Geological and Geomorphological study of the original hill at the base of Fourth Dynasty Egyptian monuments. Etude géologique et géomorphologique de la colline originelle à la base des monuments de la quatrième dynastie égyptienne

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Key words: original hill, egyptian pyramids, stratigraphy, geomorphology.
Mots clefs : colline originelle, pyramides égyptiennes, stratigraphie, géomorphologie

ABSTRACT
Rock foundations of the Kephren and Kheops pyramids are examined in comparison with other Fourth Dynasty monuments: the Sphinx, Queen Kentkawes' mastaba and the Abu Rawash pyramid. This study is based on geological and geomorphological observations, visual observation, and photomontages. Results, correlated with those of former studies, demonstrate the existence of natural hills used as substrata in the construction of the two great pyramids. The minimum volume of these hills can be estimated at 12% and 23% respectively of the volumes of the Kephren and Kheops pyramids. The use of worked rock hills appears to be a characteristic of the construction methods under the Fourth Dynasty.

RESUME
Le substratum rocheux des pyramides de Kheops et Khephren est étudié en comparaison avec celui d'autres monuments de la quatrième dynastie de l'ancienne Egypte : le Sphinx, le mastaba de la reine Kentkawes et la pyramide d'Abu Rawash. Cette étude est basée sur des observations géologiques et géomorphologiques, l'observation visuelle et des photomontages, ainsi que des mesures réalisées sur le terrain. Les résultats, corrélés avec ceux d'études antérieures, démontrent l'existence de collines naturelles utilisées comme assises pour la construction des deux grandes pyramides. Le volume minimum de ces collines peut être estimé par rapport au volume total à 12% pour Khephren et 23% pour Kheops. L'utilisation de collines rocheuses pour asseoir la construction d'un monument apparaît être caractéristique des méthodes de construction utilisées sous la quatrième dynastie.

INTRODUCTION

This study discusses the relationship of the construction of Egyptian Old Empire Fourth Dynasty monuments the Abu Rawash pyramid and, on the Giza plateau, the Kheops and Khephren pyramids, the Sphinx and Queen Kentkawes' mastaba with their geological and geomorphological environments. Located in the Cairo area on the left bank of the Nile (Fig. 1), they were built between 2639 and 2504 BC, during a relatively short period [Damiano-Appia, 1999]: the Great Pyramid under the reign of Khoufou (Kheops), second king of the fourth dynasty, the Abu Rawash pyramid under Djedefrà (Didoufri), third king of the dynasty and Khephren under the reign of the fourth king (Khafra). The construction of the Sphinx is attributed either to Djedefra or to Menkaoura (Mykerinos), fifth king of the dynasty, and Queen Kentkawes' mastaba to Mykerinos' sister.
Vallogia's study of the dismantled Abu Rawash pyramid shows that the builders used a hill as the nucleus for the monument [Vallogia, 2001]. According to his calculations this original hill represented 44% of the volume of the structure. On the Giza plateau, two monuments also incorporate a rock hill outcrop: the Sphinx and Queen Kentkawes' mastaba. The Sphinx is entirely sculpted in the rock. The lower part of Queen Kentkawes' mastaba also consists of natural rock carved out of the local geological series. Moreover, Petrie and other authors [Petrie, 1883] [Eyth, 1908] [Dormion, 2004] observed natural rock in the galleries of the pyramid of Kheops where the lining of the wall had disappeared,. Petrie made the same observations inside Khephren. Dowidar [Dowidar & Abd-Allah, 2001] described as « elevated foundation bedrock » the rock which crops out at the NE corner of Kheops. Bertho et al [Bertho *et al.,* 2004] calculated the volume of natural rock hill outcrops inside Kheops and Khephren, at 30% to 50% of the total volume of the pyramids.
The aims of this study are:

1- To clearly demonstrate the pre-existence of these natural rock outcrops by examining their relationship with the local geological series;
2- To describe the morphology of these worked rock hills where they are clearly visible: The Abu Rawash pyramid, which is located 8 km North of the Guiza plateau; the Sphinx and Queen Kentkawes' mastaba, which are located on the Guiza's plateau ;
3- To map the outcrops of natural stone at the base of Kheops and Khephren pyramids;
4- To propose a model of size and morphology for the original hill as worked for the construction of Kheops and Khephren.

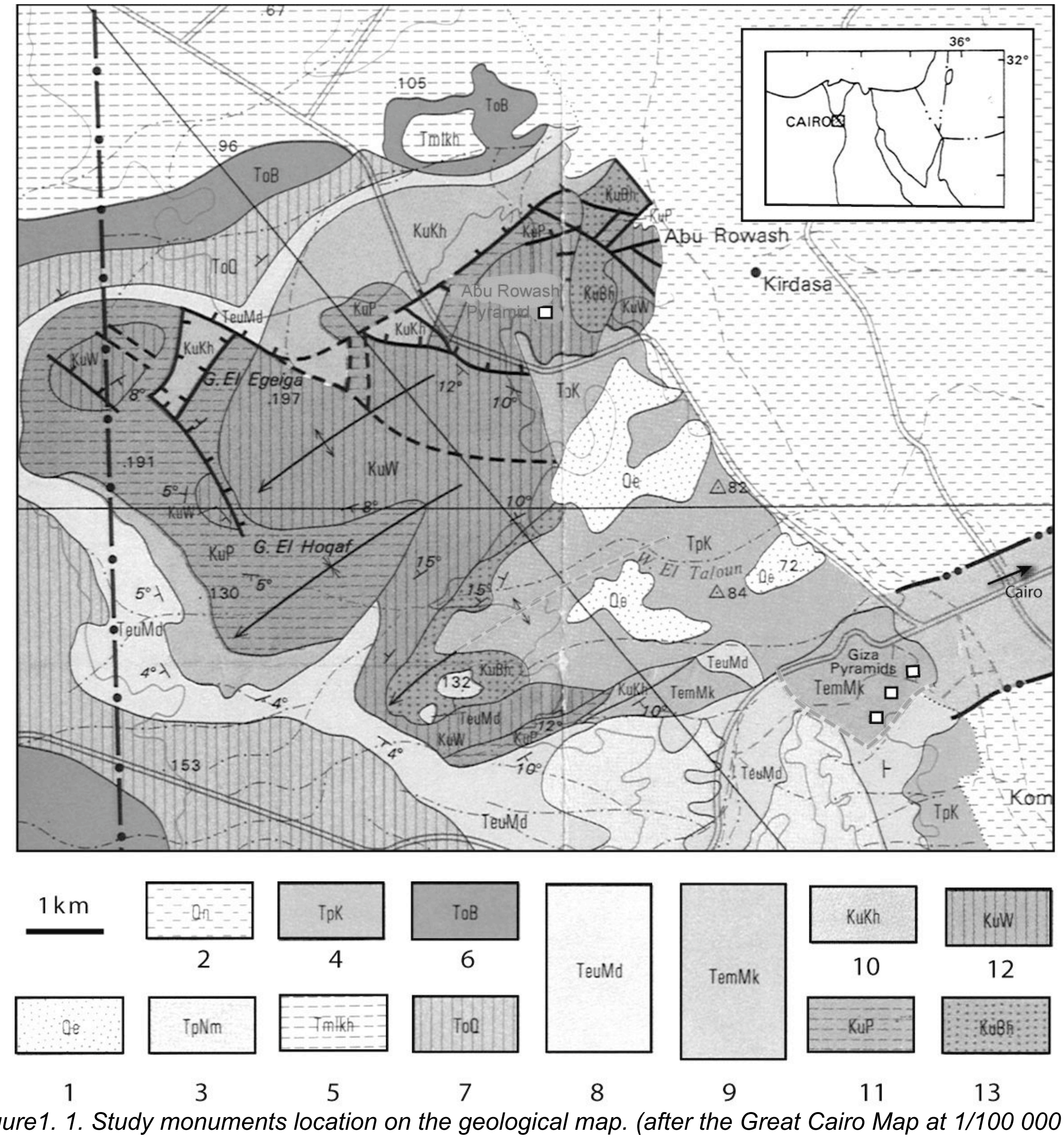


Figure1. 1. Study monuments location on the geological map. (after the Great Cairo Map at 1/100 000 scale). Quaternary: 1. Eolian deposits – sand dunes and sheets; 2. Nile deposits – cultivated area. Tertiary: 3. Continental Pliocene; 4. Marine Pliocene; 5. Lower Miocene; 6. Oligocene basalt flows; 7. Basal Oligocene; 8. Upper Eocene - Maadi Formation; 9. Middle Eocene - Mokattam Formation. Secondary: 10. Maastrichtian; 11. Santonian; 12. Turonian; 13. Cenomanian.
Figure 1. Localisation des monuments étudiés. Quaternaire : 1. Dépôts éoliens – grès dunaires et marins; 2. Dépôts du Nil – zones cultivées. Tertiaire : 3. Pliocène continental; 4. Pliocène marin; 5. Miocène inférieur; 6. Coulées de laves oligocène; 7. Oligocène basal; 8. Eocène supérieur – Formation de Maadi; 9. Eocène moyen – Formation de Mokattam. Secondaire : 10. Maestrichtien; 11. Santonien; 12. Turonien; 13. Cénomanien

Geological context

According to the Greater Cairo 100/000 geological map (Fig. 1), monuments of the present study are located in an area where cropping out geological formations are dated between the Late Cretaceous (Cenomanian) and Quaternary eras. The Abu Rawash pyramid lies on Turonian formations and the Giza plateau monuments on Middle Eocene series (Mokattam formation). Structurally the entire zone is part of the Abu Rawash Complex [OMara, 1952], a group of synclines and anticlines, NE-SW oriented, formed during Late Cretaceous compression. These tectonic events are related to the movement of the North African plate toward Europe [Said, 1990). Since the late Cretaceous these movements have been responsible for structural uplifts and basins throughout the northern part of Egypt, and have strongly affected the paleogeography and sedimentation patterns [Hume, 1912] [Shukri, 1954] [Salem, 1976].

According to René Guiraud (oral information), the NE- SW oriented folds were outlined in Late Santonian (84 My) and first accentuated at the end of the Cretaceous (65 My). During the Eocene, sediments unconformably overlay these folds {Guiraud, 1999 #48}, which were slightly accentuated in Late Eocene (approximately 37 My).

Methodology

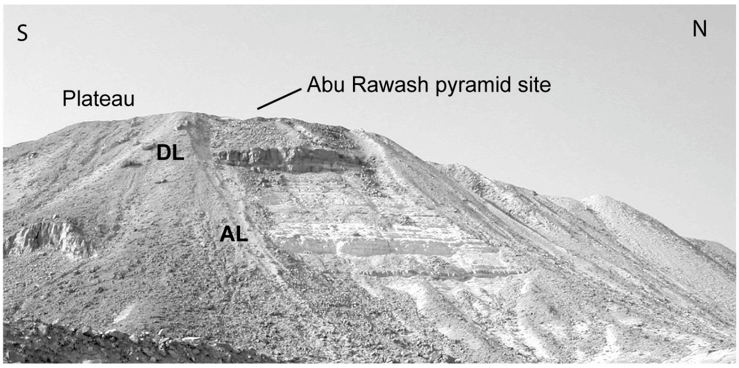
As direct access to the inner parts of the monuments is not possible, this work focuses on external observations and measurements. Petrological, sedimentological and structural characteristics of local geological formations were studied using detailed field observation and dip measurements, and correlated with the geomorphology and topography of the sites. Study of the monuments themselves relied principally on detailed visual observation, photographs and photomontages. In order to propose a model for the morphology of the rock outcrops, the results have been correlated with earlier geological and architectural studies of the interiors of the monuments.

ABU RAWASH PYRAMID.

Geological context of the Abu Rawash pyramid

The Abu Rawash pyramid is built on a plateau overlooking the Abu Rawash village. This plateau is composed of a Late Cretaceous series of white argillaceous and brown dolomitic limestone strata [Said, 1962] (Fig. 2a). According to the Greater Cairo geological map (Fig. 1), this series belongs to the Turonian (Wata Formation). The original hill is clearly a continuation of the Abu Rawash plateau stratigraphic series.

a



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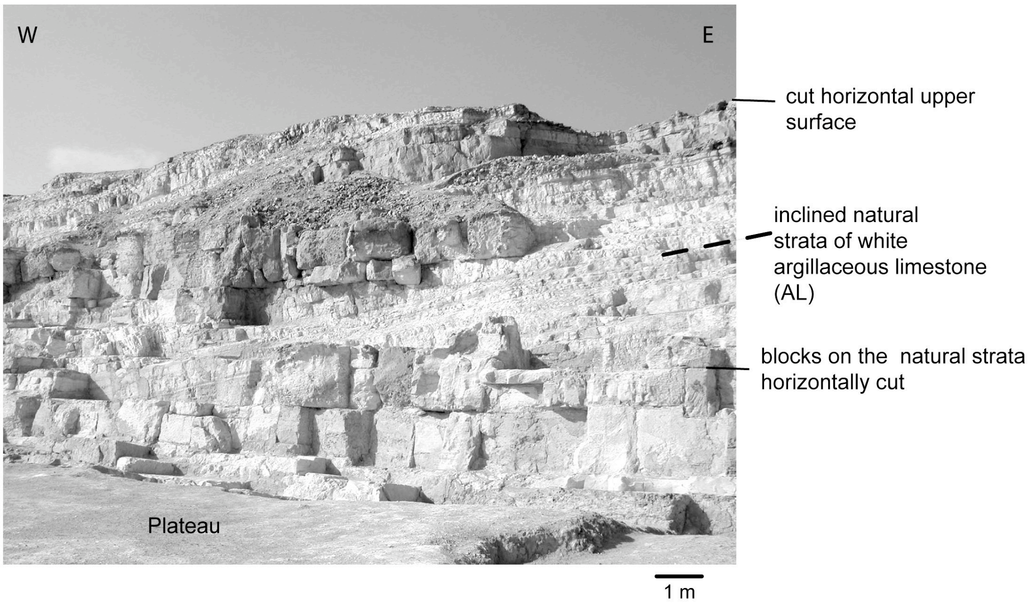

Figure 2. Abu Rawash pyramid and the local geological series.

a. *View of the geological series of the plateau under the pyramid. DL: brown dolomitic limestone; AL: white argillaceous limestone*
b. *View of the southern face of the Abu Rawash pyramid showing the original hill composed by natural W inclined strata of white argillaceous limestones, the horizontal steps carved in the strata and some blocks of backing stones in place on the steps.*

Figure 2. La pyramide d'Abu Rawash et la série géologique locale.

a. *Vue de la série géologique composant le plateau sous la pyramide. DL : Calcaire dolomitique brun; AL : calcaire argileux blanc.*
b. *Vue de la face sud de la pyramide d'Abu Rawash montrant : la colline originelle composée de strates inclinees vers l'Ouest de calcaires argileux blancs, les marches horizontals taillées dans ces couches et des blocs de pierre en place sur les marches.*

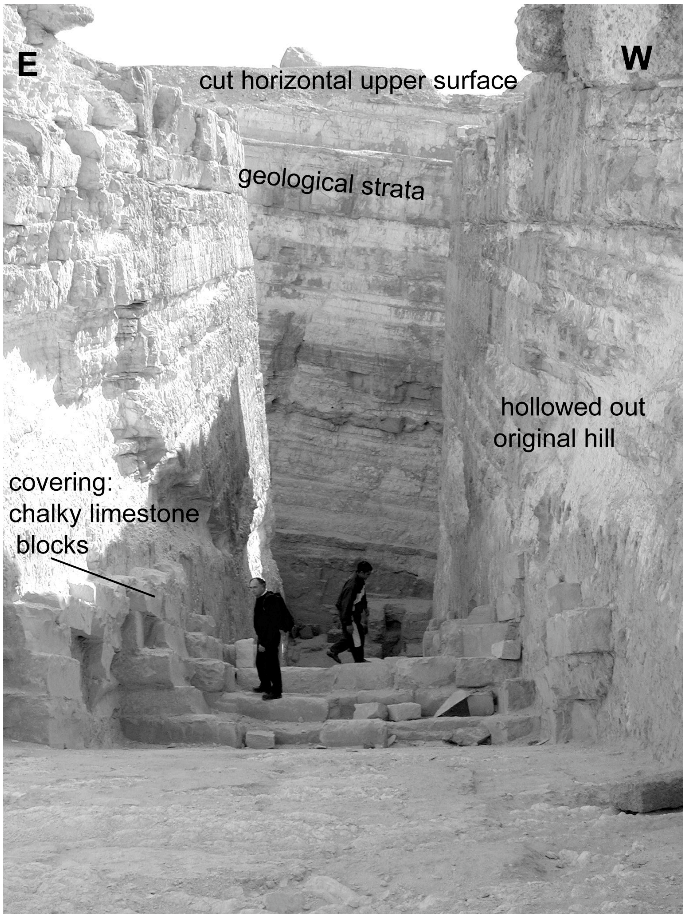

Figure 3. Abu Rawash pyramid and the local geological series. View of the passage carved into the original hill from the north face of the pyramid.
Figure 3. La pyramide d'Abu Rawash et la série géologique locale. Vue de la descenderie creusée dans la colline originelle à partir de la face Nord de la pyramide.

The horizontal steps of the pyramid are cut into the upper part (12 meters) of these formations and are mainly composed of Turonian white argillaceous limestone levels. Blocks lying on the steps are white argillaceous limestone, flint limestone, and brown dolomitic limestone (Fig. 2b). These blocks come either from the hill itself or from a nearby quarry, as demonstrated by Vallogia. The dip of the strata measured on the original hill, 12°W, is the same as that measured on the north and south outcrops near the pyramid.
The original hillrock hill stratigraphic series are visible on 20m height (up to 20m high] inside the pyramid (Fig. 3). At the base of this series is a 1,5m light beige mudstone layer. Then 40 to 90cm levels of white argillaceous limestone are inter-laid with further argillaceous layers each a few centimetres thick. The upper level of this series is a light beige mudstone stratum (80cm). Visible also in this series are:

- two flint layers, one near the base and the other near the top;
- three levels of dolomitic limestone: the lowestone is 80cm thick. The middle one is 1.80m thick and does not present a clear geometric shape. Immediately above it are two 20cm thick contiguous layers.

Description
As most of the building stones have been removed, the original rock hill is clearly visible. Vallogia dated the dismantling of the pyramid to Roman times, 2nd century AD [Vallogia, 1995]; [Vallogia, 2005]. Moreover, Petrie [Petrie, 1883] mentions camel trains descending the roadway north of Abu Rawash, during Nile floods, heavily laden with stones taken from the pyramid.

A topographical layout of the original hill [Vallogia, 2001] shows that its morphology (square base, steep slopes) recalls the shape of an inselberg with an estimated length of 200 royal cubits (or 104.72m) and a height of 12m. Excavation of the pyramid showed that the monument's general dimensions are closely related to those of Mykerinos pyramid: 106.2m for each side, an estimated height of 68m and an average external slope of 52°. According to these data, the hill represents up to 44% of the pyramid's total volume.

MONUMENTS OF THE GIZA PLATEAU

Location of the study monuments.

The Kheops and Khephren pyramids are located in the north-western part of the Giza plateau (Fig. 4). The altitude above sea level of the rock bases surrounding these monuments is approximately 68m for Khephren and 62m for Kheops (60m at the SE corner). The Sphinx and Queen Kentkawes' mastaba lie further down on the plateau towards the Nile Valley. Their rock base altitudes are approximately 22m around the Sphinx and 38m around Kentkawes.

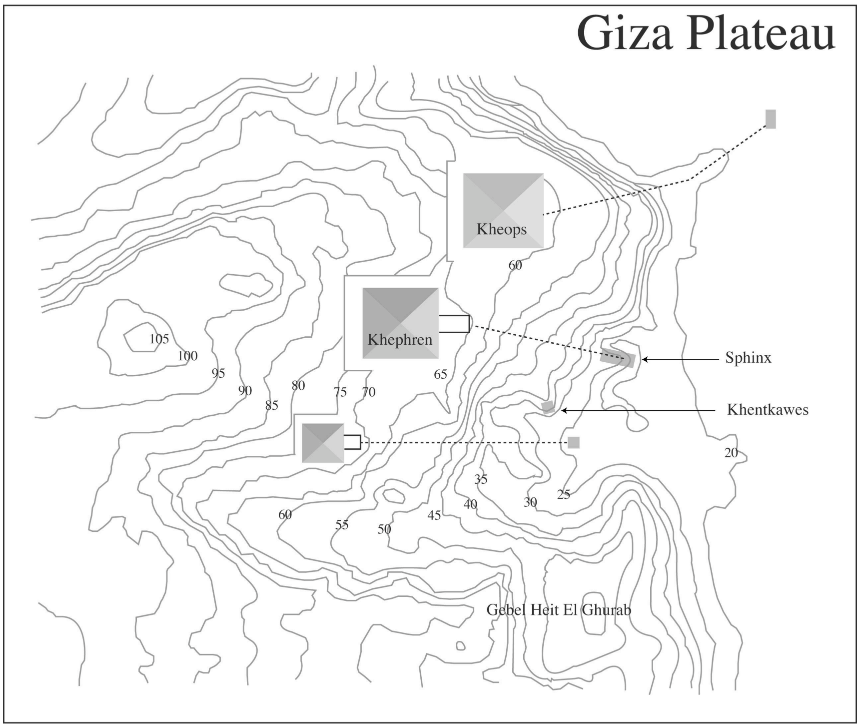

Figure 4. Topographic map of the Giza plateau
(after http://oi.uchicago.edu/research/projects/giz/comp_model.html, modified) and location of the study monuments
Figure 4. Carte topographique actuelle du plateau de Guizeh et localisation de smonuments étudiés (d'après : http://oi.uchicago.edu/research/projects/giz/comp_model.html, modifié).

General geological context of Giza plateau.

The Giza plateau is the subject of numerous geological studies, among them, structural stratigraphic and sedimentological studies by [Zittel, 1883] [Blanckenhorn, 1921] [Cuvillier, 1930] [Said, 1962, 1990] [OMara, 1952] [Aigner, 1983] [Strougo, 1985]. These studies show that the monuments of the fourth dynasty of the plateau of Giza are built on a sedimentary sequence with dominant carbonated formations deposited in an epicontinental sea of variable depth. All the authors agree that these sedimentary layers have the characteristics of the Mokattam formation and Maadi formation, from Middle to Late Eocene age. According to Said [Said, 1990] the intermediate formation known as the Observatory is also

represented. Authors disagree about the stratigraphic position of the limit between the end of the Middle Eocene and the beginning of Late Eocene.
OMara, [OMara, 1952], Yehia [Yehia, 1985] and Dowidar [Dowidar *et al*., 2001] carried out structural studies on the Giza Pyramids Plateau. The plateau is an oriented NE-SW and dipping SE monocline. This monocline is the SE anticlinal limb of the Wadi El Toulon anticline, lying in the southern part of the Abu Rawash folded complex (Fig. 1). The dip of the layers of this monoclinal structure is homogeneous. Dowidar gives a value ranging between 4 and 7° for the zone carrying the study sites. According to our measurements the direction of the layers is NE-SW and the actual dip is about 10° towards the SE.
This monoclinal is affected by hectometric faults with normal dominant and weak throw oriented NW-SE which do not affect the study sites. On the 1/100 000 map of Greater Cairo the plateau is located in the Mokattam formation of the Middle Eocene, linked in the south by faults with the Maadi formation of the Late Eocene. The weak throw and the orientation of these faults essentially suggest (Guiraud, oral communication) a discrete deformation by synsedimentary normal faults during the Eocene deposition period.
The entire plateau is affected by karstic processes, described by El Aref and Refai [El Aref *et al*., 1987] and Dowidar and Abd-Allah [Dowidar *et al*., 2001], which developed according to the local structural and stratigraphic conditions and led to a particular morphology of stepped terraced escarpments, karst ridges and isolated hills. These authors relate the development of karst features to Mediterranean climatic conditions.

The Sphinx and Queen Kentkawes' monuments

The Sphinx and Queen Kentkawes' monument are located on the SE part of the Giza plateau. They have different dimensions and purposes but show very similar building methods.

Sphinx description

The Sphinx lies in a WE axis and looks towards the E. It is 19.8m high (including 5m for the head), 14m wide and 73.2m long. As most of the facing of small stones has disappeared it is cleary visible that the monument has been carved in the rock. The Sphinx's body (Fig. 5) is cut into a series of marl limestone layers in which layers of limestone 40cm to 2m thick are alternated with 10 to 60cm marl layers. The neck is a 3m thick marl bed. The 5m high head is carved in a succession of 5 beds of competent brown dolomite limestone, 30cm to 1.6m thick. This series dips evenly towards the SE (around 10°). That these levels are visibly in stratigraphic continuity with the geological series of the plateau. It is apparent that the Sphinx was carved out of the local marl-limestone series on its south and est sides.

Figure 5. South Eastern view of the Sphinx and the natural outcrop behind the Sphinx. (s0): inclined natural strata.
Figure 5. Vue SE du Sphinx et de l'affleurement derrière le Sphinx. (s0) strates naturelles inclinées.

<u>*Queen Kentkawes' monument*</u>

Description:
Queen Kentkawes' monument comprises two superposed mastabas (truncated pyramids) (Fig. 6). The base of the lower mastaba measures 45.8 x 45.5m for its basis, the height 10m, and the slope of its faces is 74°. The measurements for the upper mastaba are respectively 28.5 x 21m, 7m, and the face slope is also 74° (website: Kentkawes, Encyclopaedia of the Orient). Calculation of volumes gives respectively 18,520m^3 for the lower mastaba and 10,350m^3 for the upper mastaba. As the facing has almost completely disappeared it is clear that the higher part of the monument is made of blocks whereas the lower part is sculpted in the rock. Two faces are directed N175 E and the other two N80 E. Like the Sphinx, the lower mastaba was carved from a marl-limestone series. It shows eight 30 cm to 1.3m thick marl-limestone levels, interbedded with 10 to 80cm thick marl layers. Above, this a layer of partially dolomitized marl-limestone, approx. 80cm thick, overlays a 1.6m thick competent brown dolomitic limestone level. This series is clearly in stratigraphical continuity with the series on the nearby cliffs on the N and NE sides of the monument. Dolomitic levels are found as strata as well as irregular masses. As they are more competent than the marl-limestone they appear in relief in the landscape. As in the case of the Sphinx, this series dips evenly towards the SE (around 10°). Compared with the surrounding topography, this hill continues the natural topographic slope and the geological strata on the North side of the monument. As the other three sides overlook the surrounding plain, it appears that the monument was carved into a rocky spur overlooking the Wadi.

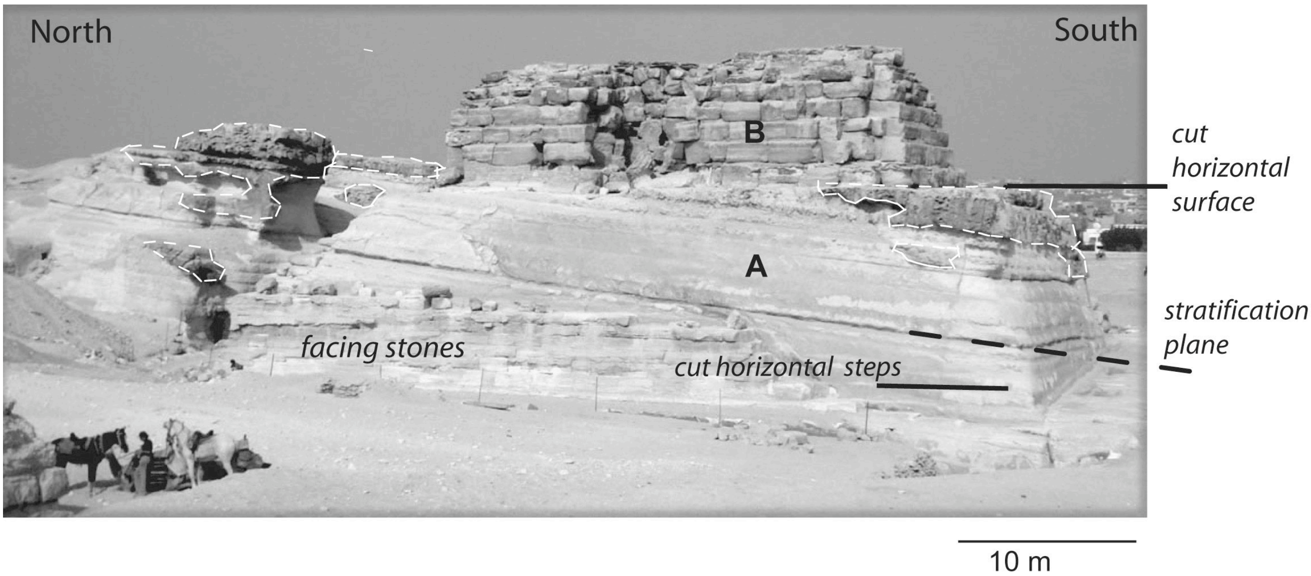

Figure 6. Mastaba of queen Kentkawes
View of the west face showing (A) the original hill comprising the lower part and (B) the constructed upper part. White dashed lines highlight the morphology of the dolomitized sedimentary bodies.
Figure 6. Mastaba de la reine Kentkawes. Vue de la face ouest montrant (A) la colline originelle à la base et (B) la partie supérieure construite. Les pointillés blancs soulignent a morphologie des corps sédimentaires dolomitisés.

Reconstruction of the Monument:
Observation of the existing facing at the lower part of the north face (NW angle) shows that this casing was about 1 m thick. Using the present measurements we have modeled the initial geometry of the monument. If the global monument was really a mastaba (Fig. 7) with a 74° outside face slope , its minimum total volume, deduced from the volumes of both mastabas, was 28,875m^3. The hill would then represent around 64% of this volume.

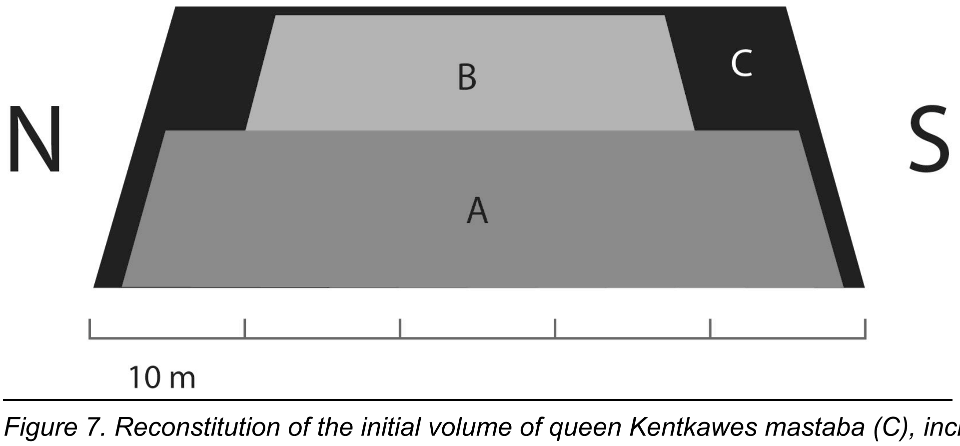

Figure 7. Reconstitution of the initial volume of queen Kentkawes mastaba (C), including the present geometry of the original hill (A) and the reconstituted constructed part (B).
Figure 7. Reconstitution du volume initial du mastaba de la reine Kentkawes © incluant la géométrie actuelle de la colline originelle (A) et la partie construite (B).

Geological story of the stratigraphic series

In the earlier paragraphs we described the nature and organization of the sedimentary levels making up the original hill of each monument.

Sphinx stratigraphy has been studied in detail several times [OMara, 1952] [Said, 1962] [Gauri, 1984; Gauri, Sinai, & B-andyopadhyay, 1995]. All the authors agree that Queen Kentkawes monument was carved in the same stratigraphic series as the Sphinx, however we did not find a precise description of the Kentkawes series.
Gauri describes the visible part of the Sphinx as a cyclothemic series of seven fine-grained limestone units, which, generally, become more durable towards the top of the sequence; the head and neck of the sphinx are carved from perhaps the only exposure of the upper strata at Giza. El Aref et al. [El Aref *et al.*, 1987] describe these Sphinx formations: thickness about 15m of hard grey porous dolomitic limestone at the base, followed by beds of alternating argillaceous limestone and calcareous mudstone. Many authors name this stratigraphic series « the Observatory Formation ». In accordance with OMara and Said, El Aref dates the Sphinx's head, sculpted in a very hard and compact dolomitic limestone, to the Late Eocene. According to Swedan [Swedan, 1991], the Observatory Formation is composed of white to yellowish white marly and chalky limestone inter-bedded with several levels of hard grey dolomitic limestone. According to our observations the dolomitization is a secondary phenomenon. Dolomitized masses outcrop either in irregularly thick beds or in diffuse masses (Fig. 6). For some authors, the Observatory Formation is located between Mokattam's series (Middle Eocene), constituting most of the Giza plateau, and Maadi's series (Late Eocene), present in the Sphinx's head and in Gebel El Gurat (in the south). In fact, these levels form a stratigraphic continuity with the levels N and NW, of the Khephren and Kheops pyramids, which leads us, like Zahi Hawass and Lehner [Hawass *et al.*, 1994], to agree with Aigner's conclusions [Aigner, 1983] that a shoal reef facies is well exposed in the basal part of the Sphinx ditch and along the road from the Sphinx Temple up to the Pyramids, followed by the marl sequence in the Sphinx body. According to our observations, gypsum rich levels in Gebel Heit El Ghurab, south of the Sphinx, characterize a lagoon environment with a slow emergence during the Late Eocene.

Geomorphology of the sites of the two monuments.

The geomorphology is the result of the interaction of three major factorsthe nature of the rock and the arrangement of the sedimentary series;the tectonic fracturation which has affected this series and the effects of weathering on these formations.

Geomorphology and structure:
According to Dowidar [Dowidar *et al.*, 2001], the area around the Sphinx is affected by regularly spaced fractures. Most of them are oriented NW-SE. A second set is oriented NE-SW and a less important one ENE-WSW.
There are also some EW and NS oriented fractures. Dowidar points out NE-SW fractures on the Sphinx's body. These fractures are also found on Queen Kentkawes' lower mastaba and on the surrounding outcrops. An E-NE oriented fracture is situated between the north side of the mastaba and the neighbouring cliff. It was probably naturally widened by weathering, which the architects took advantage of. The original hill has steep slopes that give it the morphology of an inselberg.

Geomorphology and weathering:
In the Sphinx and Kentkawes area, the geomorphology is mainly due to dissolution phenomena affecting joints: statigraphic joints as well as tectonic fractures [El Aref *et al.*, 1987] [Dowidar *et al.*, 2001]. According to El Aref, karst ridges are frequently dissected by deep dry solution gullies, separating the ridges into chains of isolated hills. The separating gullies are a few meters wide and have steep or gently inclined walls. The hills are of rectangular or square shape ranging from 5 - 10m high and 10-50m wide. The body of the sphinx itself is considered as an isolated karst-residual hill similar to various others characterizing the area. The development of these karst features indicates that the study

area was subjected to intensive seasonal rainfall and evaporation in temperate (Mediterranean) climatic conditions. This description not only applies to the Sphinx but perfectly matches Kentkawes' lower mastaba morphology with 50m sides, 10m height and steep faces. The larger space (4 to 5 meters) between the monument and the natural wall on the North side could be explained by a natural widening of the karst gullies., or by this natural widening completed by human action.

Site choice.
These geomorphological and geological characteristics led fourth dynasty architects to choose these hills as natural bases for the monuments. The similarity of the sites is remarkable. The dolomitic formation whose five levels outcropped at the site of the head of the Sphinx (Fig. 5) is a recurring phenomenon in the whole zone and it is clear that the construction sites of the Sphinx and Kentkawes were selected accordingly. In the case of the Sphinx the presence of resistant dolomitic levels allowed the fine sculpture of the head, and in the case of Kentkawes this dolomitized limestone offers a stronger base for the upper constructed section
Another similarity is the situation of these two monuments compared to topography. We noted that the Sphinx as well as Kentkawes has two or three sides dominating the plain and one or two sides closely related to the plateau. The sides dominating the plain are either the natural limit of the plateau or old quarry working faces. The spaces between the monuments and the plateau can be related to natural karstic fractures widened by human action.
In the surrounding landscape Gebel Heit El Ghurab now shows a raw rectangular shape and sides with a very steep slope, like the hills described by El Aref [El Aref *et al.*, 1987]. With, at the top, the remains of a much more resistant higher level appearing in relief (Fig. 8) it seems to be a good example of the original hill used to construct the Sphinx and the mastaba of queen Kentkawes. It can be related to an inselberg, as evoked by Vallogia [Vallogia, 2001] to describe the original hill of the Abu Rawash pyramid.

Figure 8. Gebel Heit El Ghurab view from the Sphinx.
Figure 8. Vue du Gebel Heit El Ghurab depuis le Sphinx.

Khephren and Kheops Pyramids

Description

On the Giza pyramids, the rock basement is visible at the base of the monument, where the facing stones are missing. The main difficulty encountered where the monuments is still covered by their facing stones is to differentiate the rock foundation from a block of stone cut in a similar rock. This differentiation is possible by observing three points, as illustrated by Khephren's NW corner (Fig.9):

Figure 9. Khephren Pyramid. View of the northern part of the W face. The visible part of the original hill (delimited by the white line) shows horizontal steps without horizontal or vertical block breaks. K1: karst natural fracture, K2: discontinuities showing advanced dissolution processes along the strata surface.
Figure 9. Pyramide de Khephren. Vue de la partie N de la face W de la pyramide. La partie visible de la colline originelle est délimitée par un trait blanc. Elle montre des marches sans traces de limites de blocs visibles. K1 : fracture karstique; K2 : discontinuities montrant des processus de dissolution avancés le long d'un joint de stratification.

- lateral continuity of the steps for a distance several times longer than the average length of the blocks: as in the case of the first six steps;
- vertical continuity of the steps without visible delineation of blocks;
- karstic structures identical to those in the surrounding area, in continuity with the diaclases of the rock base.(Fig. 9, K1);
- spatial continuity between the geological layers of the base of the pyramid and of the cliff facing it (Fig. 10 a, b, c) This continuity is visible in the rock facies as well as in its dip.
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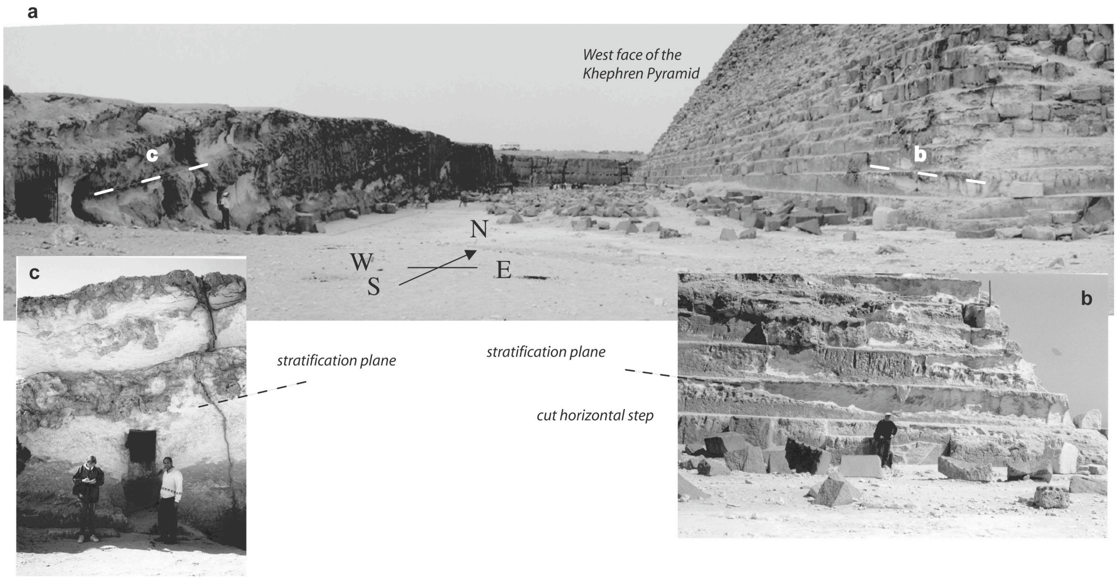

Figure 10. Khephren Pyramid.

a. View of the western part of the pyramid at right and of cliff opposite.
b. View of the natural strata in the weathered lower steps of the SW corner of the pyramid.
c. View of the geological series of the natural cliff.

The dashed lines at b and c indicate the apparent dip of the strata.

Figure 10. Pyramide de Khephren.

a. Vue de la partie W de la pyramide et de la falaise en vis à vis.
b. Vue des strates naturelles sécantes sur les marches inférieures horizontales à l'angle SW de la pyramide.
c. Vue de la série géologique de la falaise naturelle.

<u>The geological series around the monuments.</u>

The natural outcrops are visible at the level of the esplanades around the two pyramids, in cliffs N and W of Khephren (Fig. 10), and in the boat pits (Fig. 11).

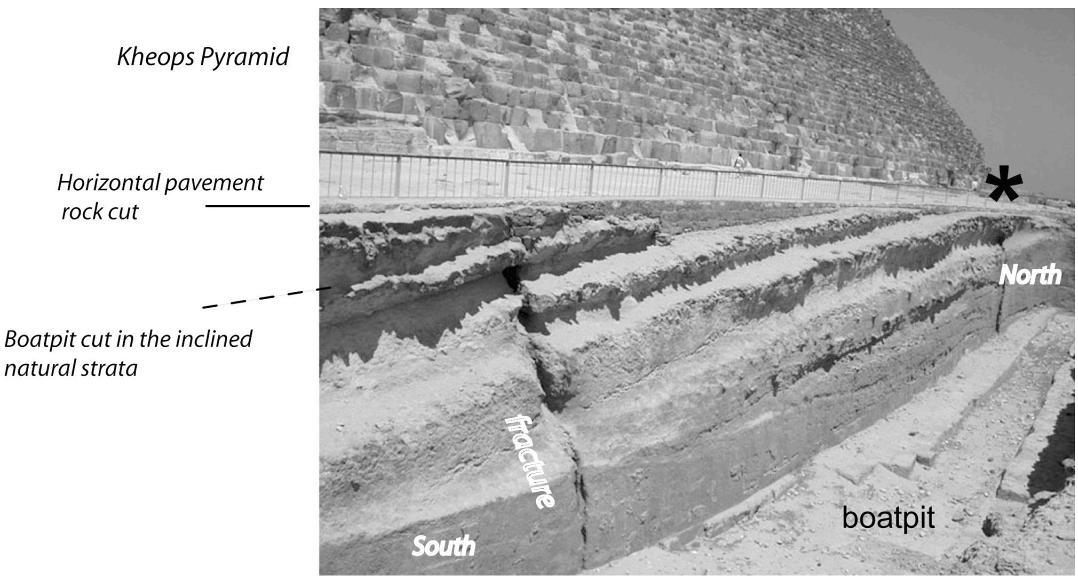

*Figure 11. Kheops Pyramid. Boatpit located at the NE of the pyramid showing pyramid base geological series. * Figure 15 localization.*
*Figure 11. Pyramide de Kheops. Fosse à bateau au NE de la pyramide montrant la série géologique sous la pyramide. *Localisation de la figure 15.*

The local series presents an alternation of bioclastic and marly limestone, separated by decimetre marly levels. It is dated from Middle Eocene and called the Mokkatam series. The thickness of the benches is irregular and lentoid terminations are visible (Fig 10c and 11). Apart from zones of variation in the thickness of the benches the general dip is constant, 8° to 12° towards the SE. For the same stratigraphic level one observes rapid side variations of facies.

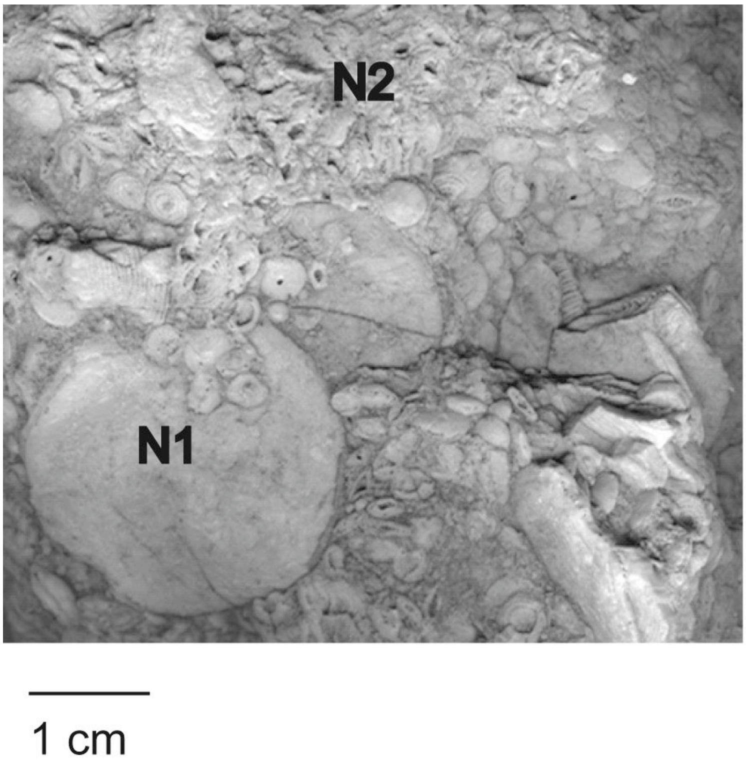

Figure 12. Kheops Pyramid. Microfacies of the packstone levels of the substratum, including two sets of Nummulites Gizehensis N1: larger forms and N2: smaller forms.
Figure 12. Pyramide de Kheops. Microfacies des niveaux de packstone du substratum incluant deux ensembles de Nummulites Gizehensis N1 : grande taille et N2 : petite taille

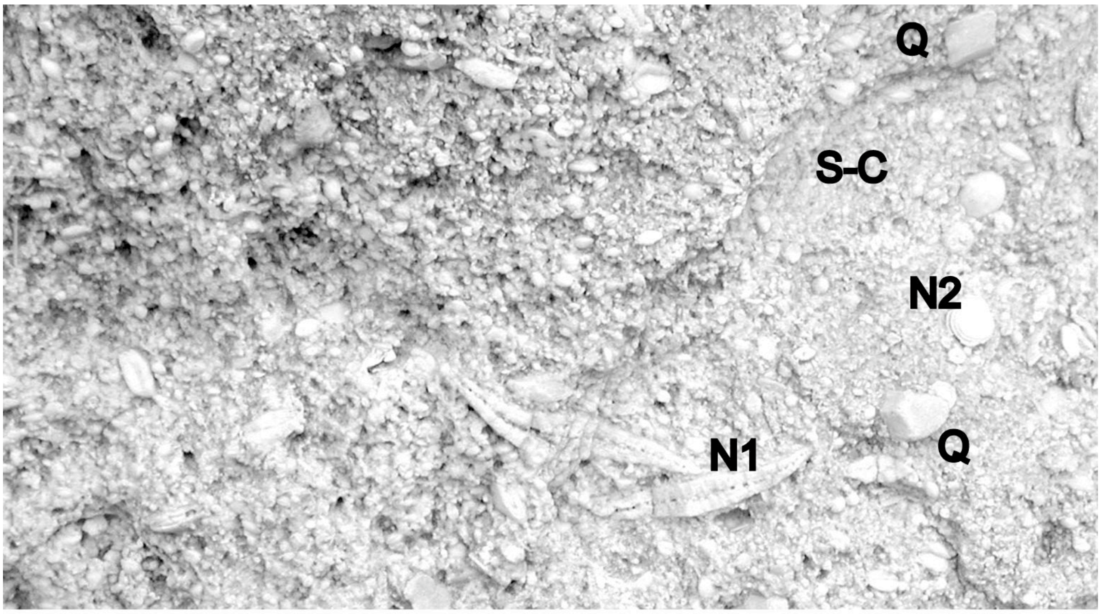

Figure 13. Khephren Pyramid. Microfacies of the wackestone levels of the substratum, including the two sets of Nummulites Gizehensis. Q: quartz gravel, N: nummulites, S-C: sand and clay.
Figure 13. Microfacies des niveaux de wackestone du substratum incluant deux ensembles de Nummulites Gizehensis N1 : grande taille et N2 : petite taille. Q : graviers de quartz, N : nummulites; C-S : argile et sable.

The most remarkable is visible from Kheops to Khephren. It evolves from a bioclastic nummulitic packstone (Kheops area) to more argillaceous formations (between Kheops and Khephren) and finally to a detritic nummulitic wackestone (Khephren area). Fig. 12 shows the packstone of the Kheops' area. It has an argillaceous and calcareous matrix including two different sizes of gizehensis nummulites. This packstone is found in some of Kheops' blocks. Fig. 13 shows the wackestone of Kephren's area with sand, clay and quartz gravels as well as the two different sizes of gizehensis nummulites. This wackestone is also found in some of Khephren's blocks. According to Aigner [Aigner, 1983] we consider that these lateral variations are due to the sedimentation of these formations in a shallow coastal environment.

<u>Khephren</u>

At the base of Khephren's west façade, facing and backing stone blocks have been removed. The rock base is visible, from which the first 6 steps are formed (Fig. 9). These steps continue along the entire W façade. Their appearance (natural or due to a coating visible at many places) is a uniform pink to dark red colour, and shows tool traces. The next three types of observations demonstrate that these steps are a part of the local geological formation:
- (i): natural fractures crossing all steps, oriented NW-SE, present the morphology and the orientation of the karst fractures described by El Aref & E Refai [El Aref *et al*., 1987] and can be followed through the esplanade up to the cliff. Aligned dissolution holes occur under the natural limestone bedding. These karstologic structures (Fig. 9) belong to the karst network of the Giza plateau "which is mostly controlled by the jointing and bedding characteristics of the limestone" and suggests development under phreatic, vadose or alternating vadose-phreatic environments.
- (ii): in the SW corner of the pyramid (Fig. 10) these steps are weathered and the erosion has differentially modified the morphology of the surface rock, with clayey layers eroded out and more carbonated strata in relief. This differential erosion and the alignment of dissolution holes demonstrate the SE 12°E dip of natural bedding, consistent with the measured dip of

the strata of the cliffs. Therefore it is clear that the outcrop and the cliff formations are in continuity, as visible in the illustration .
- (iii): the petrographic facies of the nummulitic sandy limestone levels alternating with clayey levels are the same in the cliffs and in the base steps of the pyramid (Fig. 10 a, b, c). Extrapolating from these observations it isapparent that the surrounding esplanad of the monument has been carved between cliffs and a primitive hillock constituting the nucleus of the pyramid.

Morphological study of the original hill: This study is based on external data from our observations and on the monument's internal structures as reported in former studies. External data: The rocky outcrop is visible at the base of the four sides of the monument, at various heights (Fig. 14):

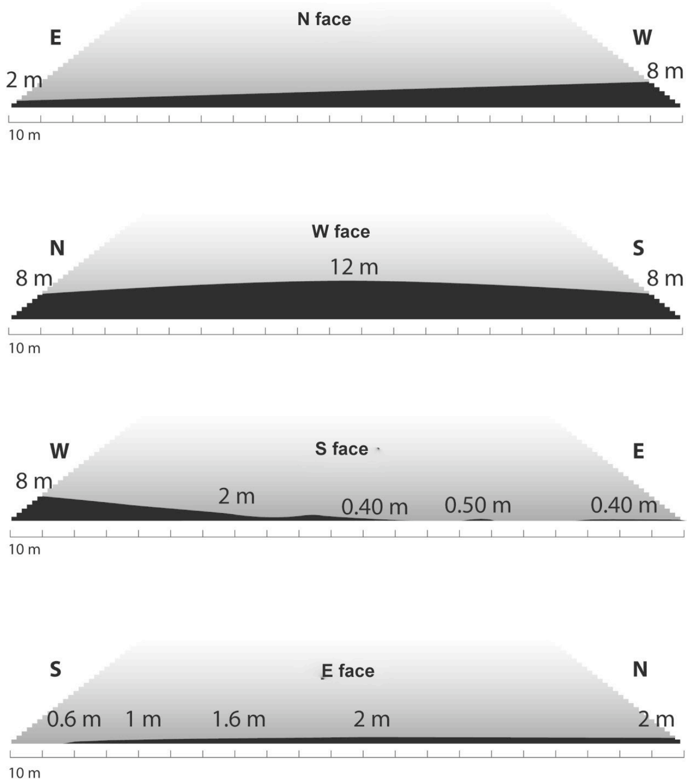

Figure 14. Khephren Pyramid.Localization of the visible outcrops of the original hill.
Figure 14. Pyramide de Khephren. Localisation des affleurements visibles de la colline originelle.

- northern face: continuous outcrop from 2m at the NE corner to 8m at the NW corner. ;
- western face: continuous outcrop from 8m at the NW corner, rising to 12m in the centre of the face, 8m at the SW corner ;
- southern face: 8m at the SW corner decreasing to 0.40m at the centre of the face, and locally outcropping from 0.40 to 0.50m between the centre and the SE corner. ;
- eastern face: outcrop begins at 15m from the SE corner at a height of 0.60m , 1m at 30m from the corner and rises to 2m from the centre of the face to the NE corner.

Petrie [Petrie, 1883] described natural rock outcropping in the inner descent of Khephren at a height of 5m above the reference level of the surrounding esplanade. He also reported that the great chamber is entirely cut into the rock. These observations led him to suppose the existence of a original hill under the pyramid. He draws it with a constant height of approximately 5m compared to the level of the esplanade

Kheops

From the observations made in the boat-pits (Fig. 11), at the NE corner of the pyramid (Fig. 15) and on the esplanade around the pyramid, we have seen that the rock base of the monument is mainly composed of nummulitic packstone. Observations at Kheops, based on the same criteria as Khephren, show that the rocky basement is not very visible in the lower parts of the pyramid. It is however possible to establish the presence of a original rocky hill as described below.

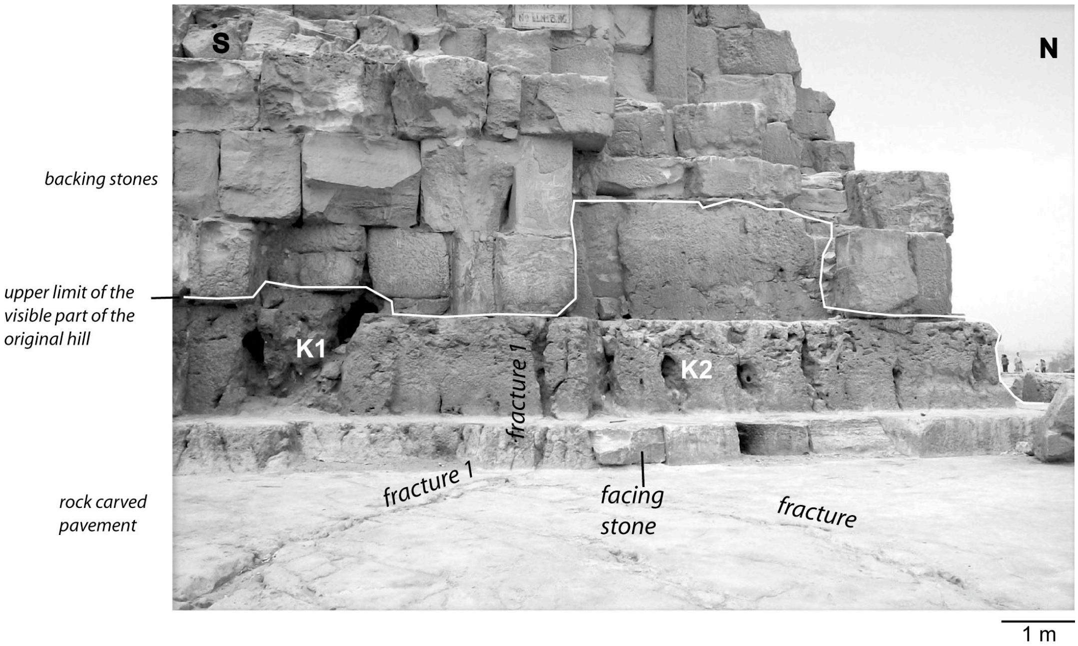

Figure 15. Kheops Pyramid. View of the NE corner located on figure 11. The white line outlines the visible part of the natural rock affected by fractures and solution phenomena. K1: karst natural fracture, K2: cavities showing advanced dissolution processes along the stratum surface.
Figure 15. Pyramide de Kheops.Vue de l'angle NE localisée sur la figure 11. La ligne blanche souligne la partie visible du rocher affecté par des fractures et des phénomènes de dissolution. K1 : fracture naturelle karstified; K2 : cavités résultant de processus de dissolution dans le joint stratigraphique

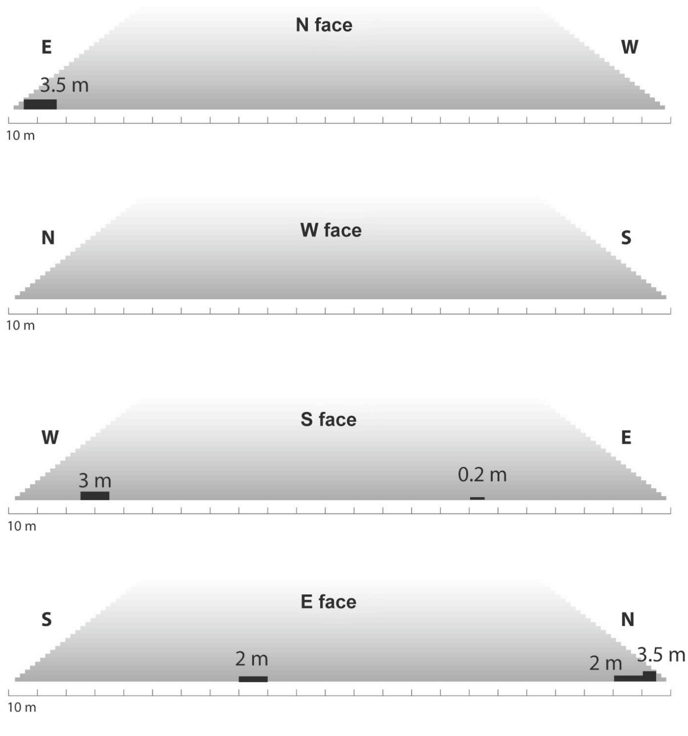

Figure 16. Kheops Pyramid. Localization of the visible outcrops of the original hill.
Figure 16. Pyramide de Kheops. Localisation des affleurements visibles de la colline originelle.

Morphological study of the original hill: External data: the original hill visible at the base of three sides of the monument, at various heights (Fig. 16):

- northern face: 3,5m. height over a 12m. length from the NE corner .
- western face: no visible outcrops
- southern face: 3m. height on a 10m. length, 25m from the SW corner . Then a 0.20m height on a 4m. length, at 65 m from the SE corner.
- eastern face: 2 m. height between 80 and 90m from the SE corner and 2m to 3.5m on an 18 m. length from the NE corner .

Several authors show a surelevated rock outcrop inside Kheops pyramid (Fig. 17). Petrie [Petrie, 1883] observed the rock in the inner descent at an height of 8m above the level of the esplanad. For Eyth [Eyth, 1908] the maximum height of the rocky platform is 12.5m, for Dormion [Dormion, 2004] it reaches only 6.60m. Their different profiles of the rock outcrop are shown in Fig. 17.

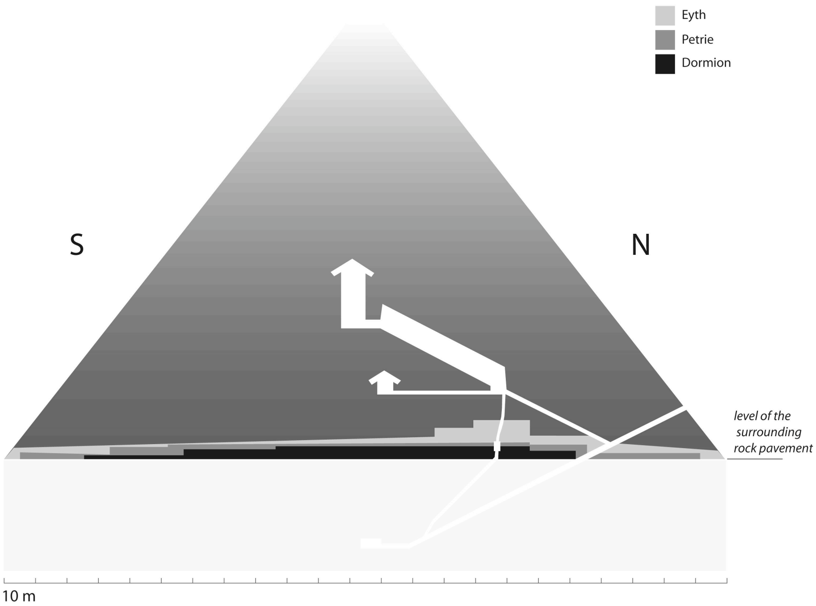

Figure 17. Kheops Pyramid NS cross section showing the earlier data on the original hill morphology.
Figure 17. Pyramide de Kheops. Section NS montrant les données antérieures sur la géométrie de la colline originelle.

Discussion

<u>*Volume of the original hill and their importance in the monument*</u>

The preceding observations lead us to assert that the great pyramids were built on a carved outcrop , using the existing topography at the time of their construction. The current state of the monuments does not allow a direct measurement of these rock outcrops as has been done for Abu Rawash. It is however possible to derive a minimum volume by using external and internal data as well as local topography.

Khephren Pyramid: Petrie's internal description tallies with our external observations. This enables us to build a three-dimensional representation of the visible part of the original hill(Fig. 18) and calculate its minimal volume: 245,000m^3 corresponding to 11.5% of the volume of the pyramid.

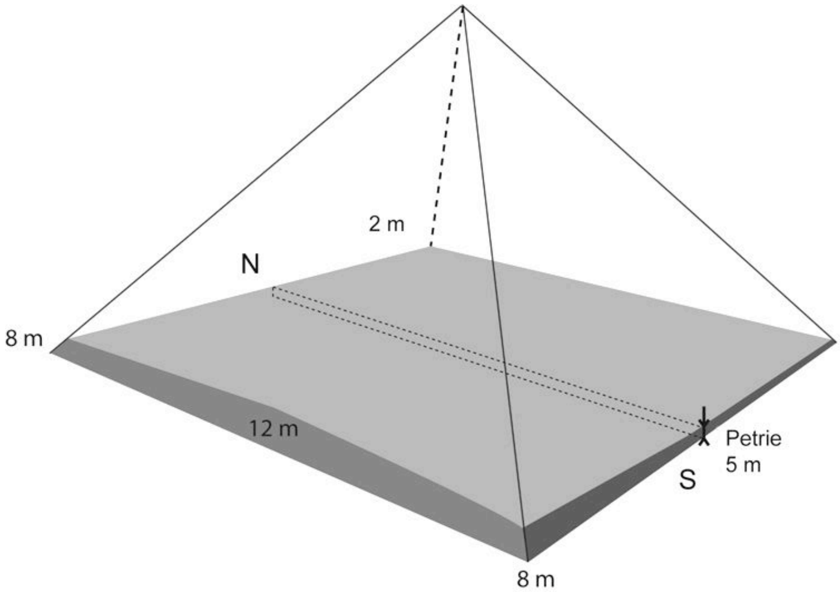

Figure 18. Khephren Pyramid. Three-dimensional representation of the visible part of the original hill, including Petrie's observations.
Figure 18. Pyramide de Khephren Représentation tridimensionelle de la partie visible de la colline originelle incluant les observations de Petrie.

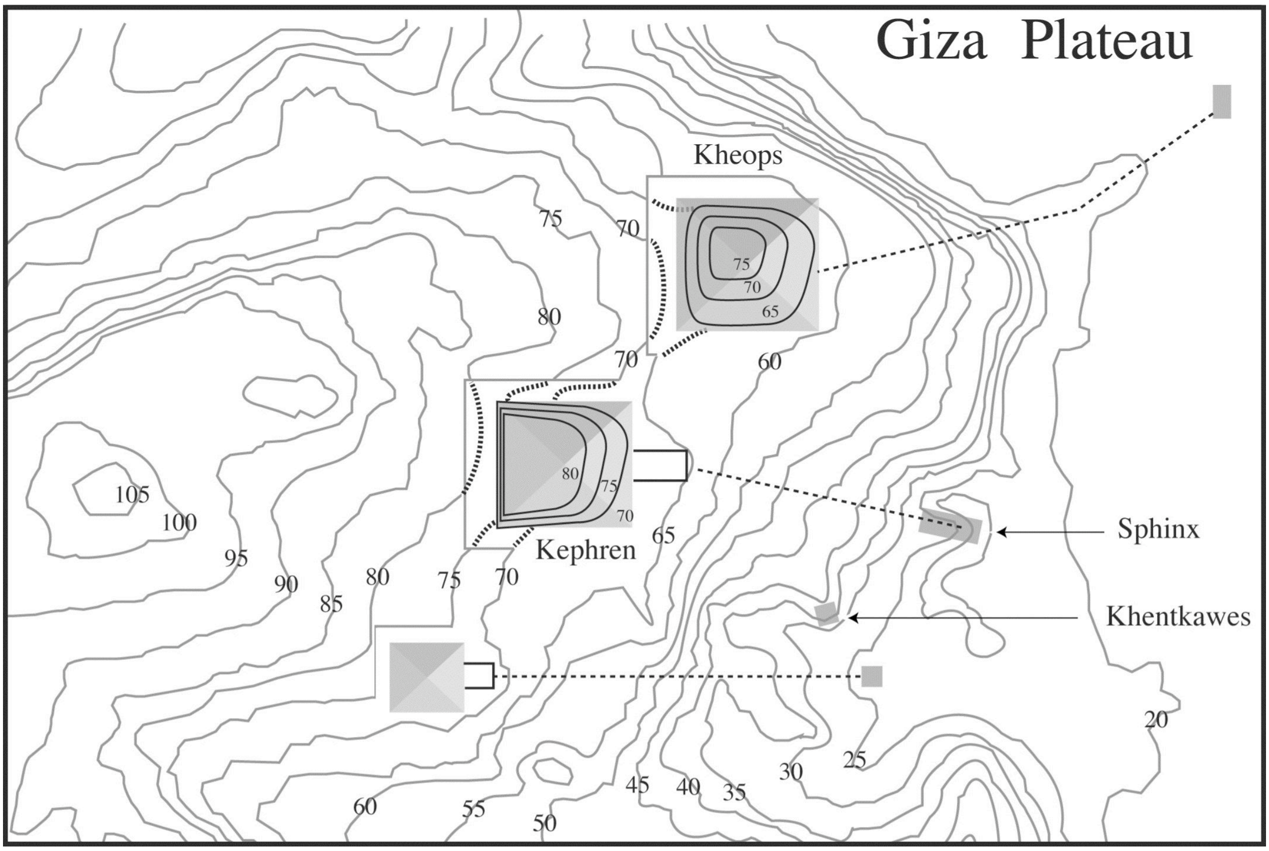

Figure 19. Giza plateau topographic map including level line reconstitutions of the visible parts of rock outcrops under Khephren and Kheops (figure 14 et 16).
Figure 19. Carte topographique du plateau de Guizeh avec les courbes de niveau des collines originelles de Kheops et Khephren reconstituées à partir des cartes d'affleurements des figures 16 et 18.

If one reconstitutes the topography of the carved outcrop, one sees a very good match of the level lines of the original hill with the level lines of the site. (Fig. 19). It also shows the importance of the carving work carried out W and N of the pyramid (Fig. 19).

Kheops Pyramid: The external observations are insufficient to establish, as for Khephren, a three-dimensional representation of the hillock. However, combined with the internal height of 12.5m reported by Eyth, they enable us to propose a reconstitution of the topography of the carved outcrop . It also reveals a very good match of the level lines of the original hill with the level lines of the site. (Fig.19). On this basis the minimum volume of the outcrop can be estimated at 600,000m^3, and corresponds to 23% of the volume of the monument.

Geomorphology of the construction sites

The builders took advantage of the topographic and geological configuration of the ground to build their monuments. As stated for the Sphinx and for Kentkawes' mastaba, the geomorphology of the site is governed by the nature of outcropping rocks and by the fracturation and karstification of the rock. These phenomena led to a landscape of more or less isolated outcrops with abrupt slopes such as Gebel Heit El Ghurab (Fig. 8). Outcropping of competent bioclastic nummulitic limestone in a series of more clayey formations favours relief in a direction perpendicular to the dip of the strata. If we look at the topographic map of the plateau we can see that the three pyramids are aligned on a NE-SW direction, parallel to the NE-SW nummulitic outcropping and perpendicular to its general SE 10° dip. The best-shaped site is the croup under Kheops, the first monument built on the site. The setting up of Khephren required more earthworks, with digging on the northern and western parts and filling at the southeastern part of the monument.

Modelling the size and form of the original hill.

The calculations of the volume of the rock outcrops of Kheops and Khephren are minimum estimates based on observation of their visible parts. The actual volume of these rock outcrops is likely to be larger, and one can try to build a model of their actual size and form. In a preliminary paper by Bertho et al. [Bertho *et al*., 2004], ' the original hill of the great pyramids was represented as a hill the morphology of which was close to the morphology of a pyramid with a weaker slope. However, the morphology of Abu Rawash and Kentkawes' original hill, as well as that of Gebel Heit El Gurat, is close to that of an inselberg with strongly sloped sides and a summit whose surface is roughly horizontal. The model of the original hill under the great pyramids is thus constrained by these observations. This leads us to suggest that Kheops and Khephren's rock outcrops have the shape of an inselberg.
The volume of the Abu Rawash original hill as calculated by Vallogia is about 44% of the total volume of the pyramid. If one calculates the height of the original hill under Khephren and Kheops with this assumption one obtains a original hill height of around 20m. The additional level lines that are added according to this assumption fit well with the reconstituted topographic map of the rock outcrops of Kheops and Khephren (Fig. 19). We thus suggest the following model: an original hill with an approximate height of 20m and the overall shape of a truncated pyramid (Fig. 20). It is however obvious that only a geophysical study adapted to the problem will make it possible to know the precise topography of the original hill under Khephren and Kheops.

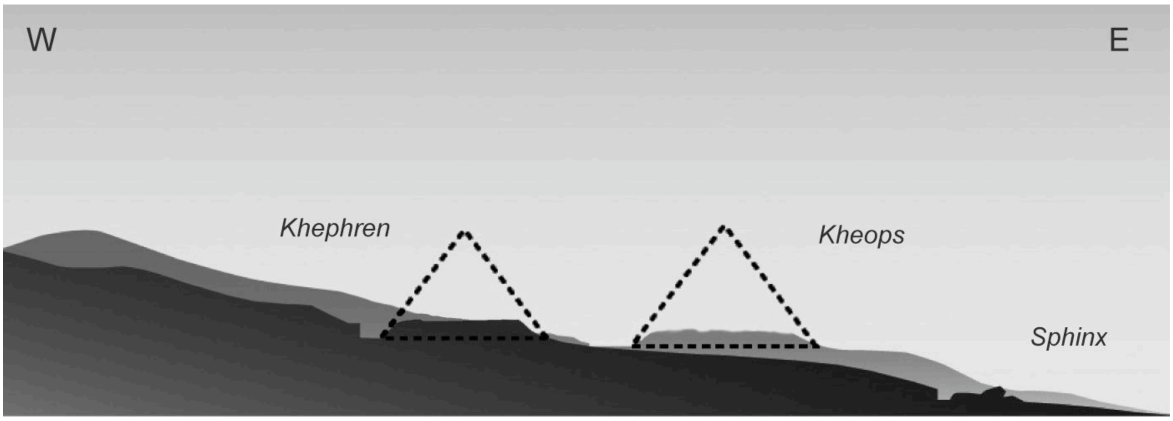

Figure 20. Schematic reconstitution of the original hills in the general topography of the Giza plateau.
Figure 20. Reconstitution schématique des collines originelles dans la topogrpahie générale du plateau de Guizeh.

CONCLUSION

We studied the geology, morphology and topography of the rocky foundation of the pyramids of Kheops and Khephren in comparison with that of other monuments of the fourth dynasty, whose rock base and core are visible: Sphinx, mastaba of queen Kentkawes as well as the Abu Rawash pyramid.

Through this study, we described the local geological context of the monuments and the complex relations between the base of the monuments and the local geological series. The geomorphology of the sites, resulting from the interaction between the sedimentary sequences, the tectonic events and the effects of erosion, has been reconstituted.

The results obtained show the broad use of the topographic characteristics of the sites by the builders of the IV° dynasty. Apart from the Sphinx and and the previously described Abu Rawash pyramid, this study shows the existence of a original hill of large volume under the monument of queen Kentkawes and under the two great pyramids. The volume of this original hill is about 64% of the total volume of the monument for the mastaba of Kentkawes, 11.5% for the pyramid of Khephren and about 23% for the pyramid of Kheops. These results are deduced from direct observation and should be regarded as minimum values. For the great pyramids, we propose a model postulating larger volumes and heights of approximately 20m. Real volumes could be specified only by adequate geophysical study.

Our results show that it is necessary to reconsider most of the former studies, on the one hand for the morphology of the base and on the other hand for the calculation of the total volume of stone used.

The utilization of a carved natural rise as a construction site seems to be a general characteristic of architecture under the fourth dynasty. One can only speculate whether this architectural choice is related to economic constraints or to a symbolic signification.

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