, IFAO).



**Fig. 10.** Empreinte sur l'angle d'un bloc et confrontation de celle-ci avec une corde exhumée.



**Fig. 11.** Maillet en hêtre et ciseaux en cuivre modernes utilisés lors de la première campagne.

de diamètre moindre, donc plus légers, et faits de bois plus sec ont montré qu'ils étaient moins résistants. L'expérimentation de ce chantier a été menée par 5 personnes qui se sont relayées à tour de rôle sur deux postes. La taille proprement dite mobilisait 4 d'entre elles ; l'évacuation des déblais et l'apport d'eau étaient dévolus à la cinquième. Il est utile de préciser que parmi les 5 personnes engagées sur cette expérience, seul Franck Burgos était un professionnel de la taille de pierre.



**Fig. 12.** Les premiers coups de ciseaux dans la zone d'extraction moderne : préparation du front de taille et du lit supérieur.

### Les vertus de l'eau

Une fois l'emplacement défini, la première étape a consisté à dessiner l'emprise du bloc sur le front de taille et le sommet de l'affleurement rocheux. À partir de là, trois tranchées verticales formant un U ont été implantées (fig. 12). Les quatre tailleurs de pierre se sont alors répartis sur différents postes comparables à ceux observés dans la carrière : trois étaient installés au sommet de chacune des tranchées, tandis que l'autre se tenait debout face au front de taille. Ce dernier avait la charge des extrémités des deux tranchées opposées. Les carriers 2 et 3 travaillaient dans le prolongement de chacune d'elles. Le quatrième était quant à lui installé dans la tranchée du fond. Une telle organisation avait l'intérêt de répartir équitablement le travail à un groupe d'hommes et de leur permettre de travailler simultanément. Que ce soit en position debout ou accroupie, l'espace de travail de chaque ouvrier correspond approximativement à une surface de 50 cm de large, soit la largeur minimale de la tranchée pour qu'un homme puisse y travailler, et de 50 cm environ de profondeur. Le rythme des tailleurs n'étant pas nécessairement le même, il s'est formé naturellement des paliers tout à fait comparables à ceux que nous avons vus autour du bloc inachevé dans la carrière antique.

Ces différences entre les hauteurs de paliers n'étaient pas contraignantes ; au contraire, elles augmentaient le confort du travail en équipe car ainsi les hommes se gênaient moins. Au fond de la tranchée, un homme accroupi avait peu de possibilités pour varier sa position de travail. Il devait le plus souvent travailler un pied à plat devant lui et le genou relevé, la fesse posée sur l'autre jambe. Il pouvait aussi travailler les deux genoux à terre, ce qui avait l'intérêt de projeter un peu plus le corps vers l'avant. Le carrier qui travaillait debout bénéficiait d'une posture plus confortable et avançait globalement plus vite que les autres.

Dès les premiers coups de maillets, le ciseau en cuivre s'est montré tout à fait résistant et efficace pour attaquer la roche. Le tranchant de la partie active a été maintenu en le rabattant régulièrement sur une enclume. En revanche la taille du calcaire s'est révélée laborieuse du fait de sa dureté. À chaque impact de l'outil, seuls quelques petits éclats étaient séparés de la roche. Le travail était de plus particulièrement difficile sur le premier centimètre de l'épiderme qui est couvert de calcin (carbonate de calcium).<sup>20</sup> Une fois le calcin retiré, la roche était plus tendre mais le débitage restait malgré tout long et la progression semblait peu vraisemblable au regard de l'estimation des 2,3 millions de blocs qui avaient été extraits pour construire la grande pyramide. La consommation de maillets en bois était d'autre part extrêmement dispendieuse. Après 3 jours de pénible labeur, l'avancement était dérisoire : seulement une vingtaine de centimètres avait été creusés. Sur un poste de travail d'une surface de 0,25 m<sup>2</sup> le décaissement était d'environ 20 cm en 15 h, soit 0,0033 m<sup>3</sup>/h ou 303 h/m<sup>3</sup>. Sachant que dans notre contexte il y avait 3 tranchées totalisant un volume de 2 m<sup>3</sup>, c'est presque 606 heures de travail qui auraient été nécessaires pour les creuser. Les deux jours durant lesquels fut poursuivie l'expérience nous convainquirent que la méthode n'était pas la bonne. Franck Burgos eut alors l'idée de mouiller la pierre. Il avait en effet remarqué que la roche du site était particulièrement salée. À l'entrée de certaines galeries, on peut d'ailleurs observer de nombreuses efflorescences de sel. De toute évidence, celui-ci avait contribué par un processus de lithification à la diagenèse de la pierre, en la rendant très cohérente. La forte concentration du sel contenu dans la roche était d'autre part maintenue par une faible pluviométrie dans la région. Comment la pierre allait-elle donc réagir au contact de l'eau sachant que le sel se dissout dans celle-ci ? Pour cela, il constitua une dépression à fond horizontal d'environ 50 x 50 cm et y versa environ deux litres d'eau. De manière inattendue, elle fut absorbée par la pierre en moins de 3 minutes et celle-ci changea littéralement de consistance et d'aspect (fig. 13). La pierre qui avait pris une teinte plus sombre s'était attendrie sur une profondeur d'environ 7 cm. L'action des ciseaux était alors plus efficace en détachant de plus gros éclats de roche (fig. 14). Sous les pieds, les résidus de taille qui s'amoncelaient avaient une apparence marneuse (fig. 15). Tant qu'ils étaient humides, ceux-ci pouvaient être agglomérés par pression. Cette matière ainsi compactée se désagrégait toutefois après séchage. Concrètement, nous avions compris que l'eau dissolvait les sels mais agissait également sur les argiles contenues dans la roche.<sup>21</sup> Il était intéressant de remarquer qu'une roche qui avait été trempée ne retrouvait pas ses mêmes propriétés après séchage : elle demeurait plus tendre. En humidifiant la roche, nous avons constaté un important gain de productivité : la capacité d'extraction était d'environ 0,021 m<sup>3</sup>/h, soit presque 6 fois plus rapide qu'avec de la pierre sèche ! L'emploi de l'eau pouvait d'autre part engendrer des économies substantielles en matériaux. Les outils – ciseaux et maillets – étaient moins sollicités et leur consommation était réduite. Elle offrait

<sup>20</sup> Vu la dureté, il n'est pas impossible que cette épaisseur ait été attaquée jadis au moyen d'outils lithiques.

<sup>21</sup> L'absorption de l'eau par le calcaire local est surprenante tant elle est rapide. C'est sans doute à cette étrange propriété de la pierre que Barsanti a été confronté lors de sa fouille de la grande fosse de Zawiyet el-Aryan en mars 1905 : 'Une véritable trombe s'abattit sur la montagne de Zaouiét el-Aryān, et le puits fut inondé jusqu'à la hauteur de 3 mètres; vers minuit, l'eau baissa brusquement d'environ un mètre. Je ne puis expliquer ce phénomène qu'en supposant qu'elle s'engloutit dans quelque galerie souterraine, assez vaste pour contenir 380 mètres cubes d'eau' (Barsanti (1906), p. 286).



**Fig. 13.** Eau versée dans le fond de la tranchée. Après absorption, et une vraisemblable dissolution des sels, la roche devient plus tendre.



**Fig. 14.** Taille de la roche après qu'elle ait été humidifiée. Les impacts de l'outil deviennent beaucoup plus efficaces. Des fragments plus gros sont détachés. Le résidu de taille s'apparente à du sable grossier.



**Fig. 15.** Aspect des résidus générés par la taille sur pierre humide.

enfin des conditions moins éprouvantes pour les carriers. En contrepartie, il était nécessaire d'approvisionner la carrière en eau. Les 3 tranchées verticales totalisent un volume d'environ 2 m<sup>3</sup> ; en théorie, 300 litres d'eau étaient nécessaires.<sup>22</sup> Nous pensons toutefois qu'avec une meilleure gestion, ce chiffre pouvait être réduit de moitié. La progression dans les tranchées s'est poursuivie avec cette méthode jusqu'à la base du bloc (fig. 16).



**Fig. 16.** Synopsis de la première campagne d'expérimentation montrant le principe de progression de l'extraction.

À mi-chemin, nous avons traversé une couche de quelques centimètres plus dure qu'ailleurs qui nous a contraints à modifier notre protocole. La pierre, plus dense, avait une porosité plus faible, si bien que l'eau avait peu d'effets sur celle-ci. Les outils en cuivre étant alors peu efficaces, nous avons utilisé de l'outillage lithique : de simples galets de calcaire dur. Ceux-ci ont été très efficaces. On imagine que les pics à gorges (fig. 9) retrouvés sur le site pouvaient répondre à ce type de situation. Durant toute l'opération, il fallait veiller à bien respecter les aplombs des parois. En effet, une correction de ceux-ci après coup aurait entraîné un important surcoût de travail, car dans cette configuration l'eau doit être projetée sur les parois. En ruisselant, celle-ci imprègne mal la roche – 1 à 2 cm tout au plus – ce qui génère une plus grande consommation. La posture des carriers qui restent accroupis de haut en bas de la tranchée est très inconfortable et traumatisante pour les articulations (fig. 17). Comme ils ne pouvaient pas varier leurs positions, le travail était rythmé par des temps de récupération indispensables.

<sup>22</sup> Sur notre site, il existait deux possibilités d'approvisionnement en eau : la source, aujourd'hui dans le monastère Saint-Paul, situé à 10 km à l'ouest ou la mer, à 3 km à l'est. Nous n'avons pas expérimenté l'eau de mer mais il n'est pas exclu que cela fonctionne également. L'approvisionnement pouvait être assuré par des ânes dont la capacité de portage pouvait atteindre 100 kg.



**Fig. 17.** Position du carriére à l'intérieur de la tranchée.

Dans les faits, nous avons achevé la taille des 3 tranchées verticales en 6 journées de 6 heures par 5 personnes (quatre à la taille + une aide). Ce temps tient compte de nos hésitations, de nos réflexions et de notre apprentissage de la méthode. En théorie, la progression devait être plus rapide. Avec une progression moyenne quotidienne de 25 cm sur l'ensemble des tranchées (soit 4 m linéaires) la base du bloc serait atteinte en 4 jours. À ce terme, 2 m<sup>3</sup> de roche auraient été extraits. On calcule ainsi qu'un homme pourrait extraire 0,125 m<sup>3</sup> de roche par journée de 6 heures. Il s'agit là d'une base pour les estimations. Le rendement des carriers antiques était sans doute encore meilleur ; on peut raisonnablement penser qu'il était de 20 à 30 % supérieur à nos chiffres. Précisons enfin qu'il s'agit là de conclusions portées sur un calcaire local assez dur. Les chiffres pourraient donc varier sensiblement d'un site à l'autre en fonction de la qualité de la pierre.

### Le décollement du bloc par fracturation

Une fois que le bloc fut libéré sur ses 4 côtés, la dernière étape a consisté à détacher sa face inférieure qui le maintenait encore au banc. Nous l'avons vu, la méthode qui était employée est incertaine. À ouadi el-Jarf, nous n'avons retrouvé aucune trace au fond des tranchées d'extraction étayant la méthode du bois mouillé décrite par Reisner, ni aucune trace indiquant l'usage de coins d'ailleurs. Plus globalement, nous avons jugé que l'usage de bois trempé devait être compliqué en termes de logistique et qu'il devait exister d'autres solutions plus simples à mettre en œuvre. Le procédé le plus économique consistait à exploiter d'éventuelles opportunités géologiques, comme les couches argileuses par exemple, pour détacher le bloc. Dans ce cas, toute la difficulté consistait à choisir judicieusement son gisement au préalable. Quand cela était possible, les anciens carriers

dévraient certainement privilégier cette méthode qui était la moins laborieuse. Sinon, il fallait procéder autrement en creusant une tranchée en sape, comme en témoigne le bloc dont nous avons découvert l'empreinte dans la carrière et dont le détachement n'avait profité d'aucun litage particulier. En fait, nous avions repéré sur cette face d'arrachement qu'une moitié de celle-ci portait des traces d'outils tandis que l'autre partie avait été fracturée (fig. 3B et fig. 7). C'est cette méthode, qui est la plus contraignante, que nous avons choisi d'expérimenter.



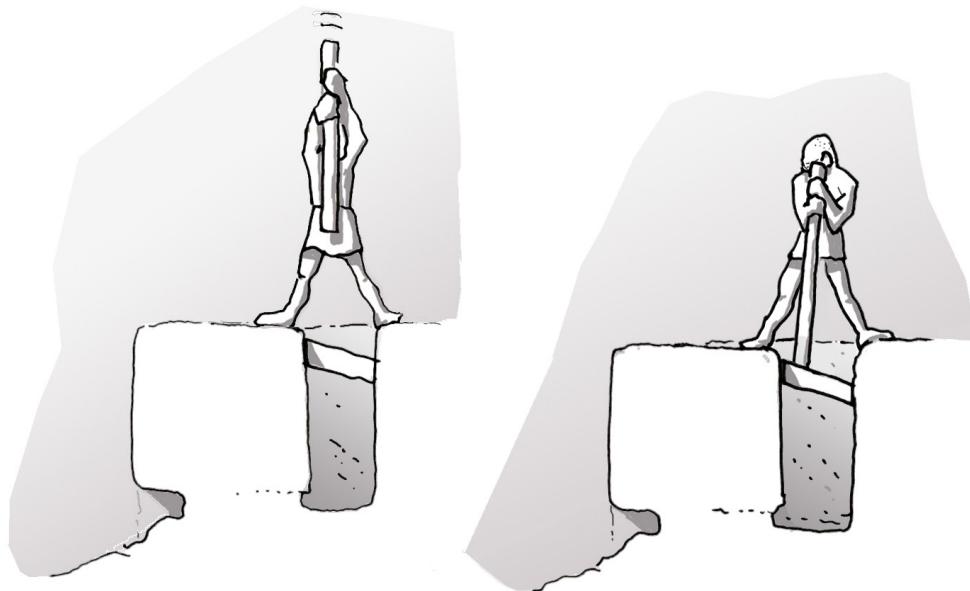
**Fig. 18.** Taille en sape d'une tranchée périphérique à la base du bloc avant son détachement par fracturation.

Pour décoller ainsi le bloc, il a tout d'abord été nécessaire d'amorcer une tranchée horizontale à la base du bloc (fig. 18). Une taille en sape a ainsi été réalisée sur une quarantaine de centimètres à l'avant de ce dernier. Sur les autres cotés, c'est-à-dire à l'intérieur des tranchées, le manque d'espace rendait la taille particulièrement difficile si bien que les saignées sous le bloc ne dépassaient pas une dizaine de centimètres. Le bloc ainsi préparé, nous avons tenté dans un premier temps de le détacher par fracturation à l'aide de leviers. Deux pièces de bois de section carrée de 10 cm et de 3 m de long ont été placées contre la face arrière. Les deux leviers étaient installés de manière à ce qu'ils prennent appui sur des cales elles-mêmes adossées sur le bord de la tranchée et que leur extrémité touche le bloc. Deux hommes par levier ont tiré pour tenter de détacher le bloc. Malheureusement, la tranchée était trop large et il était difficile de trouver un appui convenable si bien que la tentative se solda par un échec. Nous avons renouvelé l'expérience après avoir approfondi les tranchées sous le bloc mais celui-ci ne bougea pas d'avantage. Manifestement, les forces exercées par les leviers



**Fig. 19.** Mise en compression d'un bouton en bois à l'arrière du bloc pour opérer la rupture, c'est-à-dire le détachement de son banc.

n'étaient pas suffisantes bien que ceux-ci aient été poussés à la limite de leur résistance. La manière – par à-coups – avec laquelle ont été manipulés les leviers n'était d'autre part pas efficace. Nous avons alors pensé à entrer en force une pièce de bois de 10 x 10 cm de section dans la tranchée arrière. Le bouton, légèrement plus long que la tranchée elle-même, a été placé dans l'axe du bloc dans sa deuxième moitié supérieure. L'une de ses extrémités était située en partie haute contre le bloc tandis que l'autre prenait appui sur la paroi opposée. L'opération a ensuite consisté à mettre en pression la pièce de bois en frappant sur la partie haute à l'aide d'un madrier (fig. 19 et 20). Celui-ci, tel un marteau, était actionné verticalement par un homme dont les jambes prenaient appui sur le bloc et sur le bord de la tranchée. Après 5 minutes de mise en pression, le bloc céda et une fissure horizontale se dessina au fond de tranchée horizontale à la base du bloc. Cette technique telle que nous l'avons expérimentée s'est donc montrée très efficace et facile à mettre en place. Elle a l'intérêt d'engendrer de grandes pressions en continu. On imagine que sur le même principe plusieurs boutons pouvaient être placés dans le fond de la fosse pour augmenter les poussées. La mise en compression se ferait par un martelage avec des outils lithiques – pic à gorges par exemple – en alternance d'un bouton à l'autre comme on pourrait le faire avec des coins. En intercalant une grande pièce de bois entre les boutons et le bloc les forces pourraient être encore mieux réparties sur celui-ci. Il est possible que la grande pression engendrée par ce système dans le sens de la sédimentation de la pierre puisse être suffisante pour détacher le bloc sans qu'il soit nécessaire de creuser de tranchées horizontales aussi profondes que celles que nous avons réalisées. Il s'agit là d'une piste de recherche car cette solution n'a pas encore été expérimentée.



**Fig. 20.** Restitution de la méthode de mise en pression des butons en bois telle que nous l'avons expérimentée. La pièce de bois qui est légèrement plus longue que la largeur de la tranchée est entrée en force par battage. Le principe est d'exercer des pressions parallèles au sens du lit de la pierre. La rupture, c'est à dire le détachement du bloc, est atteinte au-delà d'une certaine tension.

## Les mesures et estimations

Nos explorations menées à ouadi el-Jarf sur la taille du calcaire au moyen de ciseaux en cuivre et de l'utilisation de l'eau nous ont montré qu'on pouvait atteindre un rendement de  $0,021 \text{ m}^3/\text{h}$ .<sup>23</sup> Dans notre configuration, l'extraction d'un bloc d' $1 \text{ m}^3$  a nécessité le creusement de 3 tranchées verticales de 0,50 m de large qui totalisent un volume de  $2 \text{ m}^2$ . Ce travail serait réalisé en 4 jours (de 6 heures) par 4 personnes – nous ne comptons pas là, la cinquième personne préposée à l'évacuation des déblais. La taille de la tranchée horizontale et le décollement du bloc ont, quant à eux, nécessité une journée supplémentaire à l'équipe. Ces estimations conduisent ainsi à un ratio d'un bloc pour 20 jours/homme soit  $0,05 \text{ bloc/jour/homme}$ . Ce chiffre concerne une extraction dans le contexte particulier du ouadi el-Jarf où les blocs étaient, semble-t-il, plutôt extraits en fonction des besoins et surtout de la proximité des gisements.<sup>24</sup> L'extraction que nous avons expérimentée s'appelle un défermage ; c'est un cas particulier qui consiste à retirer le premier bloc d'un front de taille et qui nécessite la découpe de 3 tranchées verticales. Dans une logique de production rationnelle, la moyenne du temps d'extraction peut baisser considérablement. Une exploitation intensive à l'instar de celle de la pyramide de Khephren par exemple (fig. 4) offre en effet des conditions d'extraction optimales. Dans ce cas – un découpage régulier sur une grande surface – le dégagement d'un bloc ne nécessite que la taille de deux tranchées verticales perpendiculaires l'une à l'autre ; chacune d'elles permet en effet de dégager deux faces de bloc. Si on reste sur le cas d'un bloc de  $1 \text{ m}^3$ , cette organisation de la découpe implique le dégagement de  $1,25 \text{ m}^3$  de pierre ce qui amène le ratio à  $1/14$ , soit  $0,071 \text{ bloc/jour/homme}$ . Avec l'extraction de blocs plus gros, ce ratio peut encore être amélioré.

Ces résultats peuvent être confrontés à l'expérimentation NOVA<sup>25</sup> qui s'était intéressée à l'extraction des pierres pour la construction de la grande pyramide. Celle-ci ayant été réalisée avec des outils modernes en acier, la comparaison entre les deux expériences demeure toutefois très limitée. Il est rapporté qu'une équipe de 12 hommes ont produit 186 blocs en 22 jours, ce qui représente un rendement de  $186/264$  soit  $0,70 \text{ bloc/homme/jour}$ . Compte tenu de l'utilisation d'outils en acier, Mark Lehner pondère toutefois ce ratio à 322 blocs par jour pour 1212 hommes, soit un rendement à  $0,26 \text{ bloc/homme/jour}$ . Avec de telles performances, la grande pyramide qui est constituée d'environ 2,3 millions de blocs<sup>26</sup> pourrait être construite en 20 ans. Selon nos estimations, l'extraction nécessiterait des effectifs plus importants ; pour atteindre un rythme quotidien de 340 blocs, il faudrait 4788 hommes. Si on augmente la période du chantier de la pyramide à 27 ans, ce qui est tout à fait envisageable, la production journalière requise descendrait à 250 blocs, ce qui nécessiterait en théorie 3521 carriers.<sup>27</sup>

<sup>23</sup> Dans un tout autre contexte et à titre d'exemple, le rendement avec des outils en acier à Pétra, dans du grès, à la période romaine, a été estimé à  $0,066 \text{ m}^3/\text{h}$  (Bessac (2007a), p. 360).

<sup>24</sup> Au ouadi el-Jarf, le nombre de blocs nécessaires à la fermeture des galeries n'était pas suffisant pour développer des zones en extension qui auraient été plus productives. Une exploitation des ressources à plus grande échelle aurait d'autre part eu un fort impact sur le paysage, ce qui aurait été en contradiction avec la vocation du complexe portuaire qui au contraire cherchait à dissimuler des galeries de stockage.

<sup>25</sup> Lehner (1997), pp. 206-209 ; Lehner (1996), pp. 46-93.

<sup>26</sup> Avec une base de 230,22 m de côté et une hauteur de 146,59 m, la pyramide a un volume total de  $2\ 592\ 297 \text{ m}^3$ . Elle est partiellement construite sur un massif rocheux, qu'on estimera à  $330\ 000 \text{ m}^3$ , si bien que le volume de la maçonnerie est d'environ  $2\ 260\ 000 \text{ m}^3$ . Selon M. Lehner le bloc moyen mis en place dans la construction aurait un volume d'environ  $1 \text{ m}^3$  (Lehner (1997), p. 207). Avec une hauteur moyenne de 0,73 m ( $146,59/201$  hauteurs d'assises), le bloc parallélépipédique moyen mesurerait  $1 \times 1,36 \text{ m}$  de côté. Si on soustrait les volumes de vides et les blocs spéciaux de dimension hors norme, on peut raisonnablement évaluer le nombre de blocs installés à 2 300 000. Petrie estime quant à lui que 500 blocs devaient être extraits et installés quotidiennement : Petrie (1930).

<sup>27</sup> On raisonne ici sur le principe que la pyramide est entièrement bâtie avec des blocs. Rien n'interdit cependant qu'elle soit en partie construite avec des caissons remplis de moellons, de déchets de taille ou de sable.

Enfin, nous avons constaté que la méthode d'extraction que nous avons expérimentée générait une quantité considérable de déchets dont le ratio est d'environ 1 pour 1 voire supérieur : un volume de pierre extrait produit le même volume en déchet. En considérant que le coefficient de foisonnement de la roche calcaire soit d'environ 1,5 – ce ratio correspond à une moyenne basse du calcaire fragmenté ou une roche concassée – nous obtenons pour 1 m<sup>3</sup> de roche extraite 1,5 m<sup>3</sup> de gravats, un matériau compactable et très stable qui peut servir pour la réalisation de rampes ou d'échafaudages. Si on estime que 2 000 000 m<sup>3</sup> ont été extraits sur le plateau de Gizeh pour la construction de la pyramide, c'est près de 3 000 000 m<sup>3</sup> qu'il a fallu évacuer ou plutôt utiliser. Avec un tel volume de matière disponible qui était produit en continu au fur et à mesure de la production des blocs, on comprend qu'il était logique et évident de l'utiliser pour éléver des rampes ou des échafaudages. Ce constat va ainsi à l'encontre de l'idée parfois avancée que des systèmes autres que les rampes aient pu être utilisés pour monter les blocs dans la construction. On imagine ainsi volontiers qu'une grande rampe frontale ait pu être construite progressivement à mesure que s'élevait la pyramide ; une hypothèse qui n'interdit pas non plus la présence de rampes annexes reliant différents gisements à celle-ci.<sup>28</sup> À la fin du chantier, les matériaux constituant les rampes pouvaient être nivelés et étendus en lieu et place des carrières ou pour corriger la topographie du site.

## Conclusion

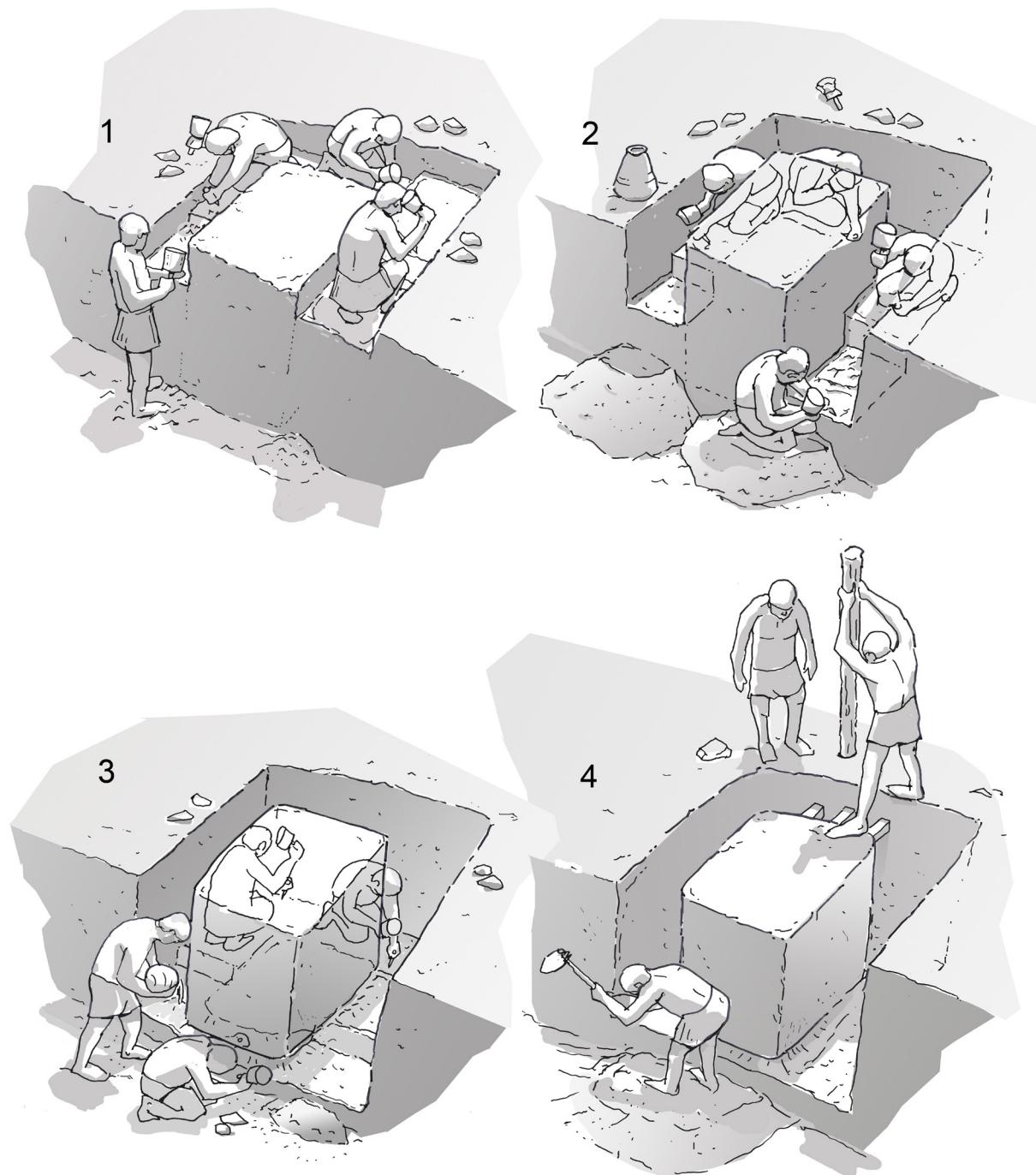
La découverte d'une carrière et des outils associés à ouadi el-Jarf a livré de nombreuses informations inédites sur les procédés d'extraction à l'Ancien Empire (fig. 21). En confrontant les outils retrouvés sur place – pics à gorge, cordes, pointes de ciseau en cuivre, maillets, enclumes – avec les traces laissées par ceux-ci mêmes dans les fonds des tranchées, nous avons affiné notre connaissance sur les méthodes employées. L'expérimentation que nous avons entreprise sur place, dans les conditions identiques à celles d'autrefois, avec les outils comparables et avec la même roche, a quant à elle permis non seulement de retrouver les gestes et les postures des anciens carriers mais également de comprendre comment s'organisait le partage des tâches au sein des équipes. Rappelons ici les informations majeures mises en exergue par notre expérience :

- Une remarquable connaissance de l'environnement géologique de la part des carriers.
- L'indispensable battage à froid régulier des pointes des ciseaux en cuivre pour les affûter.
- L'humidification du calcaire pour l'attendrir.
- La technique de fracturation de la pierre à l'aide de pièces de bois entrées en force.
- L'énorme quantité de déchets générée par la méthode d'extraction.

Les gestes et les méthodes qui ont été opérés à ouadi el-Jarf et que nous restituons à travers notre expérimentation sont ceux d'hommes très qualifiés, réunis en équipes extrêmement soudées. Nos résultats rapportent la grande force du système managérial égyptien qui savait développer des synergies en divisant adroïtement les tâches certes, mais en s'appuyant surtout sur une combinaison parfaite des compétences de ses ressources humaines. Le marquage systématique des outils, des blocs ou des jarres tel que nous l'observons à ouadi el-Jarf, témoigne de l'importance de l'organisation des effectifs au sein des équipes. C'est ce qu'atteste également l'exceptionnel papyrus de Merer découvert sur le site.

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<sup>28</sup> Sur l'hypothèse de la rampe frontale voir Lauer (2003), pp. 282-286. L'auteur estime qu'une telle rampe aurait un volume de 1 560 000 m<sup>3</sup> environ, soit en deçà de la masse de déchets générés par l'extraction.



**Fig. 21.** La restitution en 4 étapes de l'extraction d'un bloc à ouadi el-Jarf par une équipe de 4 personnes : 1) préparation du front de taille et mise en place des trois tranchées verticales ; 2) creusement des tranchées ; 3) poursuite du creusement des tranchées verticales et creusement d'une sape périphérique à la base du bloc ; 4) mise en tension de la pierre pour la fracturer à sa base à l'aide de butons en bois enfoncés en force.

## Bibliographie

- Abdul Massih J. et Bessac, J.-Cl. (2009), *Glossaire technique Trilingue de la Pierre. L'exploitation en carrière*, Guides Archéologiques de l'Institut Français du Proche-Orient 7, Damas.
- Arnold, D. (1991), *Building in Egypt, Pharaonic Stone Masonry*, New York : Oxford University Press.
- Barsanti, A. (1906), 'Fouilles de Zaouiét el-Aryân, 1904-1905', *ASAE* 7, pp.257-286.
- Bessac, J.-Cl. (2007a), *Le travail de la pierre à Pétra : technique, économie et culture*, Paris : ERC.
- Bessac, J.-Cl. (2007b), 'Étude technique et interprétations du monument rupestre de Qadamgah (Fars)', *Iranica Antiqua* 42, pp. 185-206.
- Bessac, J.-Cl. (2014), 'Le travail de la pierre à Aksum', *Annales d'Ethiopie* 29, pp. 147-178.
- Clarke, S. et Engelbach, R. (1930), *Ancient Egyptian Construction and Architecture*, Londres.
- Goyon, J.-Cl., Golvin, J.-Cl., Simon-Boidot, Cl. et Martinet, G. (2004), *La construction pharaonique du Moyen Empire à l'époque gréco-romaine*, Paris : Éditions Picard.
- Goyon, G. (1977), *Le secret des bâtisseurs des grandes pyramides*, Khéops, Paris : Éditions Pygmalion.
- Goyon, G. (1978), 'Les rangs d'assises de la Grande Pyramide', *BIFAO* 78, pp. 405-413.
- Harrell, J. A. et Storemyr P. (2015), 'Limestone and sandstone quarrying in Ancient Egypt: tools, methods and analogues', dans *Marmora, An international journal for archaeology, history and archaeometry of marbles and stones*, vol. 9, pp. 19-43.
- Hölscher, U. (1912), *Das Grabdenkmal des Königs Chephren*, 1912, Leipzig : J. C. Hinrichs'sche Buchhandlung.
- Isler, M. (2001), *Sticks, Stones, and Shadows, Building the Egyptian Pyramids*, Norma: University of Oklahoma Press.
- Kelany, A., Harrell, J. et Brown, V. M. (2010), 'Dolerite pounders: Petrology, sources and use', *Journal of Lithic Technology* 35/2, pp. 127-148.
- Lauer, J.-Ph. (1936), *La pyramide à degrés, l'architecture*, tome 1, Le Caire.
- Lauer, J.-Ph. (2003), 'Levage, bardage et transport de gros blocs de pierre dans l'Égypte ancienne', dans *Encyclopédie des Métiers, La maçonnerie et la taille de la pierre, tome 5 / Les outils*, pp. 278-286, Paris : Compagnons du Devoir.
- Lehner, M. (1996), 'The Pyramid', dans Barnes M., Brightwell R., Von Hagen A., Lehner M. et Page C., *Secrets of Lost Empires, Reconstructing the Glories of Ages Past*, Londres et New York, pp. 46-93.
- Lehner, M. (1997), *The complete pyramids*, London: Thames and Hudson.
- Lehner, M. et Hawass, Z. (2017), *Giza and the Pyramids. The Definitive History*. Chicago : University of Chicago Press.
- Lucas, A. (1927), 'Copper in Ancient Egypt', *JEA* 13, pp. 162-170.
- Monnier, F., 'Le mégalithisme appareillé dans les pyramides de l'Ancien Empire' (en préparation).
- Noël, P. (1968), *Technologie de la pierre de taille*, Paris : Société de diffusion des techniques du bâtiment et des travaux publics.
- Odler, M. (2016), *Old Kingdom Copper Tools and Model Tools*, Archaeopress Egyptology 14, Oxford.
- Petrie, F. (1917), *Tools and Weapons*, Londres.
- Petrie, F. (1930), 'The Building of the pyramid', *AncEg*, part II, june, pp. 33-39.
- Reisner, G. A. et Fisher, C. S. (1914), 'Preliminary report on the work of the Harvard-Boston Expedition in 1911-1913', *ASAE* 13, 1914, pp. 227-252.
- Reisner, G. A. (1931), *Mycerinus. Temples of the Third pyramid at Giza*, Cambridge: Harvard University Press.
- Tallet, P., Marouard, G. et Laisney, D. (2012), 'Un port de la IVe dynastie au Ouadi el-Jarf (mer Rouge)', *BIFAO* 112, pp. 399-346.
- Tallet, P. (2014), 'Des papyrus du temps de Chéops au ouadi el-Jarf (golfe de Suez)', *BSFE*, 188, pp. 25-49.
- Tallet, P. (2017), *Les papyrus de la mer Rouge I. Le journal de Merer (Papyrus Jarf A et B)*, MIFAO 136, Le Caire.
- Tarrell, J. et Petrie, F. (1925), 'The Great Pyramid Courses', *Ancient Egypt* Part II, June, pp.36-39.
- Vyse, H. (1840), *Operations Carried on at the pyramids of Gizeh in 1837 with an account of a voyage into Upper Egypt, and an appendix*, Vol. 1, London.



# The accurate construction of the right angles of the Great Pyramid's ground plan

Louis Clerc

## *Abstract:*

*Ancient Egyptian surveyors constructed 90-degree angles at the corners of the Great Pyramid to an accuracy of one part in ten-thousand. This paper proposes that the surveyors achieved this reliably by using an approximation technique and measuring rods and extending the resulting perpendicular lines along the pyramid's sides. Computations based on realistic and testable assumptions yield results that are persuasively close to those observed archaeologically. Using a 20 by 30 m base/side isosceles survey triangle to construct the perpendiculars at the right-angled corners produces a resultant angular deviation of 35.6 arc seconds, compared to the measured average of 37 arc seconds. Similarly, the calculated difference in the length of the sides is 3.93 cm compared to the measured differences in the lengths between the northern and western sides of 4.4 cm and between the northern and the eastern sides of 4.1 cm. Further discoveries at the pyramid's base dating to the appropriate era and found in the appropriate locations also support the historical use of the method. Additional considerations show how sophisticated geometrical intuition was developed during the 4th dynasty and that it was fundamental to the construction of highly symmetrical pyramids.*

## Introduction

Although Khufu's pyramid was aligned to the cardinal points with an accuracy better than 4 arc minutes,<sup>1</sup> ancient surveyors constructed the 90-degree corner angles with even greater accuracy. Surveyed data now indicates that this was achieved to one-ten-thousandth of 90 degrees, or under 1 arc minute.<sup>2</sup> Until now, there has been no satisfactory answer to how they constructed right angles with such unbelievably low uncertainty. To date, no calculations have been carried out that confirm the viability of any suggested techniques through a correlation of predicted values and observed archaeologically measured values. On the contrary, some pyramid specialists either doubt that the required precision referred to was indeed achieved<sup>3</sup> or simply explain it away as “they obviously mastered the practice of exact survey.”<sup>4</sup> That the measured deviation of the corner angles is 5 times smaller than the deviation of the pyramid's side alignments from the average length indicates that a particular angular measuring technique was most likely used. To investigate this, the historical context within which the 4<sup>th</sup> dynasty construction took place and the geometrical fundamentals involved in the process were studied. The conclusions of these studies are presented here for the first time. The paper presents and develops a new concept that avoids all the objections raised

<sup>1</sup> Dash (2017), p. 1; Lightbody (2020a), p. 31.

<sup>2</sup>  $0^{\circ}37'' / 90^{\circ} = 1,1 \cdot 10^{-4}$ . Cf. footnote 28.

<sup>3</sup> Stadelmann (1991), p. 220.

<sup>4</sup> Müller-Römer (2011), p. 377. Translated from German by the author.

regarding previous proposals, such as the low dimensional and directional stability of the available tools, the absence of a clearly-stated geometric criterion as a final objective, dependency on other right-angle constructions, or overly-cumbersome procedures. This paper utilizes a trigonometric model and the law of error propagation to evaluate if a two-step approximation technique employing measuring rods (ATMR) and the subsequent extension of the perpendiculars to the opposite side (EP) of the pyramid yields the expected result. The following wide-ranging discussion outlines how useful such a method would have been for the ancient Egyptian people in the absence of advanced theoretical knowledge. The analysis concludes that the use of the technique has a sound historical basis. It also investigates how the use of the method may relate to the later use of similar methods in the context of the Greek culture.

## Detecting the pyramid's ground plan

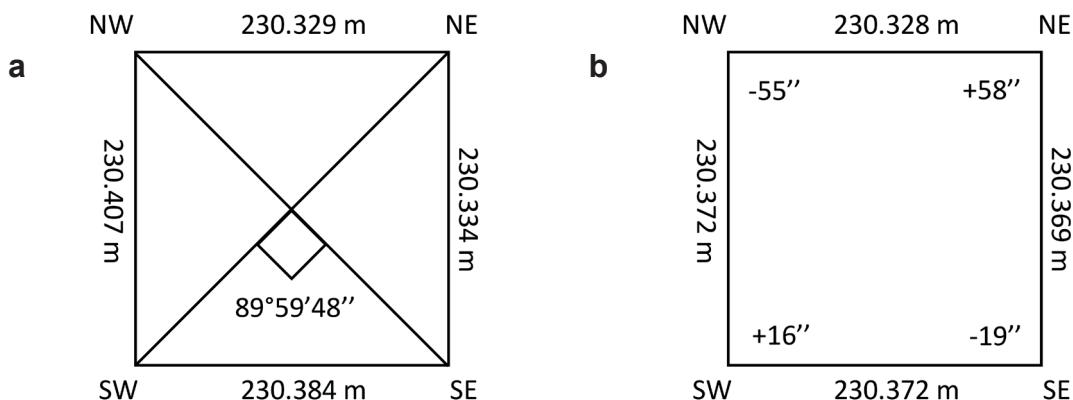
Originally, the Great Pyramid of Giza was completely covered in smoothed Tura limestone casing blocks. Only a few of the casing stones are still extant along the ground level platform and these are weather-worn and often badly damaged. Almost all are located in the middle sections of the sides. The original dimensions of the casing can no longer be established with absolute certainty, as the corners are gone today, but their positions can be reconstructed by intersecting the extrapolated reconstructed baselines out to the corners. For the sake of reliability, only survey work carried out after all four sides were cleared of rubble and other debris has been considered in this paper. Several points along the original edges can be found and fitted lines drawn through them. The difference in the azimuths between the two crossing baselines at each corner determines the corner angle.<sup>5</sup> To obtain the best data set, Lehner identified 84 points along traces of the original baselines left by the edges of the casing's footprint on the platform stones, which he discovered during a meticulous search.<sup>6</sup> He mapped them on the grid of the Giza Plateau Measuring Project (GPMP).<sup>7</sup> In 2015, Dash repeated the survey and also mapped them onto the control grid of the GPMP. He further defined the baselines as being the best fit line passing through these points using the statistical method of linear regression analysis. By extrapolating and crossing these lines, he determined the corner positions within an area of a few centimeters.<sup>8</sup> He subsequently calculated the distances between the neighboring corners as well as the lengths of the diagonals, and most importantly for this study, the angles at the crossings of the sides and diagonals (fig. 1-a.). A similar survey had already been completed by Dorner, and of the eight angular deviation value ranges calculated for the corner right angles measured by Dash and Dorner, seven are under 60 arc seconds, and the overall average is 45 arc seconds. The values of the side lengths and relevant angles are compiled and set out in fig. 1.

<sup>5</sup> Dorner (1981), p. 75.

<sup>6</sup> Dash (2012), p. 13.

<sup>7</sup> Lehner (2020).

<sup>8</sup> Dash (2015), p. 10.

**Fig. 1.**

a. Ground plan square defined by the casing baselines according to Dash. The diagonals connect the opposite corners of the casing (redrawn and modified from Dash).

b. Ground plan square with sides as measured by Dorner; deviations of the corner angles from 90 degrees calculated from the sides' azimuths. A perfect square is defined by 4 equal sides and 4 right angled corners leading to a perfect 90-degree angle of the crossing diagonals. Thus, the accuracy of the crossing angle is a substitute representing the accuracy of the corner angles. The difference between the average side lengths surveyed and calculated by Dash and Dorner was only 3 mm over 230.36 m, and this is another indicator of the accuracy of the base plan square. These values justify the conclusion that the corner angles of the casing were repeatedly and reliably achieved with an uncertainty of less than 60 arc seconds.

## Existing theories and their shortcomings

The survey data indicates that the eastern or western side<sup>9</sup> of the pyramid was first aligned towards the north with a deviation of 2 arc minutes and 47 arc seconds<sup>10</sup> and that its length was probably determined using measuring rods. The orientation of the side to the cardinal points will not be discussed further here because the process of constructing of the 90-degree angles to set out the subsequent sides based on this first side is independent of the procedure used to orient the first side to the cardinal points. Several practical techniques have been proposed that the ancient surveyors could have used to measure out the right angles. Though theoretically equivalent in intent, the methods differ significantly in practice and in their ability to achieve a given minimum uncertainty. A specific objection can be put forth arguing against the use of each method, as follows. Unterberger proposed construction using an auxiliary rectangle with diagonals positioned adjacent to the pyramid's ground level edge (fig. 2-a).<sup>11</sup> The challenge there is to set out the long diagonals accurately. To do this, the midpoint of the rectangle Pm must first be fixed with as little uncertainty as possible. This can be done either by drawing intersecting arcs with centers at the endpoints of the side, or by constructing a bisecting perpendicular extending out from the pyramid's base edge, along which the position of the center point PM can be freely chosen. The half-diagonals running from the corners to the point Pm are then completed to form diagonals defining the auxiliary rectangle and with it, the 90-degree angles at the pyramid's corners. This would be a laborious process

<sup>9</sup> Spence (2000), p. 321.

<sup>10</sup> Dorner (1981), p. 77.

<sup>11</sup> Unterberger (2008), p. 81.

demanding an additional construction step for creating the right angle at the center of the base, or to locate the point  $P_m$ , as well as extended diagonal measurements (over 230 m). The method is too complicated and prone to introducing further inaccuracies. Another procedure is to use a triangle with sides in the ratio 3-4-5 (fig. 2-b). This method certainly was and is useful for building every-day structures such as houses, however, Dorner's analysis of the minimum number of steps required to obtain the archaeologically observed right angles<sup>12</sup> using this method showed that the necessary measuring precision required when using this method was twice as high as required when using a method that used intersecting arcs (fig. 2-c). The intersecting arc technique is impressive in its simplicity and it can be applied directly at the pyramid's corners, but unfortunately, intersecting arcs must be drawn with cords, the elasticity of which make the use of such a method unlikely. The fourth possible method employs a wooden building square that is flipped by  $90^\circ$ , as proposed by Engelbach.<sup>13</sup> When compared to fig. 2-c, it is clear its use in this way produces an upside-down and extremely slender version of the isosceles triangle. In the current author's opinion, Engelbach's idea was ingenious in that it started with a dimensionally stable tool and eliminated the wooden square's inherent manufacturing error via the method of application. However, in a practical trial Engelbach was not able to achieve results of better than 1.5 arc minutes. Moreover, the perpendicular was not yet extended over 230 m to the opposite corner. The experimental application of the method, therefore, led to results with errors much larger than the archeologically observed tolerance of 1 arc minute (fig. 2-d).

Both wooden rods and cords made of natural fibers were available to measure distances. The latter had a lower resistance to external influences such as humidity change, temperature change, and strain, especially longitudinally in the measuring direction. According to Shazad, cords yield longitudinally up to 2% against the strain, equating to 104 cm over 100 cubits (52.4 m).<sup>14</sup> In a practical trial, Unterberger noted a lengthening of 1 m over 60 m and also noted the very arduous handling process.<sup>15</sup> To draw the arcs of a circle, the rope must be held tightened above the ground to avoid sagging and to evade obstacles. For precision, it must be absolutely taut. Without a high traction force this is impossible. As the ancient Egyptians could not accurately determine and maintain this type of force, they could not have used it consistently. This means that identical measurements were not repeatable. The knotting of the cord at regular intervals would have only worsened the situation. In conclusion, the measuring cord could not achieve a deviation of only a few centimeters over 230 m. Even so, it is not useless with respect to its directional stability. When held stretched it does not veer sideways and allows the marking of an accurate directional alignment. This means that leaving the measurement of the length to other, more precise longitudinal methods make good sense.

Rods are also subject to changes in temperature and air moisture content levels but they are more stable longitudinally. It has been noted that if they are cut across the wood grain they are ten times more stable longitudinally than rods cut along the grain in the measuring direction. When several such rods are connected together, long distances can be measured very accurately (fig. 5).

Despite the many objections, all the existing theories do meet the most elementary precondition. They are all able to apply one of the three possible fundamental geometrical construction methods yielding a right angle at the corners, namely, Euclid's definition, the Pythagorean theorem, or Thales' theorem (fig. 2). In practice, however, none of these theoretical methods can compensate for the negative influences encountered in the real physical world on the measuring process, and

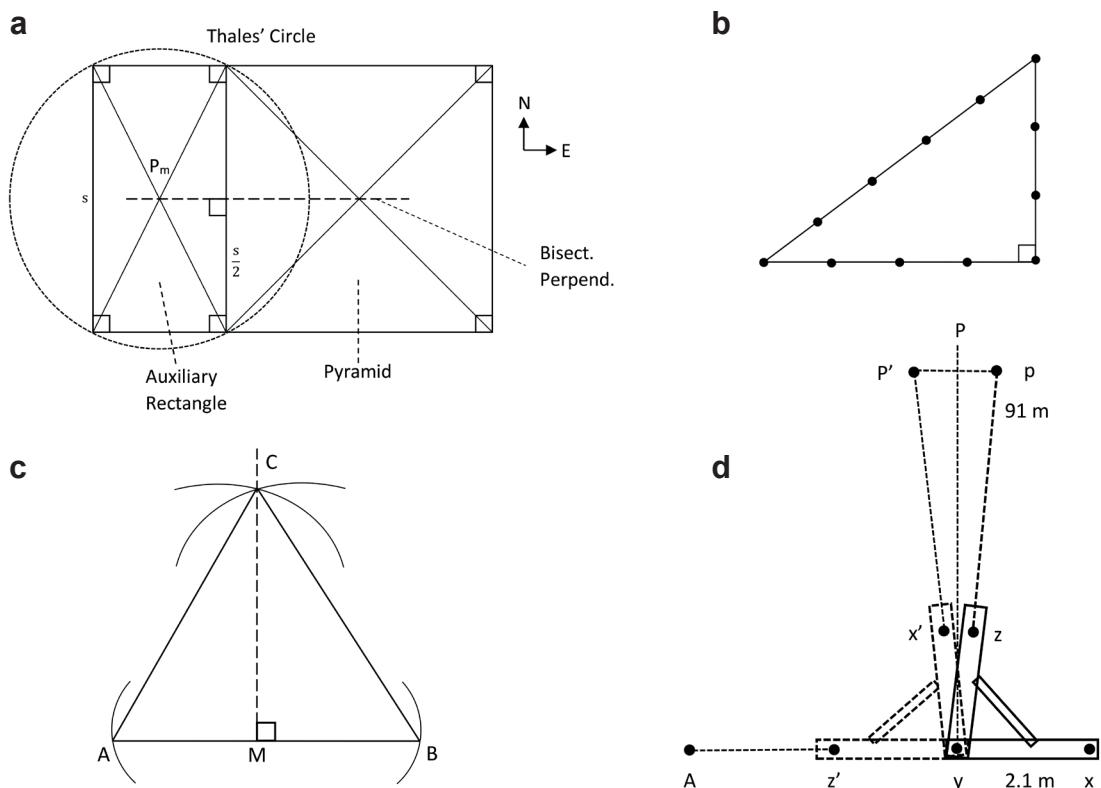
<sup>12</sup> Dorner (1981), p. 109, p. 113.

<sup>13</sup> Clarke, Engelbach (1999), p. 67.

<sup>14</sup> Shazad (2013), fig. 11.

<sup>15</sup> Unterberger (2008), p. 17.

none of them allow for the accurate extension of the perpendicular along the side. The current proposals all focus on the construction of a perpendicular on the pyramid's side that is far shorter (estimated at 30 m for practical reasons) than the pyramid's edge length. The constructed perpendicular must still then be extended over 230.36 m. This task cannot be taken for granted. It must also be surveyed and further errors will then arise. In most cases the small error of 60 arc seconds or less observed in the archaeology of the site is already accounted for by the deviation due to the construction of the 90-degree angles at the corners, leaving no room for error during the linear extension along the sides. A comprehensive workable theory must consider both parts of the task. Even so, there are intelligent concepts behind each existing theory that stimulated the development of the novel method proposed in this paper. The essence of the new theory is that once a suitably accurate linear measurement protocol had been devised, the bisecting perpendicular method shown in fig. 2-c<sup>16</sup>, enabled the ancient surveyors to execute the procedure with the archaeologically observed accuracy.



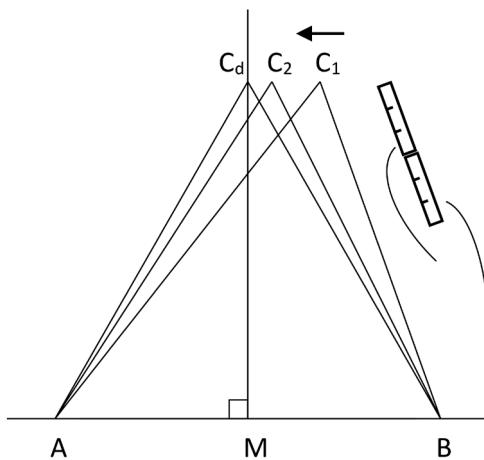
**Fig. 2.** Practical construction techniques for 90-degree angles.

- a. A circle is drawn through the diagonals of an auxiliary rectangle also illustrating the application of Thales' theorem (redrawn and modified from Unterberger).
- b. The 'Egyptian triangle' constructed with measuring cords (Pythagorean theorem and triplet).
- c. Unilateral intersecting arcs with measuring cords (based on Euclid's definition).  $\overline{AM} = \overline{BM}$ ;  $\overline{AC} = \overline{BC}$ .
- d. A flipped building square. Engelbach described the one he used in the field. The length of the legs was about 7 feet (2.1 m). It was not clear how the segments defined by the square legs of 2.1 m were extended to 91 m. In sum, the method cannot replicate the archeologically observed precision of less than 1 arc minute deviation over 230 m (redrawn from Clarke and Engelbach 1999, p. 67).

16 Robins, Shute (1987), p. 47.

## The approximation technique with measuring rods

The ATMR proposed here is based on Euclid's definition of a right angle, and proposition 11 of Book 1 of Elements.<sup>17</sup> After aligning the first side of the pyramid and fixing its endpoints, the straight line is extended laterally beyond the pyramid's corner M (the horizontal line on fig. 3). Points A and B are then marked at the same distance on either side of the pyramid's corner M. Point C<sub>1</sub> is then placed at an appropriate distance from the corner. After measuring the distances between C<sub>1</sub> and A as well as C<sub>1</sub> and B, point C is shifted toward the longer leg's side. This measurement process is repeated until equidistance is reached at C<sub>d</sub>. The connection between C<sub>d</sub> and the corner M is thus a perpendicular line whose extension at a right angle to the first side yields the second side, at the end of which the next corner can be fixed. The method is applied again and again until the pyramid's entire perimeter ground plan is established. All linear measurements, from C<sub>1</sub>, C<sub>2</sub>, and C<sub>d</sub>, to A and B, as well as from M to A and B, are performed exclusively using longitudinally stable wooden measuring rods (fig. 3). These are placed alongside stretched-out directionally stable cords (fig. 5). All of the equivalent equal distances must be measured out following the same protocol (equal numbers and identical application sequence of the same individual rods, preferably only the same two). This procedural consistency improves the end results.



**Fig. 3.** The approximation technique with measuring rods (ATMR). A shift parallel to the base is not required.

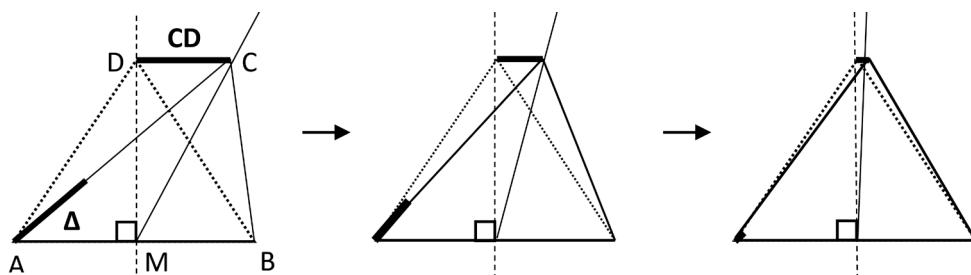
## Documentary evidence of such knowledge

The use of the method described above could indicate that the ancient Egyptians were already aware of a principle only described much later by Euclid's Elements of Geometry in proposition 11 of Book 1 of his work Elements. That was written around 300 BC, many centuries after the construction of Khufu's pyramid. No surviving document from the Old Kingdom mentions the use of such methods, however, the Rhind Mathematical Papyrus (RMP – pBM 10057&10058) dating from approximately 1,550 BC does include complex geometric algorithms. According to the scribe Ahmes, he had copied it from an earlier version dating from 1,850 BC, during the reign of the pharaoh Amenemhet of the 12th dynasty, only 700 years after the time of Khufu.

17 Euclid, (2007), Elements, Book 1, pp. 6, 16.

RMP problems 56-59 are concerned with pyramid measurement procedures. The examples demonstrate how to calculate the slopes of the pyramid's sides. The value called the seqed (or seked) of the slope was the reciprocal of the slope and was given by the run in relation to a 1-cubit rise. The illustrating figures of pyramids lack any lines referring to the height of the monuments, but the accompanying text reads “the seqed is taken to be half the width of the base divided by the height...”<sup>18</sup> Furthermore, in problems 57-59, the seqed quoted is the same as that of Khafre’s pyramid.<sup>19</sup> In these examples the height was undoubtedly used as the bisecting perpendicular of an isosceles triangle that formed the vertical cross section of the pyramid. When considered together with the dimensions in problem 56 that correspond to those of a large Old Kingdom pyramid, it seems most likely that this document reflects knowledge that came down from the Old Kingdom.

The close relationship between the pharaohs, state rituals, and the state’s pharaonic architecture is also documented on the Palermo Stone. Several entries reference the building of temples and the laying out of ground plans using the “stretching of the cord” ritual.<sup>20</sup> A Pyramid Text also includes reference to the ‘establishment and encircling’ of a pyramid, an action that resembles the idea of an encircling survey to establish the ground plan of a monument at the start of construction.<sup>21</sup>



**Fig. 4.** Construction of the bisecting perpendicular through M using the surveying triangle: depiction of the correlation between the angular deviation at the apex and the difference in the lengths of the legs during the procedure.  $\Delta$  is the leg length difference, CD is the lateral deviation from the ideal perpendicular, and M is the pyramid’s corner.

### Validation of approximation technique with measuring rods and extension of perpendicular

The reason that the ATMR procedure together with the EP (extension of the perpendicular described below) can successfully replicate the accuracy observed in the monument’s ground plan is the result of an elementary geometrical relationship. For a scalene triangle, where all the three sides are of different length, but of similar magnitude, the difference in length between the two legs ( $\Delta$ ) and the lateral deviation CD of the apex from the perpendicular bisecting its base, are close to equal. In the special case where the base length will also be equal to the final leg lengths (equilateral), this is in fact described by the equation  $\Delta = CD$  (see equation 5b<sup>22</sup> in the appendix

<sup>18</sup> Robins, Shute (1987), p. 47.

<sup>19</sup> Robins, Shute (1987), p. 47.

<sup>20</sup> Wilkinson (2000), p. 111-112.

<sup>21</sup> Lightbody (2020b), p. 57-59.

<sup>22</sup> To illustrate, the equilateral special case of the intended isosceles triangle was chosen because the length difference and apex deviation were equal. This can be seen in more detail in fig. 11. and equations 5b for the equilateral and 5a for the more general case.

along with the more complex mathematical demonstrations). Fig. 4. demonstrates the basic principles that underpin the survey work. The work begins with the selection of a provisional apex point, roughly chosen at an appropriate distance from the corner M to ensure adequate accuracy. When a difference in length between the triangle's two legs is observed, the surveyor knows that the triangle is still scalene. As a result, the apex point is shifted in the appropriate direction, and the comparison of the legs is repeated until they no longer have a difference in length. This is the final objective criterion. The bisecting perpendicular is then constructed by joining the apex to the bisection point at the base, which was the corner point M defined initially. In reality, the resultant form is not an ideal isosceles triangle, but the remaining errors can be evaluated. In fig. 4, the evolution of the form and the trigonometric laws behind the procedure can be seen as the method unfolds during the implementation of the ATMR. From the measured angular deviation observed at the archaeological site, the level of uncertainty left behind by the length measurements used on the construction site can be appreciated. The measuring techniques used can subsequently be guessed at and the viability of any proposed method checked by an appropriate computation.

### Carrying out measurements on the construction site

The proposed ATMR technique is relatively straightforward, however, establishing exactly how it was implemented on the construction site poses some remaining challenges. First, the procedure used must have a high degree of directional and dimensional stability. This must have been dealt with by choosing the tools to implement the procedure carefully. Second, the scale of the pyramid means that the measurements could not have been carried out in one operation. The task must have been split up into several successive steps. Third, measurements in the real world are physical procedures, and as such, they are inevitably subject to errors. Therefore, error analysis of some description would have been necessary.

With respect to the selection of tools, it is concluded here that measurement rods were used and that the extended distances must have been partitioned up and every subsection measured separately. In the measurement of each subsection, a small error arises. The exact value of the error is unknown but the order of its magnitude can be estimated through repeated observations (fig. 6). Due to the procedure followed during the implementation of the ATMR, the number and length of subsections in both legs are equal or close to equal. It is reasonable to assume that each error was of the same order of magnitude, although individually different and of varying algebraic sign.<sup>23</sup> Each new error was summed and passed along during the implementation of the procedure up to the end of the measurement. At first glance the more numerous the single measurements were, the harder it would be to achieve a certain accuracy. Yet, in some subsections the random errors are positive and in others, negative, thus, partially canceling each other out. This works in the surveyor's favor and makes the quest for high accuracy more achievable. The law of error propagation is also based on the same principle, and as a result it is possible to estimate the influence of all the errors on the final outcome, starting from the beginning of the procedure and continuing up to the end of the measurements. It is not necessary to fully understand the abstract mathematics involved, but the underlying principle is demonstrated in figs. 5, 6 and 7 below. These describe a measuring technique as it was most likely known and used during the 4<sup>th</sup> dynasty, based on the availability of the tools involved and the simplicity of handling them.

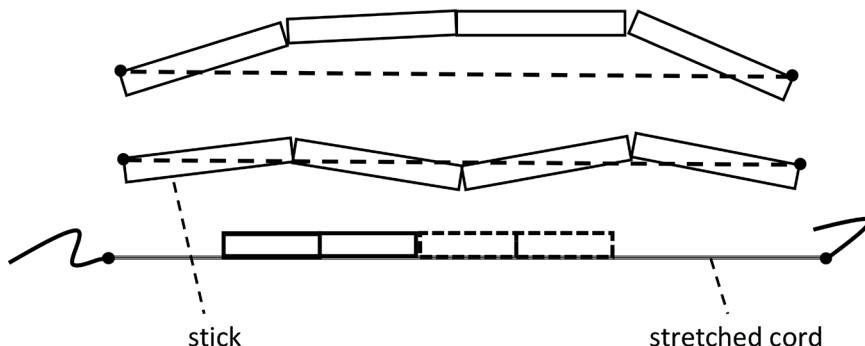
The maximum level of accuracy or minimum level of uncertainty is determined by two crucial parameters, namely, the precision of the tools used and the law of error propagation. The precision

23 Dorner (2007), p. 50.

is dependent on material properties such as the flexibility of cords and wooden rods, physiological constraints of the operator (including of the human eye), and the measuring protocol used. Finally, the different factors must work together to produce a resultant  $\Delta$  small enough to match or exceed the archaeologically observed angular deviation.

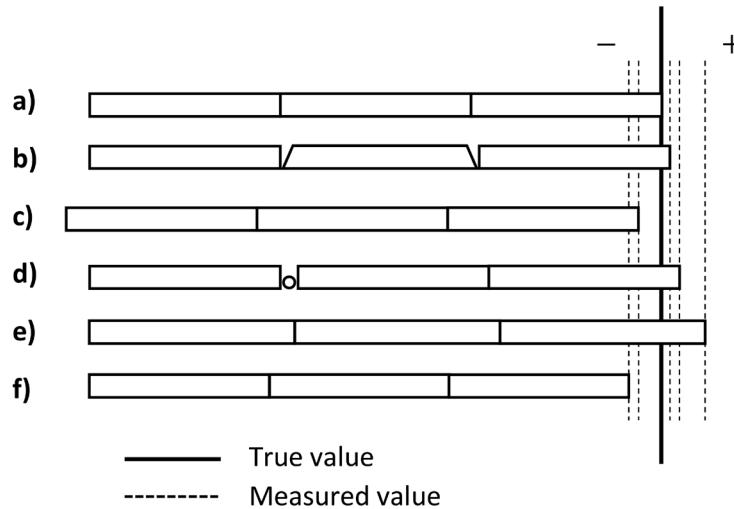
### The accurate measurement of a distance between two points

Ultimately, the construction of right-angled corners with such high levels of accuracy relies on accurate linear measurements. The effectiveness of the rod–cord combination technique is best assessed by evaluating the ratio of the total error compared to the total measured length. This is called relative accuracy (RA). The lower the value, the higher the precision. Clearly, the RA of the constituent steps must be lower than that for the eventual outcome. For the corner angles this was  $1 \times 10^{-4}$  (see footnote 2). In fact, the measurement accuracy achievable with dimensionally stable rods is astonishing. With 8-cubit rods (4.2 m), interface clearances of 0.25 mm, a stable temperature, and relatively dust-free surroundings, for a pyramid's side of 230.36 m, the achievable error is 1.85 mm ( $RA = 8 \times 10^{-6}$ ).<sup>24</sup> Similarly, for a surveyor's isosceles triangle with sides of 30 m, the error is 0.667 mm ( $RA = 2.25 \times 10^{-5}$ ). This demonstrates that longer distances can be measured with higher precision and that with smaller orders of magnitude of the RAs, achieving the small angular values for deviations observed at the pyramid's corners is readily achievable.



**Fig. 5.** Directional stability using measurement with rods aligned alongside a stretched rope. The rope is a directional guide that prevents curvature and zigzagging and ensures that the shortest line connecting the ends is measured, and thus, that it is a straight line. The rope is not used as a linear measurement device.

<sup>24</sup> 440 cubits side length gives 55 interfaces between the ends of rods of 8 cubits. If there is a 0.25mm linear error between each rod, the resultant error propagates to only 1.85 mm = 0.25mm x 55^0.5.



**Fig. 6.** The types of random errors that can occur when using dimensionally stable rods. Not to scale. The resulting uncertainties are positive in some cases and negative in others, therefore, they partially cancel each other out in cases of successive measurements. a. The intended true value, b. Joint gaps due to incongruent end cuts and unequal pressure applied when joined together, c. Inadvertent backward shifting of the initial position, d. Fine sand grain contamination, e. Thermal expansion and extension, and f. Thermal shrinking and shortening. The total error does not increase in direct proportion to the number “n” of subsections, but with the square root  $\sqrt{n}$ . With increasing n, the relative accuracy (RA) becomes more precise. Simply put, with 100 subsections, the distance grows 100 times but the total error only 10 times.

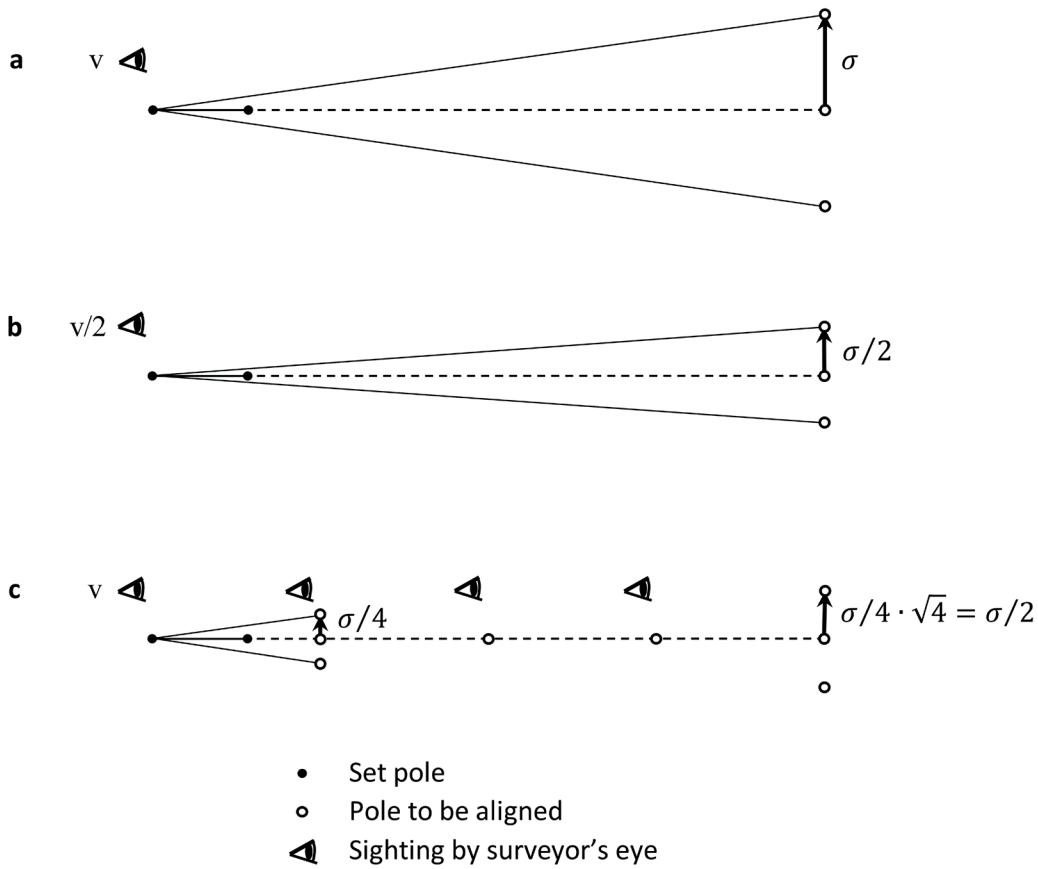
### The accurate extension of a straight line in segments over a defined distance

This is achieved by setting out and aligning a series of straight line segments using ranging poles positioned at certain intervals and by sighting along them with a given visual acuity.<sup>25</sup> With each sighting, a small random angular error arises that obeys the law of error propagation. The angular errors are perpendicular to the measuring direction (fig. 7), and with a constant visual acuity they are directly proportional to the distance between the ranging poles. This leads to a surprising consequence. The total angular accuracy can be enhanced by shortening the pole intervals. This is very significant, as the side length is 230 m and the intervals can easily be as short as 10 m. With shorter intervals, the large linear extension causes only a limited increase in the final error outcome (equations 11 and 12).

### Surveying the ground plan on the construction site

A corner point on the north side is chosen through which a segment of a straight line is drawn oriented to the north. This segment can be extended south from the corner point to determine the position the southern neighboring corner point. This is achieved by sighting along ranging poles set out in sequence and measuring the distance between them with rods aligned along cords stretched between them (fig. 5). The remaining corners are then surveyed and positioned by applying ATMR and EP.

<sup>25</sup> The best possible visual acuity of the human eye is 0.4 arc minutes or 24 arc seconds.



**Fig. 7.** Increasing the sighting precision by shortening the pole intervals.

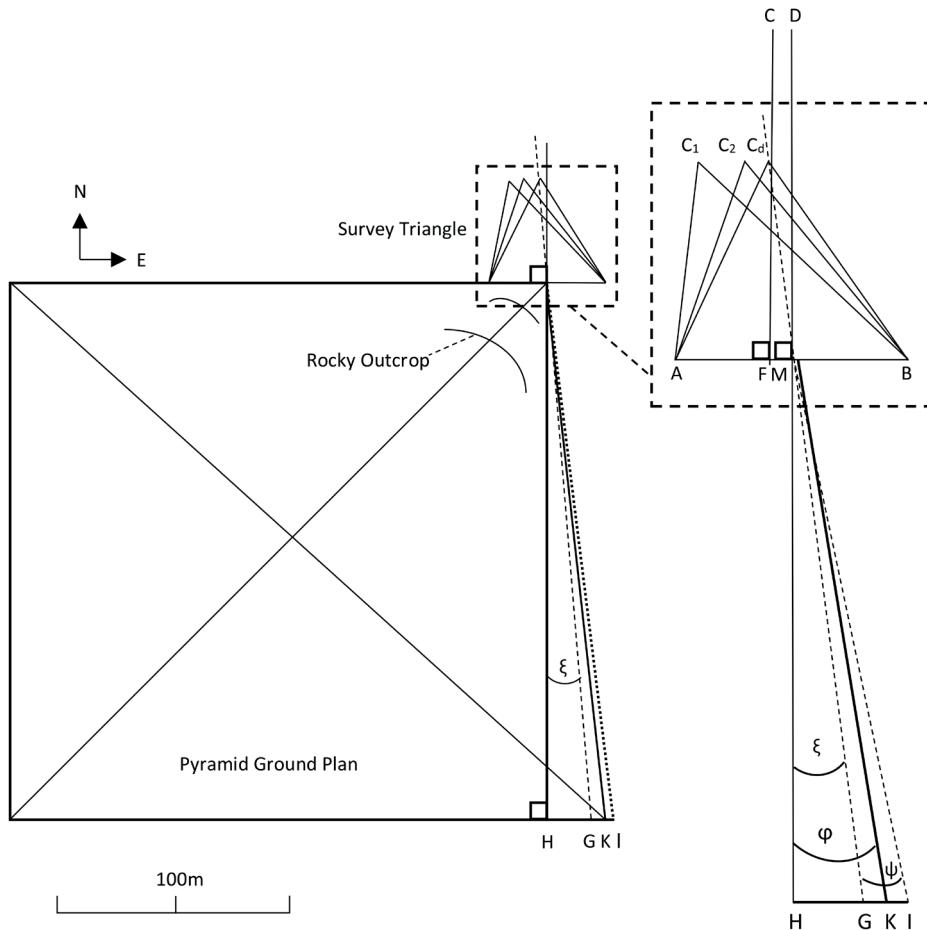
a. With a given visual acuity (visual angle  $v$ ) a single sighting results in an error of  $\sigma$ .

b. Double visual acuity (angle  $v/2$ ) results in half the error ( $\sigma/2$ ).

c. The same half error ( $\sigma/2$ ) can be attained with visual acuity  $v$  by 4 successive sightings using  $1/4$  length intervals. The error of a single sighting is  $\sigma/4$  as it is proportional to the interval size, and this is multiplied by the square root of the number of sightings to obtain the total error value, which is  $\sigma/4 \cdot \sqrt{4} = \sigma/2$

### Error analysis of the closed setting-out survey

The first surveyed side is an extension of a segment of a straight line aligned to the Northern Celestial Pole (NCP). The setting out of the three remaining perpendiculars with their extensions can start at either of its end points. Thus, both end points of this cardinally aligned side are at the same time starting and end points depending on whether the survey is carried out in a clockwise or anti-clockwise direction. By employing this closed survey strategy any ‘misclosure’ at these endpoints due to error propagation can be detected and the survey repeated until the ground plan’s perimeter is closed up. Furthermore, procedures used during the setting-out can also be improved iteratively and the changes evaluated by employing this closed survey strategy.



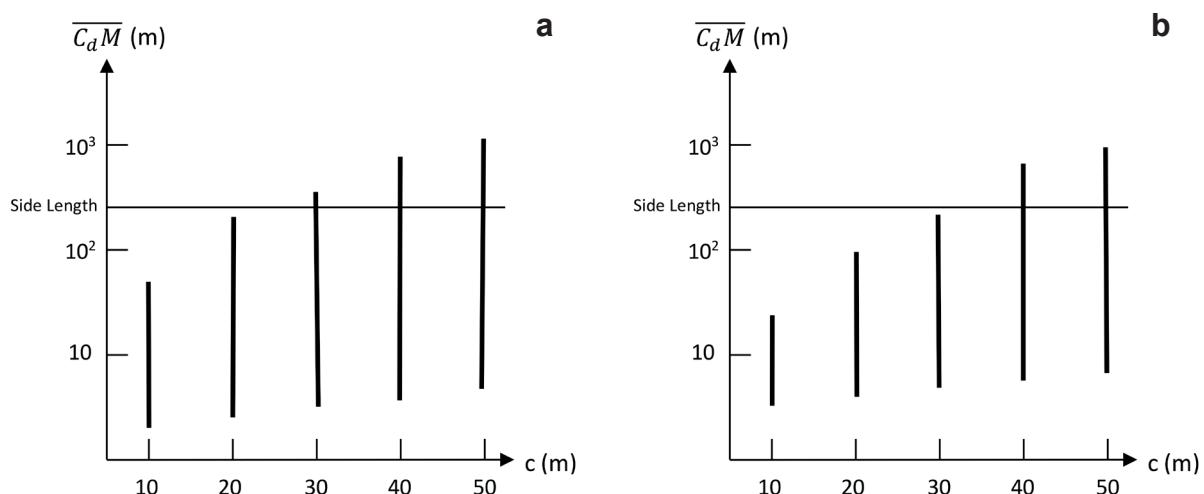
**Fig. 8.** Deviation produced at the pyramid's corners. This procedure provides an elegant solution that circumvents the rocky outcrop under the center of Khufu's pyramid, but it does introduce a degree of error.  $\overline{GH}$  is the deviation produced by projecting an initial line segment constructed as a perpendicular at the corner running through point M and extended until it intersects with the straight line formed by the extension of the opposite side.  $\overline{GI}$  is the additional deviation arising from the extension of the constructed perpendicular, which carried an initial error. The total effect of the deviation on the length of the pyramid's side  $\overline{HK}$  ( $\varphi$ ) arises from superposition during surveying of angular errors  $\overline{GH}$  ( $\xi$ ) and  $\overline{GI}$  ( $\psi$ ) (equation 12). The survey triangle and deviations  $\xi$ ,  $\psi$ , and  $\varphi$  are not to scale.

## Discussion

Based on these principles outlined above, an estimate of the real error values can be made in the following section. The angular and length measures are calculated according to the equations in the appendix and based on the precision measuring methods outlined in figs. 5, 6 and 7. For an estimate of the total random error, I assumed a 0.25 mm abutting joint clearance (fig. 6-b), a 0.13 mm layer of fine sand due to the proximity of the dusty desert (grain size 0.063-0.2 mm DIN 4200) (fig. 6-d), 0.2 mm error due to temperature changes of up to 10°C under sun exposure (Euro-code 1, European Standards 1991-1-5, 8-cubit rod = 4.2 m) (fig. 6-e), and 0.0025 mm shortening through deviation from the direction (1 cm horizontally and 1 cm vertically for 8 cubits). Summed up, the segment error is 0.58 mm for 8-cubit long rods or 0.48 mm for 4-cubit long rods.

The choice of measuring tool, either a rod or cord, is of paramount importance. Dorner analyzed the effects of temperature, air moisture, and traction on a weighted hemp cord 8 mm in diameter and about 1 m in length. The values he found extrapolated over 100 cubits (52.4 m) amount to 50 cm for both temperature and air moisture effects and as much as 100 cm under traction. He noted that during the 10-day test, the cord extended by 1 cm, although it had been strained before over several weeks<sup>26</sup> adding another 50 cm over 100 cubits (52.4 m). This level of variation means that it is unlikely that cord-based methods were used for measuring during the pyramid's construction. He considered possible special manufacturing processes for cords and he also considered rods as a long-distance measuring tool<sup>27</sup> but he did not research the latter approach in detail.

Unlike for the dimensionally unstable cords, more detailed computations can be carried out based on wooden rods. As a basis for the computations, I take 8-cubit rods (4.2 m), an error in length for each rod of 0.58 mm, and the surveyor's visual acuity to be 1 arc minute. The calculation of the error produced by the corner survey triangle (fig. 11) and its extension over the pyramid's side (fig. 8) yields, for 40/30 m and 20/30 m base/side triangles respectively, deviations of 3.4 cm (= 30.3 arc seconds) and 4 cm (= 35.6 arc seconds). The latter is an astonishingly close match to the measured mean angular error value of 37 arc seconds.<sup>28</sup> To be practically viable, ATMR had to fulfill 3 more preconditions, namely, allow the free choice of base length, allow different shapes for the isosceles triangles, allow a wide choice of possible apex positions on the ground for point C, and result in a total uncertainty of 60 arc seconds or less. Fig. 9 depicts the huge extent of available triangle sizes and shapes that can be used with 8-cubit (4.2 m) and 4-cubit (2.1 m) rods that meet the requirements and could achieve success.



**Fig. 9.** Viable range of possibilities giving an angular deviation of less than 60 arc seconds. The contribution of the perpendicular's extension to the total error is included. Here,  $c$  = base of the isosceles triangle,  $\overline{C_dM}$  = height of the isosceles triangle, and side length = 230.36 m (pyramid's side).

- a. With 8-cubit rods (1 cubit = 52.44 cm) and an error for each rod of 0.58 mm,
- b. With 4-cubit rods and an error for each rod of 0.48 mm.

26 Dorner (1981), pp. 98–99.

27 Dorner (1981), p. 99. Summarized and translated from German by the author.

28 Dorner (1981), p. 76. Arithmetical mean of 16", 19", 55", and 58".

## Conclusion

The striking discrepancy between the archaeologically observed values of construction accuracy achieved on the monuments and the lack of evidence of measuring tools or procedures (fig. 6) remains difficult to explain. Based on modern standing-building surveys the ancient surveyors could obtain a deviation due to length measurement error of only 4.3 mm over 230.36 m. In a practical test with measuring sticks, Unterberger was able to reproduce an uncertainty of less than 10 mm over 240 m.<sup>29</sup> In contrast, the differences in the lengths between the northern and western sides as well as between the northern and the eastern sides are 4.4 and 4.1 cm.<sup>30</sup> Spence compared this with the variation in the alignments of the different sides in earlier pyramids.<sup>31</sup> For the Great Pyramid of Giza, the difference in alignment between the western and eastern sides varies by 39 arc seconds,<sup>32</sup> generating a length difference of 4.35 cm. With a 20/30 m base/side survey triangle the ATMR produces 2.6 cm of variation and the EP produces 2.94 cm, which combine to produce a value of 3.93 cm (equation 12 in Appendix). This supports Dorner's proposal<sup>33</sup> and Spence's conjecture that the differences are the result of the construction of right angles at the corners while laying out the ground plan;<sup>34</sup> and it also supports the proposition that the sides were set out and aligned using a 2-step procedure.

After the technical suitability assessment, the historical plausibility of its use must be evaluated in the analysis. What motivated the pharaonic surveyors to develop such an elaborate method, which modern specialists have only now considered and find difficult to replicate? The main technical driver seems to be the disparity between the high accuracy requirement and the low linear dimensional stability of cords. Experiments in field survey have found that rods are far more reliable than cords for producing repeated and accurate measurements. The adoption of methods requiring several sequential steps, however, may have been a derivative of the ancient Egyptians' experience with cut stone construction. In those projects stone blocks of a certain dimension had to be carved to size in many stages, and this sort of iterative approach may have led them to use the ATMR. They could not differentiate between true and approximate values, but the archaeological record represented by the pyramid's base, including the levelled pavement created before the structure's erection is fascinating. "It clearly shows that the survey was executed at least 3 times with increasing accuracy".<sup>35</sup> The difference in height above sea level at the bottom of the corner sockets is 47 cm, while the surface of the leveled bedrock around them varies by 19 cm. The platform on which the pyramid was placed, however, varies only by 2.1 cm.<sup>36</sup> This accuracy is the best confirmation that a succession of approximating procedures were carried out at the appropriate places and at the appropriate times in order to produce the 4 sides and corner angles that can be observed today. When interpreted logically, the available evidence can support a compelling argument that such a technique was used.

Although a small deviation from a true right-angle seems to be a petty detail of ancient Egyptian architecture, the achievement contains more information than is visible at first glance. It allows us a glimpse into the intellectual life of the specialized scribes and architects. It is likely that the Old Kingdom Egyptians used the seqed or seked system to measure slopes, but they did not understand angles in terms of the arc and radius of a circle. The seked system, however, could not measure

<sup>29</sup> Unterberger (2008), p. 17.

<sup>30</sup> Dorner (1981), p. 77.

<sup>31</sup> Spence (2000), p. 321.

<sup>32</sup> Dorner (1981), p. 77.

<sup>33</sup> Dorner (1981), p. 95.

<sup>34</sup> Spence (2000), p. 321.

<sup>35</sup> Dorner (1981), p. 151. Translated from German by the author.

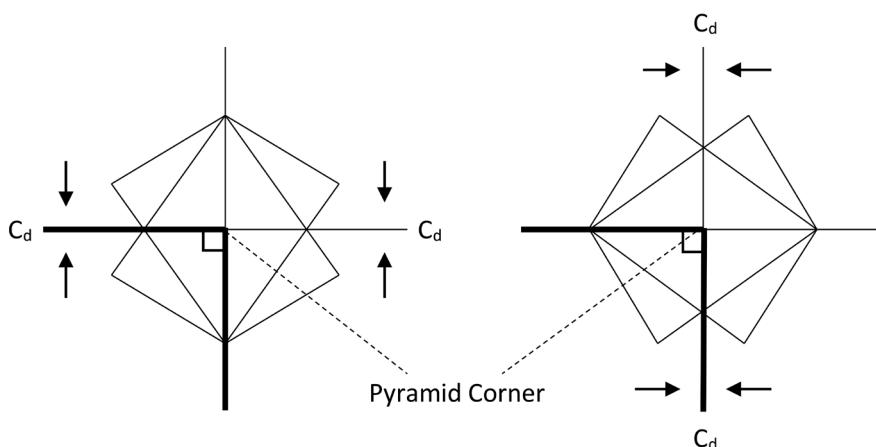
<sup>36</sup> Borchardt (1937), Heft 1, p. 6.

right angles, as it had to express a rise and a run. The solution they used to produce right angles used the idea of equidistance outlined above. It was simple and could be implemented precisely using only measurement rods and cords. The surveyors would first have chosen a point  $C_1$  fairly close to point  $C_d$  (figs. 3 and 4), and by repeating the procedure they would have reached their goal with minor effort. Afterward, they had only to extend the perpendicular along the pyramid's side.

Analysis of the ATMR, with RA values of  $0.6 \times 10^{-4}$  and  $0.52 \times 10^{-4}$  for 4-cubit and 8-cubit rods respectively, shows that the surveyors could have met or exceeded an accuracy of 60 arc seconds. It is even possible that a surveyor with the very best visual acuity of 0.4 arc minutes could have achieved a value of as little as 25.5 arc seconds of error, and in favorable atmospheric conditions, even down to 14.5 arc seconds. Similarly, the 8 possible arrangements of survey triangles at each corner (fig. 10) would have given the surveyors the freedom to choose the best layout to deal with any variations in the local topography (fig. 8). Stadelmann noted that the precision of the observed measurements can indeed be replicated, but hardly improved upon.<sup>37</sup> The current error analysis shows that the ancient Egyptians had pushed their technology close to its limits.

The most remarkable conclusion is that the use of the ATMR indicates that the ancient Egyptian specialists made use of two concepts formulated in writing only thousands of years later. These concepts are Euclid's definitions of the right angle,<sup>38</sup> and equidistance. Proposition 11, Book 1<sup>39</sup> reflects the ATMR closely. Equidistance is represented in Definition 1, Book 10 as "*summētria*" (symmetry). Its originally meaning was "in measure with" or "sharing a common measure."<sup>40</sup> "The term quickly acquired a further, more general meaning, that of a proportion relation."<sup>41</sup> This concept was what facilitated the accurate and symmetrical construction of the 4th dynasty pyramids. Its application at the pyramid's corners gives an insight into the state of geometrical knowledge at the time the Great Pyramid's construction began, around 2,554 BC<sup>42</sup> (2,480 BC).<sup>43</sup>

In conclusion, a procedure that combined the ATMR and the EP could well have been the method used to set out the ground plan of Khufu's pyramid tomb. Future research may reveal more arguments for its historicity.



**Fig. 10.** The 8 possibilities for setting out a survey triangle.

<sup>37</sup> Stadelmann (1991), p. 220.

<sup>38</sup> Euclid (2007), Elements, Book 1, Definition 10.

<sup>39</sup> Euclid (2007), Elements, Book 1, p. 16.

<sup>40</sup> Hon, Goldstein (2008), p. 71.

<sup>41</sup> Stanford Encyclopedia (Date accessed: 27 February 2020).

<sup>42</sup> Von Beckerath (1997), p. 159.

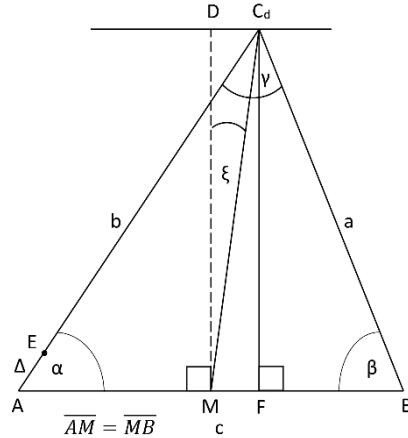
<sup>43</sup> Spence (2000), p. 320.

## Bibliography

- Borchardt, L. (1937), *Beiträge zur Ägyptischen Bauforschung und Altertumskunde*, Selbstverlag des Herausgebers Kairo.
- Clarke, S. and Engelbach, R. (1999), *Ancient Egyptian Masonry: The Building Craft Book Tree*.
- Dash, G. (2012), 'New Angles on the Great Pyramid', *Aerogram* 13-2, pp. 10-19.
- Dash, G. (2015), 'The Great Pyramid's Footprint: Results from Our 2015 Survey', *Aerogram* 16-2, pp. 8-14.
- Dash, G. (2017), 'Occam's Egyptian Razor: The Equinox and the Alignment of the Pyramid', *JAEA* 2, pp. 1-8.
- Dorner, J. (1981), *Die Absteckung und Astronomische Orientierung Ägyptischer Pyramiden*, PhD thesis, Innsbruck.
- Dorner, J. (2007), 'Die Genauigkeit der altägyptischen Streckenmessung', *Sokar* 15, pp. 50-55.
- Euclid, (2007), *Euclid's Elements of Geometry*, J. L. Heiberg (1883-1885) (Editor), Richard Fitzpatrick (Translator).
- Hon, G. and Goldstein, B. A. (2008), *From Summetria to Symmetry: The Making of a Revolutionary Scientific Concept* Springer.
- Lehner, M. 'High-Precision Measure of the Landscape', [<https://www.aeraweb.org/gpmp-project/giza-meter-by-meter/>] (Date accessed: 28 July 2020).
- Lightbody, D. I. (2020a), 'Moving heaven and earth for Khufu: Were the Trial Passages at Giza components of a rudimentary stellar observatory?', *JAEA* 4, pp. 29-53.
- Lightbody, D. I. (2020b), *On the Origins of the Cartouche and Encircling Symbolism in Old Kingdom Pyramids*, Oxford: Archaeopress.
- Müller-Römer, F. (2011), *Der Bau der Pyramiden im Alten Ägypten* Herbert Utz Verlag GmbH. München.
- Robins, G. and Shute, Ch. (1987), *The Rhind Mathematical Papyrus: An Ancient Egyptian text* London. British Museum Publications Limited. Reprint 1. August 1990.
- Shazad, A. (2013), 'A Study in Physical and Mechanical Properties of Hemp Fibres', *Advances in Materials Science and Engineering*, [<http://dx.doi.org/10.1155/2013/325085>] (Date accessed: 27 February 2020).
- Spence, K. (2000), 'Ancient Egyptian Chronology and the Astronomical Orientation of Pyramids', *NATURE* 408.
- Stadelmann, R. (1991), *Die ägyptischen Pyramiden: vom Ziegelbau zum Weltwunder von Zabern*, Mainz am Rhein.
- Stanford Encyclopedia of Philosophy: Stanford University [<https://plato.stanford.edu/>] (Date accessed: 27 February 2020).
- Unterberger, E. (2008), *Die Tricks der Pyramidenbauer – Vermessung und Bau der ägyptischen Pyramiden* Eigenverlag, Innsbruck, [<https://www.pyramidenbau.eu/BUCH/>] (Date accessed: 27 February 2020).
- Von Beckerath, J. (1997), *Chronologie des pharaonischen Ägypten* von Zabern, Mainz.
- Weisstein, E. W. 'Normal Difference Distribution, Normal Sum Distribution', [<http://mathworld.wolfram.com/NormalDifferenceDistribution.html>] (Date accessed: 27 February 2020).
- Wilkinson, T.H. (2000), *Royal Annals of Ancient Egypt*, London: Kegan Paul Ltd.

## Appendix

### Length uncertainty and angular deviation



**Fig. 11.** Uncertainty of the isosceles survey triangle.

$$\overline{C_dD} = \overline{MF} = \overline{AF} - \overline{AM} \quad (1)$$

since  $\overline{AF} = b \cdot \cos \alpha$  and  $\overline{AM} = \frac{c}{2}$

$$\overline{C_dD} = b \cdot \cos \alpha - \frac{c}{2} \quad (2)$$

as  $\cos \alpha = \frac{b^2 + c^2 - a^2}{2bc}$  law of cosines

$$\overline{C_dD} = b \frac{b^2 + c^2 - a^2}{2bc} - \frac{c}{2} \quad (3)$$

$\Delta = \overline{AE}$  and  $b = a + \Delta$  by definition

$$\overline{C_dD} = (a + \Delta) \frac{(a + \Delta)^2 + c^2 - a^2}{2(a + \Delta)c} - \frac{c}{2} \quad (4)$$

rearranged

$$\overline{C_dD} = \Delta \frac{a}{c} + \frac{\Delta^2}{2c} \quad (5)$$

$\frac{\Delta^2}{2c}$  insignificant as  $\Delta \ll c$

$$\overline{C_dD} = \Delta \frac{a}{c} \quad \text{isosceles triangle} \quad (5a)$$

$$\overline{C_dD} = \Delta \quad \text{equilateral triangle as } a = c \quad (5b)$$

## Measuring on the construction site

Symbols used in the following equations

$L_R$  = length of measuring rod

$L_P$  = distance (interval) between ranging poles

$\sigma_R$  = error of single measurement with rods

$\Sigma_R$  = total error with measuring rods

$\sigma_P$  = error of single measurement with ranging poles

The error for the whole distance of a leg  $a$  with  $\frac{a}{L_R}$  measurements can be expressed as follows:

$$\Sigma_R = \sigma_R \left( \frac{a}{L_R} \right)^{1/2} \quad (6)$$

To obtain the deviation  $\overline{C_d D}$  on the construction site, the difference  $\Delta$  between the 2 legs of the isosceles triangle must be calculated. The length of each leg comprises 2 real components, the sum (number) of measuring rods and the accumulated single measuring errors. The rods can simply be counted (measured). In contrast, the normally distributed random errors of unknown magnitude and algebraic sign can only be estimated. Due to the final criterion and the same measuring procedure on both legs, the 2 total errors  $\Sigma_R$  must be assumed to have the same order of magnitude. The difference in the rod components on each leg is 0. To calculate the difference between the normally distributed total errors, the variances (squared deviations) of the variates are taken instead and added up. This is  $2 \Sigma_R^2$ .<sup>i</sup> The resulting deviation  $\sqrt{2} \Sigma_R$  is, therefore, the square root and when plugged into equation 5a, it leads to

$$\overline{C_d D} = \sqrt{2} \Sigma_R \frac{a}{c} \quad (7)$$

after projecting point M in the direction of the constructed perpendicular  $\overline{MC_d}$  onto the opposite side, with

$$\overline{BF} = \frac{c}{2} \text{ as } \overline{MF} \ll \overline{BM} \quad \text{and}$$

$$\overline{C_d F} = \left( a^2 - \frac{c^2}{4} \right)^{1/2} \quad (8)$$

<sup>i</sup> Weisstein (2020). Amazingly, the distribution of a difference or sum of 2 normally distributed independent variates X and Y with means  $\mu_X$  and  $\mu_Y$  and variances  $\sigma_X^2$  and  $\sigma_Y^2$  is another normal distribution, with mean  $\mu_{X-Y} = \mu_X - \mu_Y$  for the difference and  $\mu_{X+Y} = \mu_X + \mu_Y$  for the sum, and variance  $\sigma_{X+Y}^2 = \sigma_X^2 + \sigma_Y^2$ . In the present case,  $\mu$  corresponds to the length measured with rods and  $\sigma^2$  to the squared total deviations  $\Sigma_R$ . X and Y are the 2 isosceles legs of the isosceles triangle.

Symbols pertaining to deviations at the pyramid corner (Fig. 8).

$\overline{GH}$  = deviation at corner contributed through the projection of M in the direction of the constructed perpendicular onto the straight line of the opposite side.

$\overline{GI}$  = deviation at corner contributed through the extension of the perpendicular

$\overline{HK}$  = total deviation due to superposition in practice (equation 12).

$$\overline{GH} = \overline{C_d D} \cdot \frac{\overline{HM}}{\overline{C_d F}} \quad \text{The deviation at the corner is} \quad (9)$$

$$\overline{GH} = \sqrt{2} \sum_R \frac{a}{c} \frac{\overline{HM}}{\overline{C_d F}} \quad (10)$$

To determine the neighboring corner, the constructed perpendicular must be extended over the pyramid's side. This is done by extending the constructed perpendicular by setting out a series of straight lines with ranging poles (Fig. 7.) at intervals of 45 m, for instance. With a surveyor's visual acuity of 1 arc minute (Snellen 20/20), an error  $\sigma_P$  of 1.3 cm arises at each measurement leading to the following:

$$\overline{GI} = \sigma_P \left( \frac{\overline{GM}}{L_P} \right)^{1/2} \quad (11)$$

The sum of the deviations is calculated according to a normal sum distribution by taking the square root of the sum of the variances (= squared deviations).

$$\overline{HK} = \left( \overline{GH}^2 + \overline{GI}^2 \right)^{1/2} \text{ ii} \quad (12)$$

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<sup>ii</sup> Weisstein (2000), see footnote i. In the present case, the angular means are both 0. The constructed perpendicular deviates only by random errors from the true 90-degree angle and the extension is in the same direction as the constructed perpendicular.