Research Article

The so-called concave faces of the Great Pyramid

Facts and cognitive bias

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Abstract

This article provides an up-to-date summary of ongoing research into the so-called concave faces of the Great Pyramid of Khufu. A re-evaluation of the condition and form of the faces of the monument is followed by a review of the descriptions recorded during all the historical eras. This work leads to a re-evaluation of the characteristics of the indentations and demonstrates that this unique feature first became apparent during the more recent history of the monument.

Keywords: surveying techniques, photogrammetry, medieval accounts, architecture, Khufu, Great Pyramid

مايعرف بالأوجه المقعره للهرم الأكبر: حقائق وتحيز معرفي

الملخص

يقدم هذا المقال ملخصا محدثا للبحوث الجارية حول ما يسمى بالأوجه المقعره لهرم خوفو الأكبر. يعقب إعادة تقييم حالة وشكل وجوه أو جوانب الأثر مراجعة الأوصاف المسجلة خلال جميع العصور التاريخية. يؤدي هذا العمل إلى إعادة تقييم خصائص الفجوات العميقه ويوضح أن هذه الخصية الفريدة ظهرت لأول مرة خلال التاريخ المعاصر للأثر.

الكلمات الدالة تقنيات المسح، المسح التصويرى، حسابات (كتابات رحالة) القرون الوسطى، العمارة، خوفو، الهرم الأكبر

1 Introduction

The pyramid of Khufu has inspired and continues to inspire an avalanche of discussions of all genres.[1] Its geometry, its interior layout, and its supposed perfection are just some of the topics that have been covered at length

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(LAUER, 1988: 151–193; LEHNER & HAWASS, 2017: 141–187; MONNIER & LIGHTBODY, 2019). While Egyptologists restrict themselves to questions of a scientific nature, alternative researchers know no such limits and have a tendency to remove it from its historical context entirely (LAUER, 1988: 151–193). The alternative movement attributes many geometric properties to the pyramid, of varying degrees of complexity. One phenomenon that does fall within the realms of possibility is that the pyramid has eight exterior faces, not four, and that this is the result of the apparent concavity of its faces.[2] Without it ever having been demonstrated, but as a result of frequent repetition alone, this hypothesis has gained the status of a proven fact. The idea has nevertheless prompted discussions about what could have caused the particular form of the creases seen running down the centers of the four faces of the pyramid. In this article, I review the development of the concave faces concept in the relevant literature. I also set out the facts of the matter and review the results of a photogrammetry survey undertaken in 2018, carried out by the French company *Iconem*. By considering the state of the archaeology, the historical documents, and the modern survey together, new information is drawn from the current analysis that indicates the probable origin of the creases on the faces of the monument.

2 The recessed courses and the supposed concavity of the faces

Flinders Petrie seems to have been the first, in 1883, to describe and give a geometric definition to the folds or creases running down the center of the faces of the Great Pyramid:

> 'With regard to the casing, at the top it must — by the above data — average about 71 ± 5 inches in thickness from the back to the top edge of each stone. Now the remaining casing stones on the N. base are of an unusual height, and therefore we may expect that their thickness on the top would be rather less, and on the bottom rather more, than the mean of all. Their top thickness averages 62 ± 8 (the bottom being 108 ± 8), and it thus agrees very fairly with 71 ± 5 inches. At the corners, however, the casing was thinner, averaging but 33.7 (difference of core plane and casing on pavement); and this is explained by the faces of the core masonry being very distinctly hollowed.
>
> This hollowing is a striking feature; and beside the general curve of the face, each side has a sort of groove specially down the middle of the face, showing that there must have been a sudden increase of the casing thickness down the midline. The whole of the hollowing was estimated at 37 on the N. face; and adding this to the casing thickness at the corners, we have 70.7, which just agrees with the result from the top (71 ± 5), and the remaining stones (62 ± 8)' (PETRIE, 1883: 43–44).

The British archaeologist attempted, in the process, to explain these observations. According to Flinders Petrie:

> 'The object of such an extra thickness down the midline of each face might be to put a specially fine line of casing, carefully adjusted to the required angle on each side; and then afterwards setting all the remainder by reference to that line and the base' (PETRIE, 1883: 43–44).

Several decades later, in 1921, this proposal by Flinders Petrie partly inspired a work that developed a considerable following in the world of alternative history and alternative archaeology: *The Great Pyramid and its Divine Message* by David Davidson (1924). It is pointless to attempt to refute all the points put forth by that author, who, like many before him and after, pretended to have uncovered calendar-related dimensions or prophecies encoded

[2] The references for this hypothesis are included below.

within the smallest proportions of the pyramid. The image that he imposed on the edifice is significant in the sense that it exercised an influence on all the commentators that followed. Flinders Petrie's geometric description of the form of the monument was taken quite literally, so Davidson concluded that the pyramid had eight faces (Figure 1) instead of four, and that each face was supposedly folded exactly down the center line of the apothem (i.e. the line from the summit to the midpoint of the base).

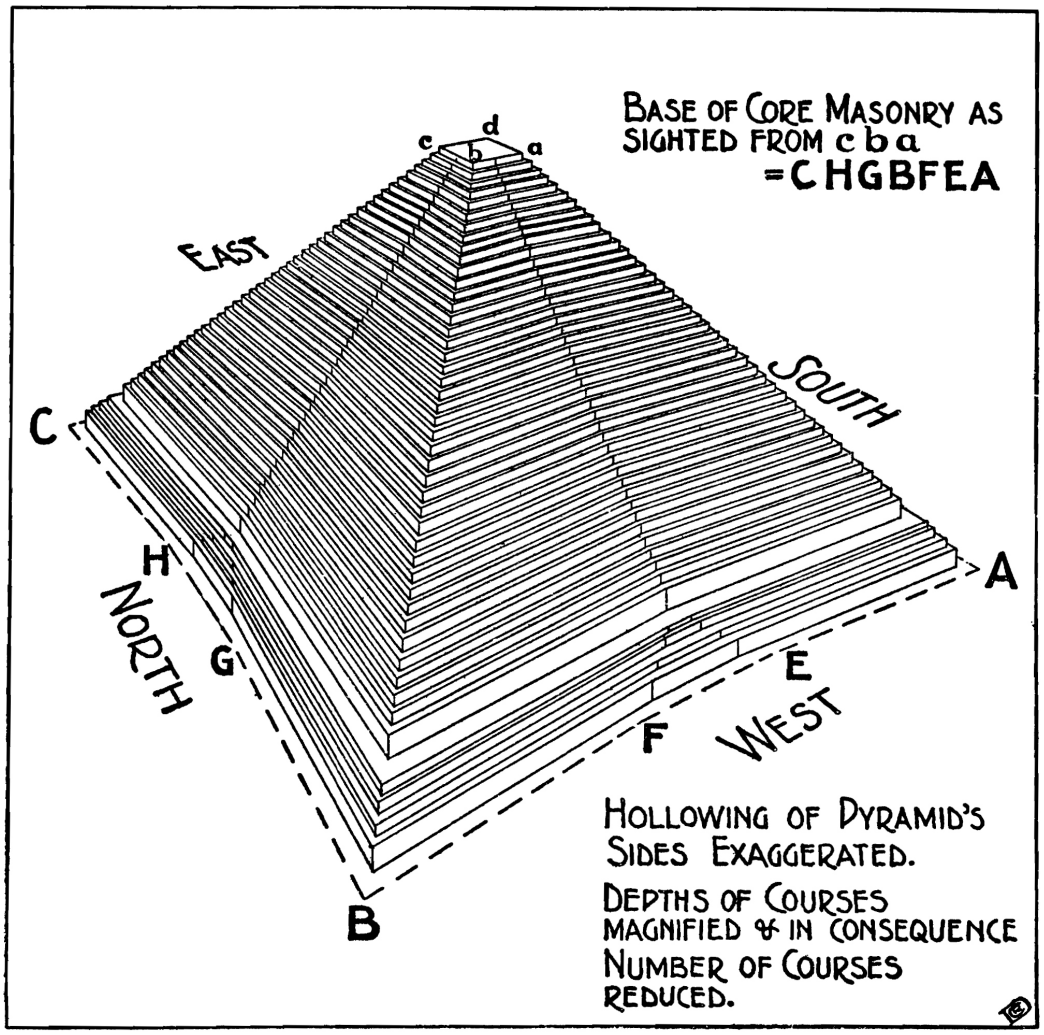

Fig. 1: Pyramid with eight faces as imagined by David Davidson in 1924 (taken from DAVIDSON, 1924:pl. XVIII).

In 1935, André Pochan presented a paper at the Egyptian Scientific Institute (*Institut d'Égypte*) where he called attention to the phenomenon where, at the time of each equinox, the sun is perfectly aligned with the east-west axis of the Great Pyramid. At that time, the shadows thrown on its north and south faces make them appear to be creased, in accordance with the description by Davidson (DAVIDSON, 1924: 273–274). Pochan was convinced that this had been deliberately designed by the Egyptians so that they would be able to detect the time of the equinoxes. While this theory passed un-noticed at the time, it was further elaborated and illustrated in detail in his book published in 1971. This fed and intensified the discussions surrounding the curious characteristic at the

end of the 20th century. Pseudo-scientists jumped on this new hypothesis with enthusiasm, and the subject would have been left as it was had not more serious scientists also applied themselves to understanding the phenomenon.

Vito Maragioglio and Celeste Rinaldi, in their magnificent description of the Great Pyramid published following their survey work, addressed the issue and the observations made by Flinders Petrie (MARAGIOGLIO & RINALDI, 1965: 16, 104). They suggested that the concavity (in their words) could have been a precaution designed to consolidate the attachment of the casing stones near the center line, in order to prevent any slippage.

In 1983, Martin Isler also proposed an explanation based on the idea that the phenomenon was the result of the particular methods used during construction (ISLER, 1983: 27–32). According to his theory, efforts by the builders to control the alignment of the sides could explain the form. The use of long cords could have led to slight variations in the levels of layers and a slight error in the alignment of the planes on each side of the faces, which increased towards the top.

In 1996, José Miguel Parra Ortiz took up the torch and, after discussing the work of Pochan in detail, concluded that the archaeo-astronomical explanation was plausible (PARRA ORTIZ, 1996: 79–86). It is worth noting that Jean-Philippe Lauer also wrote briefly on the work of Pochan, but he did not venture his own explanation for the phenomenon (LAUER, 1988: 186–187).

3 The Facts

The indentation of the faces first attracted attention once Flinders Petrie completed his survey of the monument in 1883 (see above). Only an engraving and a plate from the *Description de l'Égypte* had previously illustrated the phenomenon, which Jomard described as resembling steps, worn more in the center than at the edges (Figures 2 and 3).

In 2004, the *Scanning of the Pyramids Project* team added their laser scans to the corpus of evidence by producing a three-dimensional model of the Great Pyramid of Khufu (Figure 4) (NEUBAUER et al., 2005).

Later in 2018, drone footage was used on the Giza plateau and a photogrammetry scan was carried out by the French company *Iconem* for a TV documentary produced by François Pomès and Label News. I was involved in this project as a scientific advisor and was granted permission to analyse the produced drone images a second time for scientific goals. The data gathered during that survey provided me with new information about the state of the pyramid's faces and this is discussed below to help re-evaluate the possible explanations for the phenomenon (Figures 5 to 9)

The 3D model created from this photogrammetry survey can be broken down into horizontal sections. It is, therefore, possible to follow the course of each layer of blocks at any given level. I was able to superimpose several sections in this way, first focusing on the west face of the pyramid (Figures 5 and 6).

It turns out that the profile of the faces is far from uniform as the *Scanning of the Pyramids Project* team had already highlighted (Figure 4). The faces are neither concave nor folded exactly at the apothem. In fact, while the indentation gets more and more pronounced closer to the center, the surface is very irregular (Figure 8). Not all of the layers are recessed at the center line. Some are set back only a little (near the top), while others are particularly pronounced (predominantly on the lower half). The maximum recessed depth at the apothem exceeds two meters in places, twice the depth estimated by Flinders Petrie for the north face (PETRIE, 1883: 43–44). Each face does have a very irregular groove running from the top to the base down the central axis (Figure 9).

All of this confirms what the laser scan carried out in 2004 revealed (Figure 4) and adds significant detail to Flinders Petrie's conclusions. The errors in the latter's description were undoubtedly due to his reliance only on a

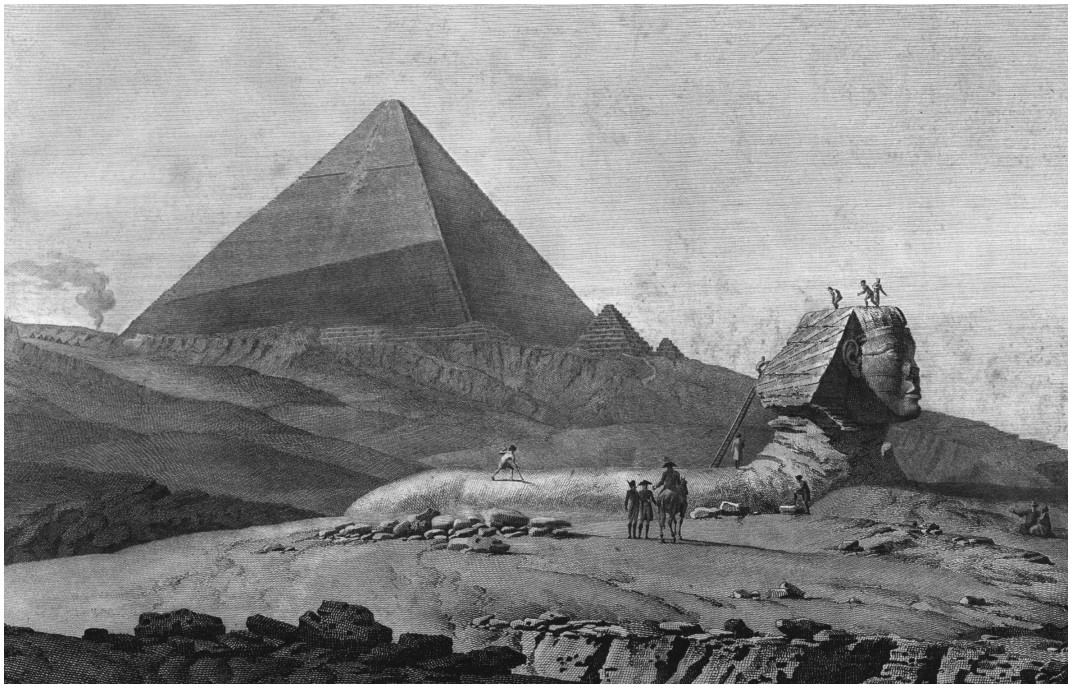

Fig. 2: Plate from the *Description de l'Égypte* that shows the furrow on the apothem on the south face of Khufu's pyramid (Description, Plate 8, Antiquités 1822: pl. 8).

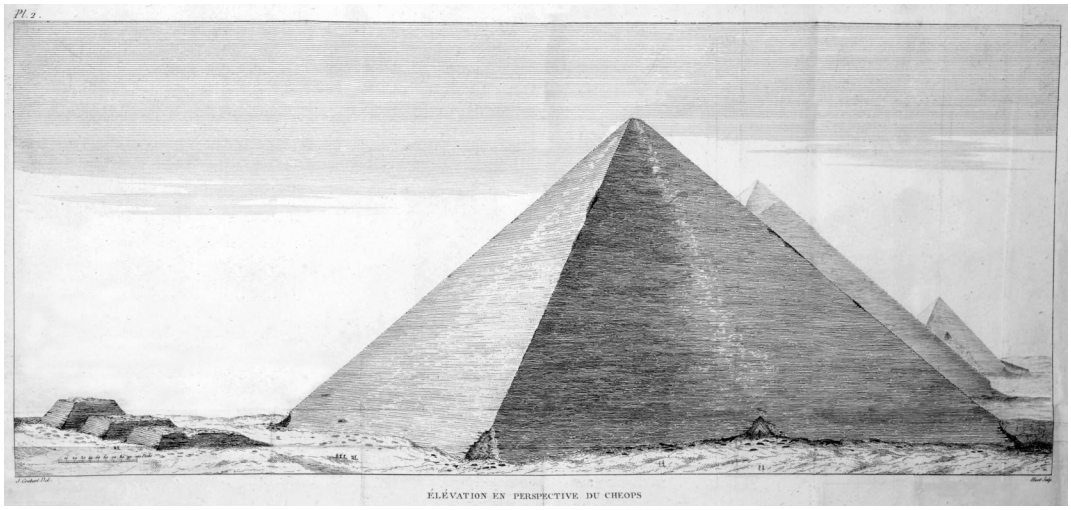

Fig. 3: Central degression illustrated on an engraving from 1801 (taken from GROBERT, 1801:pl.2).

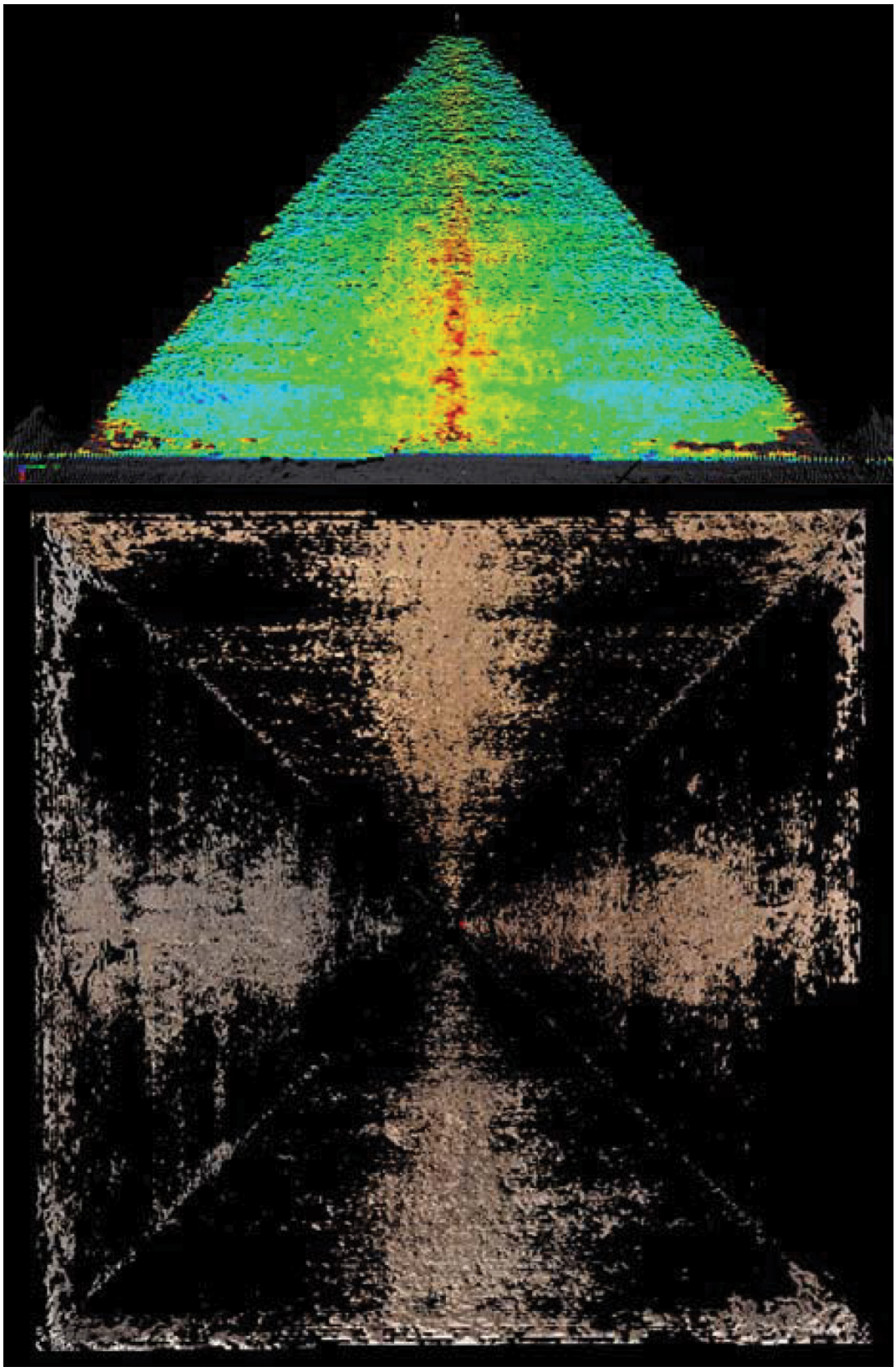

Fig. 4: Top view of the pyramid of Khufu with anomalies shown on each side, and horizontal projection of the west side with color coded deviations from the plane (Neubauer, Doneus, Studnicka, & Riegl 2005: 474); courtesy of the authors.

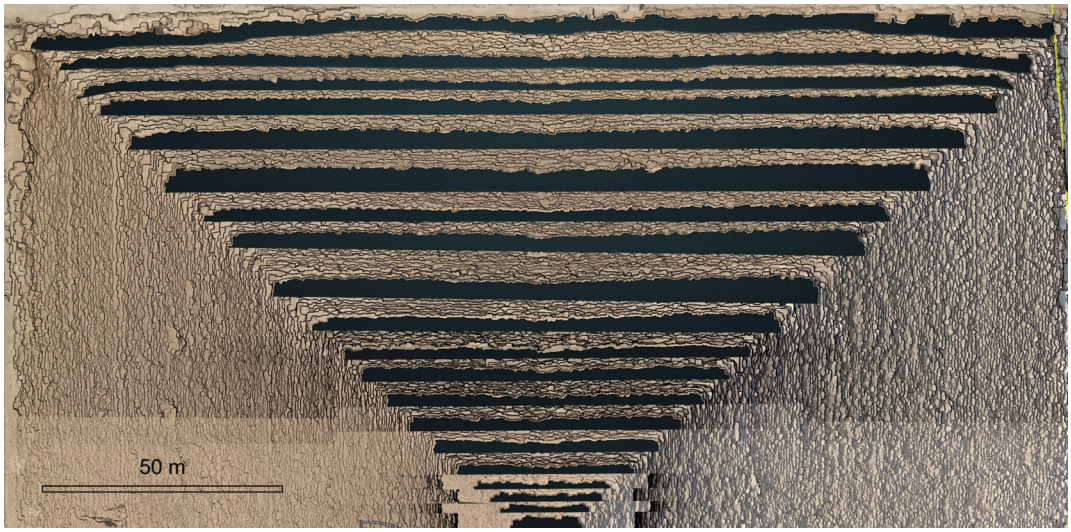

Fig. 5: Photogrammetry of Khufu's pyramid with highlighted courses as followed by several layers on the west face (@ *Label News*, *Iconem*).

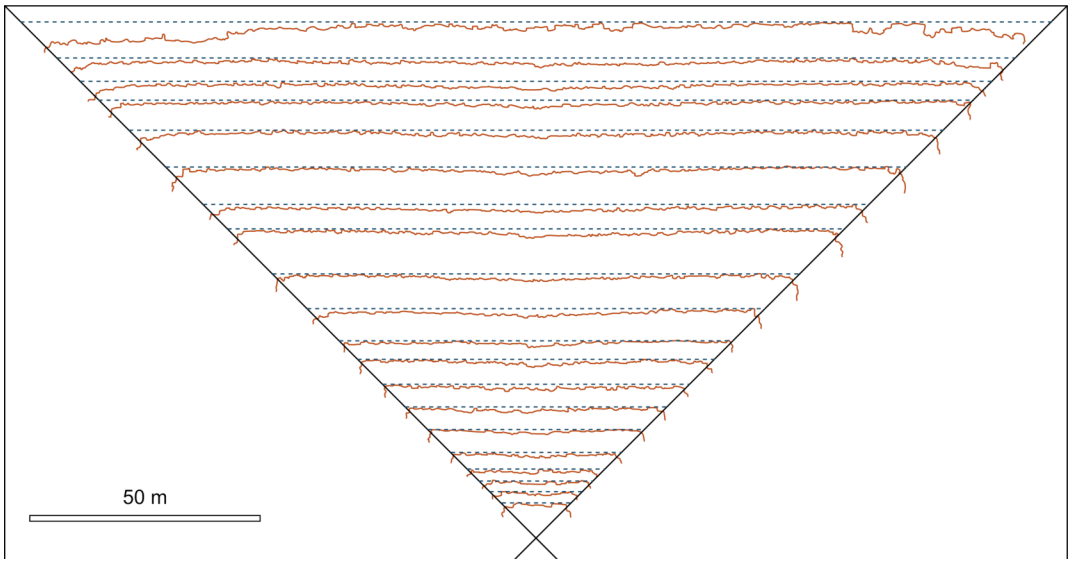

Fig. 6: Survey of several layers situated on the west face of Khufu's pyramid.

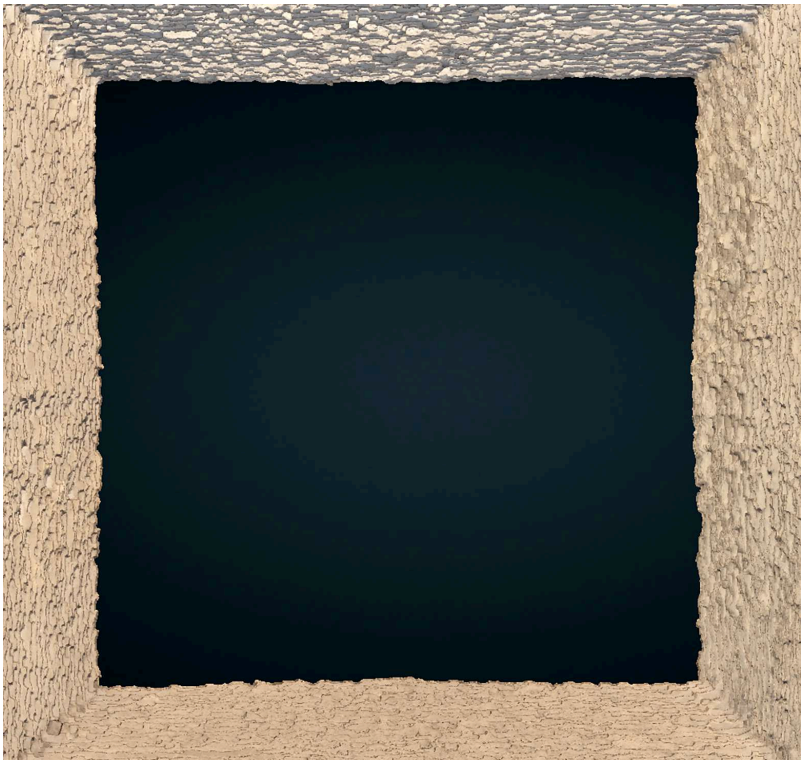

Fig. 7: Photogrammetry of Khufu's pyramid. Horizontal plan of the upper layers (@ *Label News*, *Iconem*).

Fig. 8: Photogrammetry of the east face of Khufu's pyramid. The blocks are significantly more damaged in the center than towards the edges (@ *Label News*, *Iconem*).

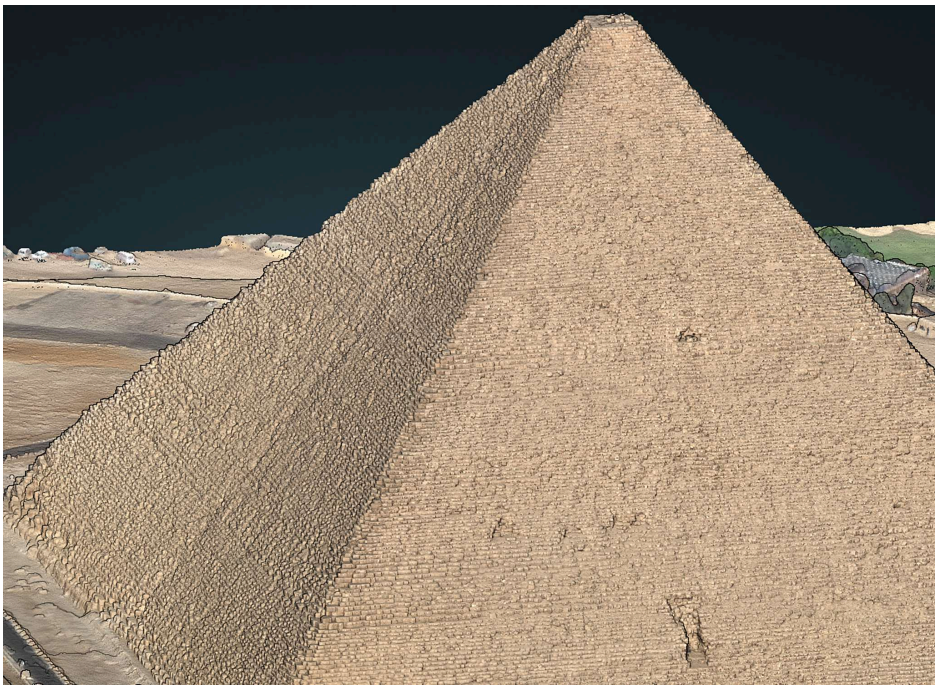

Fig. 9: Furrow following the apothem line of the western face of Khufu's pyramid (photogrammetry @ *Label News*, *Iconem*).

profile and overall view of the north face and lack of awareness of several points of detail which were technically unavailable due to the limited coverage of his survey. An average value was found in that way that was too statistically limited to clarify the true nature of the deformation. This situation led commentators to erroneously take it for granted that the faces were flat to each side of the center line and perfectly folded at the middle. Davidson's illustration was therefore absolutely false.

Much has been made of photographs taken on the day of the equinox, when the grazing light of the sun reveals the concave or folded aspect of the south face of the Great Pyramid (DAVIDSON, 1941: x; POCHAN, 1971: 225). The recessed form of the faces does exist and the impression of uniformity is reinforced by the central groove, which seems to form a clear break in the shadow down the central axis of the apothem. It must be noted, however, that this impression is stronger if the photographs are of poor quality. The low resolution blurs the many irregularities and simplifies the visual effect ultimately produced. Pareidolia also causes our brains to reinterpret the visual information in accordance with what it is supposed to perceive. Peter Tompkins was amazed that the recessed aspect of the faces had been ignored for so long, despite the existence of the engraving in the *Description de l'Égypte* (Figure 2) (TOMPKINS, 1973: 108). Yet Flinders Petrie himself only paid attention to it after taking his measurements. It was only then that, through cognitive bias, this so-called architectural feature became obvious to other commentators.

4 The origins of the concavity

Various hypotheses have already been proposed to explain this anomaly. Those related to construction and architecture are addressed in this new review of the issue.

Flinders Petrie saw the form as an artefact of the use of a device that had made it easier for builders to control the lines to be followed in laying the casing stones. The observed irregularities, however, categorically exclude this proposal. Likewise, they preclude the hypothesised means of reinforcing the stability of the masonry (MARAGIOGLIO & RINALDI, 1965: 104; VERNER, 2001: 195). The very chaotic aspect of the recessed blocks excludes the possibility that it was the result of any method of construction. If the builders had wanted to strengthen the stability of the blocks, they would have done so systematically and logically on all the stone courses. The other pyramids reveal no indication of the use of such a technique (ARNOLD, 1991a: 153–181). Martin Isler's hypothesis (ISLER, 1983: 27–32) could only be valid if the layers were recessed vertically with respect to a leveled line, and this is not the case at all (PARRA ORTIZ, 1996: 79–86). More recently, James Frederick Edwards saw the phenomenon as an argument in favor of his construction theory (EDWARDS, 2016). According to him, the pyramids could have been built by completing consecutive layers and by hoisting all the building blocks up the outer faces as they were raised. The inward forces of the moving loads would have compressed the blocks closest to the centers of the faces and thus recessed the faces around a central axis. For this argument to be valid, it would be necessary to consider that the Great Pyramid was built according to a completely different method than the other monuments of this type as it alone has such a recessed line running from bottom to top. In addition, the fine Tura limestone casing would inevitably have suffered from such treatment.

For the reasons mentioned above, it is also unlikely that the pyramid displayed concave faces for aesthetic, construction-related, or astronomical reasons. The archaeo-astronomical hypothesis according to which the recessing of the faces was only visible on equinoctial days is in principle false. The four faces are aligned to the cardinal directions, so the sun, during its daily course from east to west, reaches its zenith on the north-south axis of the pyramid of Khufu and as a result produces a grazing light on the east and west faces as it passes. The phenomenon is, therefore, observable every day of the year around noon, even if the intensity varies according to the time of year. The most important feature in this regard is the perfectly rectilinear line formed by a row of casing stone preserved at the base of the north face, which shows without any shadow of a doubt that, with its casing in place, the pyramid had perfectly flat faces (DASH, 2015: 8–14). The optical phenomenon therefore only appeared from the Middle Ages onward, after the casing stones had been removed.

A final hypothesis remains to be evaluated, that the phenomenon appeared as the result of a progressive deterioration of the faces caused by the exploitation of the casing stones. Without further analysis, Martin Isler judged that this proposal was impossible (ISLER, 1983: 27), but it does deserve further attention in view of the testimonies left by Arab authors and western travelers that are included below.

The fine limestone blocks used to construct the outer casing of Khufu's pyramid were originally extracted from the Tura quarries on the east bank of the Nile, but they were removed long ago. The builders of the Middle Ages (from the 12th century on) were determined to dislodge and reuse the outer blocks to construct buildings in Cairo and its surroundings (LAUER, 1988: 24–29; ARNOLD, 1991b: 25; LEHNER & HAWASS, 2017: 84–86).

In the 1st century BCE, Diodorus Siculus claimed that the point of the summit had already disappeared and that there was a platform there measuring 6 by 6 cubits (or 2.70 m a side, considering the roman cubit) (AUFRÈRE et al., 2021: 199). This value is, however, questionable, since Diodorus gives an incorrect base length (210 m). The fact that a measurement was made does not necessarily mean that the casing must have been dismantled (even partially) at that time, to allow the surveyor to reach the top. The most that can be assumed is that it was weathered in places. The pyramid of Khafre still has its casing on its upper third and this did not prevent members of the Prussian expedition led by Karl Richard Lepsius from climbing to the top to make a survey (LEPSIUS et al., 1897: 27–28).

According to a study of the texts of Abd Al-Latif (1161–1231 CE) by Sylvestre de Sacy, the citadel and the city walls of Cairo were built in the time of Saladin (1138–1193), by demolishing the mosques, the tombs, and the

small pyramids of Giza (DE SACY et al., 1810: 171–172, 210).

According to the same author, in 1196 CE, Sultan Malik Al-Aziz resolved to destroy the pyramids of Giza, starting with that of Menkaure:

> 'When Melic-alaziz Othman ben-Yousouf had succeeded his father, he allowed himself to be persuaded by some people of his court, people devoid of common sense, to demolish these pyramids; and this started with the red pyramid (author's note: the pyramid of Menkaure), which is the third of the great pyramids and the least considerable. The Sultan, therefore, sent laborers, miners, and quarrymen, under the leadership of some of the principal officers and emirs of his court, with orders to destroy it. To carry out the orders with which they were charged, they first established their camp near the pyramid and gathered there from all regions a great number of workers, and supported them at great expense. They remained there for eight whole months, occupying all their people in the execution of the mission with which they were responsible. After having given themselves a great deal of trouble and having exhausted all their strength, they removed one or two stones each day. Some pushed them from above with wedges and levers, while other workers pulled them from below with ropes and cables. When one of these stones finally fell, it made a terrible noise, which resounded at a very great distance, and which shook the earth and made the mountains tremble. At the end of its fall, it sank into the sand. Great efforts had to be made once again to remove it' (DE SACY et al., 1810: 177–178).[3]

Abd Al-Latif reports that during the same era, a man climbed the Great Pyramid and measured the summit platform. It was, according to him, 11 cubits on its sides (approximately 5 m) (DE SACY et al., 1810: 174–175, 216–217). Sylvestre de Sacy believed that the casing was intact in all places at that time (DE SACY et al., 1810: 214). We do not know what could have been the conditions of this escalation. Was the casing already removed in some places?

In 1395, two centuries later, the French Lord of Anglure witnessed the exploitation of its casing stones:

> ' (...) and we saw that on one of these granaries, about half way up, masonry workers were trying to remove the big cut casing stone and letting them slide down to the ground. These stones were used to make the most beautiful works of Cairo and its surroundings. The interpreter who was with us claimed that these granaries were broken up and exploited for a thousand years, even if they are still only half uncovered (...)'[4] (BONNARDOT & LONGNON, 1878: 66–67).

[3] Original text in French: 'Quand Melic-alaziz Othman ben- Yousouf eut succédé à son père, il se laissa persuader par quelques personnes de sa cour, gens dépourvus de bon sens, de démolir ces pyramides ; et l'on commença par la pyramide rouge (ndla : la pyramide de Mykérinos), qui est la troisième des grandes pyramides et la moins considérable. Le sultan y envoya donc des sapeurs, des mineurs et des carriers, sous la conduite de quelques-uns des principaux officiers et des premiers émirs de sa cour, et leur donna ordre de la détruire. Pour exécuter les ordres dont ils étaient chargés, ils établirent leur camp près de la pyramide ; ils y ramassèrent de tous côtés un grand nombre de travailleurs, et les entretinrent à grands frais. Ils y demeurèrent ainsi huit mois entiers, occupés avec tout leur monde à l'exécution de la commission dont ils étaient chargés, enlevant chaque jour, après s'être donné bien du mal et avoir épuisé toutes leurs forces, une ou deux pierres. Les uns les poussaient d'en-haut avec des coins et des leviers, tandis que d'autres travailleurs les tiraient d'en bas avec des cordes et des câbles. Quand une de ces pierres venait enfin à tomber, elle faisait un bruit épouvantable, qui retentissait à un très grand éloignement, et qui ébranlait la terre et faisait trembler les montagnes. Dans sa chute, elle s'enfonçait dans le sable ; il fallait derechef employer de grands efforts pour l'en retirer' (de Sacy 1810: 177-178).

[4] Original text in old French: '(...) Et veismes adont que sur l'un d'iceulx gregniers, ainsi comme ou milieu en montant, avoit certains ouvriers massons qui a force desmuroient les grosses pierres taillées qui font la couverture desdits greniers, et les laissoient devaller a val. D'icelles pierres sont faitz la plus grant partie des beaux ouvrages que l'en fait au Caire et en Babiloine, et que l'en y fist de long

Two 16th century engravings show the pyramid of Khufu fully stripped of its casing (MÜNSTER, 1544; HELFFRICH, 1589:last plate), while in 1615 the pyramid of Khafre had already attained its present appearance (SANDYS, 1615: 128). By that date, the exploitation of the pyramids of Giza seems to have ended.

In summary, the evidence indicates that the dismantling of the casing of the Great Pyramid started before the end of the 12th century and continued until the 16th century at the latest. Documents predating the Egyptian campaign led by Napoleon Bonaparte in 1798–1799 were not very detailed in describing the exterior condition of the pyramid. The most significant are the documents mentioned above. Edme-François Jomard, one of the scientists who took part in the French expedition, was the first to record valuable information about the general condition of the foundations and faces:

> 'These steps are better preserved towards the edges, more ruined towards the middle of the faces' (COMMISSION DES SCIENCES ET ARTS D'ÉGYPTE, 1809–1822:1818: 67).
>
> 'We are especially careful not to climb up the apothem, because it is the line with the steepest slope on each face and because debris can fall from the top platform or from other points on this line at any moment. The fall of fragments in that direction has even worn the edges of the steps to such an extent that it would be unsafe to climb up anywhere within 20 feet to the right or left of the apothem. (…) The climate undoubtedly acts to some extent on the stones at the summit; but once they are dislodged for whatever reason, the Arabs and visitors unthinkingly push them off and they are thrown down with a tremendous crash, breaking the edges of the lower steps in their fall' (COMMISSION DES SCIENCES ET ARTS D'ÉGYPTE, 1809–1822: 68).[5]

An engraving from the monumental Description de lÉgypte illustrates Jomard's words (Figure 2). Its caption reads: 'The clear area marked 10, a little below the summit, represents the dislodged stones. These are more noticeable on the apothem than anywhere else because of the trajectory taken by the stones detached from the top.'[6].

Another slightly older engraving, prepared by a soldier named Grobert who participated in the Egyptian Campaign, is even clearer (Figure 3) (GROBERT, 1801:pl.2). This author also mentioned the unintentional damage caused by the repeated attempts to climb the monument:

> 'The ascent of the pyramid is quite tiring. It is worth warning the curious about the dangers of this and even the possibility of a fatal accident. This result can be avoided by a taking simple precautions. Several stones have imperceptible cracks as they have been baked by the sun and have come apart

temps et nous fut juré et certifié par icellui drugement qui illec estoit avec nous et par autres ainsi, que jaestoient mille ans passes que l'en avoit commencié a escorcher et descouvrir iceulx greniers, et si ne sont que a moitié descouvers. (…) Et sachiés que Iceulx massons qui icellui grenier descouvrent et qui n'estoient que ainsi comme ou milieu en montant, que a peines les povons nous apparcevoir et n'en sceusmes riens jusques nous veismes cheuir les grosses pierres comme muiz a vin que iceulx massons abatoient, non obstant que nous oyens bien les cops des marteaux, mais nous ne saviens que c'estoit.'

[5] Original text in french : 'L'on se garde surtout de monter par l'apothème, parce que c'est la ligne de plus grande pente sur chaque face, et que par là il tombe à tout moment quelques débris de la plate-forme ou des autres points de cette ligne. La chute des fragments dans cette direction a même usé les bords des marches à tel point, qu'il n'y aurait aucune sûreté à monter à 20 pieds á droite ou à gauche de l'apothème. (…) Le climat agit peu sans doute sur les pierres du sommet ; mais, une fois que, par une cause quelconque, elles sont ébranlées, les Arabes et les visiteurs les détachent insensiblement, et elles sont précipitées du haut en bas avec énorme fracas, brisant dans leur chute les bords des marches inférieures' (Description, Text, Descriptions, 2, Antiquités 1818: 68).

[6] Original text in french : 'La partie claire marquée 10, un peu au-dessous du sommet, représente la rupture des pierres, qui est plus sensible sur la ligne de l'apothème que partout ailleurs, à cause de la direction que prennent dans leur chute les pierres qui se détachent du sommet.' (Description, Planches, 8, Antiquités 1822: Explications des planches)

> due to their great age. Sometimes, climbers will try to find a firm support and will reach up to the stones on the higher layers. The stone cracks due to the weight of the climber's body, although it appeared whole at first sight' (GROBERT, 1801: 57).[7]

The summit seems to have been the target of quarrymen quite early in the process of stone removal since a platform of 5 m on each side was described around 1200 CE (see above). It is worth noting that in the 17th century CE, John Greaves reduced the value to only approximately 4 m per side (GREAVES, 1752: 634). This discrepancy is surely in part attributable to the unreliability of the early measurements, but the text nevertheless shows that, between the 17th and the 20th centuries, the size of the platform had increased to its current dimensions of 11.7 by 11.9 m (KAWAE, 2005). A volume of stone equivalent to nearly 270 m^3 had, therefore, been thrown down from the top of the building in the intervening centuries.

In the first half of the 19th century, Howard Vyse and John Shae Perring produced a sectional view of the Great Pyramid that shows a largely demolished top. A shapeless group of blocks near the center of the platform rose a few courses above those around the perimeter (PERRING, 1839: pl. I).

A century later, Georges Goyon carried out a survey of the graffiti left by travelers on the stones of the Great Pyramid. He was surprised to find that none of the graffiti on the top was made prior to 1800 CE. According to Goyon, the travelers of previous centuries had probably amused themselves by pushing one or more blocks off the top to enjoy the noise caused by the fall (GOYON, 1944:XXIX (n. 2)), and so any earlier inscriptions had been lost. This type of "amusement" must, therefore, have continued into the 19th century.

5 Consequences of deterioration on the physical structure of the Great Pyramid

The pyramid of Khafre shows that the Arab quarrymen dismantled the casing from the bottom to the top (Figure 11). As the workers moved upwards, the outer blocks of each upper course were left protruding as they were cantilevered out. Less effort was, therefore, required to detach them and to allow them to fall. As a result of this rolling down of the consecutive layers of blocks, many took the same path as the previous ones, further wearing down and damaging the exposed massif below.

To assess the cumulative effect of this repeated action on the pyramid of Khufu, I estimated the distribution of the impacts produced by the repeated falls of casing blocks on a triangular face made up of about forty layers. The calculation method is extremely simple. It involves assigning a color-coded value to a cell in an Excel table that represents a specific area on the face. I first assigned each cell of a pyramid-shaped table a numerical value equal to the number of facing blocks above it. The color then changes depending on the number of upper blocks that impact that place during their falls. After repeated iterations, it logically emerges that the closer to the apothem and to the base, the greater the number of impacts. The closer to the outer edges and the summit, the fewer impacts there are.

The image produced thus sheds light on how the repeated fall of blocks had a greater and progressive effect on the apothem and the base layers of the building (Figure 10a). A hollowing out of the faces develops that does resemble a concavity.

[7] Original text in french : 'L'ascension de la pyramide est assez fatigante. Il n'est pas inutile de prévenir les curieux contre une espèce de danger qui peut devenir funeste, et auquel on peut obvier par une légère attention. Plusieurs pierres ont des lézardes imperceptibles ; elles sont cuites par le soleil et décomposées par la vétusté. Il arrive parfois qu'en croyant trouver un appui ferme sur une assise supérieure, on la saisit pour franchir celle qui est plus élevée ; la pierre se détache étant amenée par le poids du corps, quoiqu'elle ait paru entière au premier aspect.' (Grobert 1801: 57)

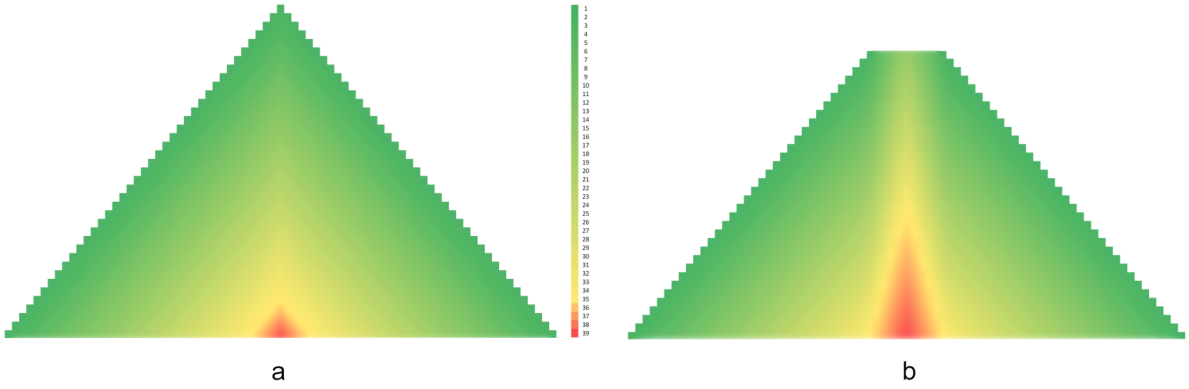

Fig. 10: Modeling of the impacts caused by the casing stones falling on the face of a pyramid, when they are dislodged from the bottom upwards. On the right, the dismantling of a volume equivalent to that of the top of Khufu's pyramid is also taken into consideration.

I completed my analysis by taking into consideration the dismantling of the summit peak, which required knocking down nearly 270 m^3 of stone blocks onto the four faces already exposed. As one might suppose, the indentations are accentuated in the centers of the faces (Figure 10b).

We can notice that the result is very close to the horizontal projection with colour coded deviations from the plane produced by the *Scanning of the Pyramids Project* in 2004 (compare Figure 4 and Figure 10). Of course, such a model should not be considered more than schematic at this stage, given that the masonry of the Great Pyramid is in fact very heterogeneous in shape, and that the blocks did not strike all the layers, or with the same levels of impact. For all these reasons and more, the actual rate of erosion was very variable. To this process can be added the damage resulting from tourists, which must have considerably increased the wear and tear on the apothems. Despite all these caveats, it is undeniable that the existing depressions follow the general lines highlighted by this graphical algorithm (see also Figure 8).

We therefore have a very plausible explanation for the phenomenon that is in accordance with the state of the archaeology and the historical documents recording the centuries of exploitation of the blocks for use in building structures elsewhere.

It is remarkable that the faces of the pyramid of Khafre are not at all hollowed out in this way (Figure 11).[8] There could be several reasons for this. First of all, its dismantling was interrupted and no damage can be attributed to travelers as they would not have risked climbing up the intact casing at the top. Its masonry is also assembled in a different way from Khufu's. The casing blocks were wedged against backing stones of smaller dimensions, themselves leaning against a mass of blocks with a more homogeneous arrangement (MONNIER, 2020:245–249, pl. 10). The backing stones, although very damaged, have mostly remained in place, because unlike the casing stones, they did not meet the material requirements sought by the quarrymen.

[8] According to the photogrammetry, it is also not present on the Red Pyramid, although, for some unspecified reason, Miroslav Verner claimed that this peculiarity was also found there (VERNER, 2001: 195).

Fig. 11: The current state of the pyramid of Khafra shows that its casing had been dismantled from the bottom to the top.

The pyramid of Menkaure, on the other hand, has an internal structure identical to that of Khufu's (MARAGIOGLIO & RINALDI, 1965: 34–38). The lower quarter of layers were nevertheless covered with a pink granite casing that remains partly intact on the north face. Photogrammetry reveals a hollowing out similar to that of the Great Pyramid (Figure 12), but only above the base formerly covered with granite, i.e. from the fifteenth course upwards (Figure 12b). The sides of the base layers remain perfectly straight.[9] Again, this difference can be explained by the method of exploitation. Granite is extremely difficult to break down and so the quarrymen would have prioritised the removal of the limestone casing above, working from bottom to top as usual. Only afterwards, and probably much later, were the granite blocks dismantled, from top to bottom this time, due to the hardness of the material (MARAGIOGLIO & RINALDI, 1967: 30).[10] This process is evidenced by the remains still in place. As the limestone blocks descended onto the hardest granite casing still in place, the latter did not suffer from repeated impacts and retained its rectilinear aspect on the four faces (Figure 12a and c).

6 Conclusions

Based on the new analysis covered in this paper, the indentation of the faces of the Great Pyramid is very probably the consequence of relatively recent activities affecting the monument rather than the result of a conscious decision made by the ancient architects. This reminds us that the history of a monument is not limited to its origins.

[9] In 2006, a Total Station survey of the pyramids of Giza was carried out by Erin Nell and Clive Ruggles. Some statements must be made here regarding their work on Menkaure's pyramid (NELL & RUGGLES, 2014: 327–328, 333). Their dataset indicated that the granite casing of Menkaure's pyramid is also concave. The photogrammetry survey carried out in 2018, however, clearly contradicts them without any possible doubt (Figure 12c). The new evidence indicates that their survey taken at several positions on the face of the pyramid of Menkaure was incorrect.

[10] Notably at the start of the 19th century.

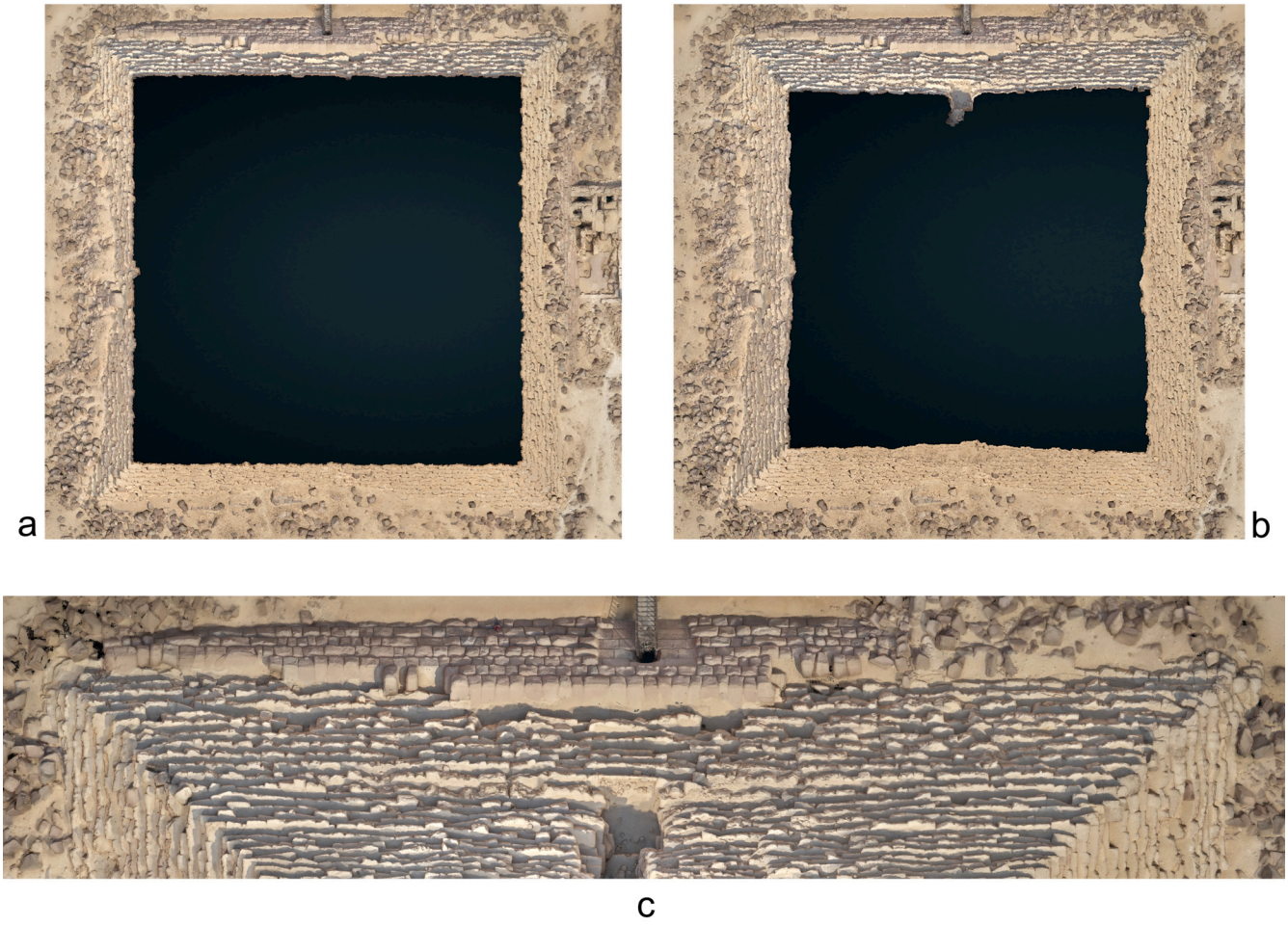

Fig. 12: Photogrammetry of Menkaure's pyramid. A: Horizontal section at the level of the lower quarter. B: Horizontal section at the level of the ancient limestone casing. C: Focus on the north face. The lower layers are perfectly straight (@ *Label News*, *Iconem*).

Its evolution—and the state in which it has reached us today—must be considered over its entirety, including its recent history.

As has been shown here, the archaeo-astronomical and architectural explanations proposed in recent years are mostly the result of unfortunate extrapolations based on a limited set of measurements taken at the end of the 19th century. In a way, they generated a case of pareidolia that was instigated by the identification of a fairly regularly shaped recessed depression by Flinders Petrie, further aggravated by the invention of the eight-sided pyramid by Davidson. This final idea imposed itself as an indisputable reality in the minds of many readers. No one had ever considered anything like that before, but it was clear how badly the faces were deteriorated. This highlights how new information (in this case, measurements) can lead to the misinterpretation of a situation if the data is incomplete, too imprecise, or dissociated from its appropriate historical context.

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