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PIXE, PIGE and NMR study of the masonry of the pyramid of Cheops at Giza

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Abstract

The mystery of the construction of the great pyramids of Egypt could be elucidated by physico-chemical measurements on small pieces of the material. In this paper, we give several arguments against the present point of view of most Egyptologists who do not admit another method than hewn blocks. We give several pieces of evidence that the masonry was entirely built by a moulding procedure involving the use of ingredients that were all available in the region of Cairo.

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1. The construction with hewn blocks represents an impossible task

The Cheops' pyramid, with a volume of 2.7×10^6 m³, was completed over a period of 20-25 years. One can then estimate the average daily cadence at 300–400 blocks having all an average volume of 1 m³ (i.e. 750–1000 tons). This represents one block put at the right place every 2 min. To achieve this goal, 1 m² of hewn face would have been ready every 20 s! What a performance with tools made of stone or soft copper! Hoisting huge blocks of more than two tons with rudimentary means (wheels and pulleys did not exist at that time) is evidently an impossible task. As several dozens of those monuments have been constructed

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on the left bank of the Nile by the Pharaohs of the first dynasties, we cannot imagine the average time of construction of each pyramid to be longer.

When looking carefully at the surface of the blocks of the pyramid of Cheops (those visible today and therefore those underlying the casing blocks, which totally disappeared), one clearly sees irregularity in the shape (Fig. 1), but a remarkable close fit of adjacent faces (Fig. 2). It would be surprising that these blocks could have been so badly cut but so perfectly joined. This admirable close fit would have been easier to achieve if the blocks had been hewn with perfect rectangular shapes! Furthermore, this care in this optimal juxtaposition was useless because these blocks (visible today) were originally hidden under the casing [1,2].

We can also see that blocks of Fig. 1 appear to be more porous in the top part than in the bottom part. This porous feature on the top of the blocks

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Fig. 1. Some details of the blocks of the pyramid of Cheops: irregular blocks but very fine close fit of their adjacent surfaces. The porosity at the top of blocks is bigger than at their bottom.



Fig. 2. Fine close fit of adjacent blocks of the pyramid of Cheops (second step) (photograph of Demortier).

cannot be explained by some climatic erosion of natural limestone but could be understood if we



Fig. 3. The structure of the narrow channel ($20 \text{ cm} \times 20 \text{ cm}$) starting from the Queen's chamber of the pyramid of Cheops (photograph of Demortier from the TV show of the Gantenbrink's robot expedition).

propose a construction similar to our modern concrete.

Narrow channels, with a section of $20 \text{ cm} \times 20$ cm, starting from the Queen's chamber and investigated by Gantenblink's robot (Fig. 3) clearly indicate that they were not carved [3]. There is no gap between the two lateral sides (walls) and the ceiling of this conduit. On a TV show of the Gantenblink's expedition, one could see that no protrude (convex) defect appears in the walls and in the ceiling of this narrow tunnel. Irregularities are only of hollow (concave) shapes. A carving procedure would have given convex and concave irregularities in equal proportions. When thinking about a moulding procedure, the apparent cavities could be understood by some loss of material during the demoulding.

Many other arguments including (a) the chaotic organisation of nummulites in the blocks, with respect to parallel alignment of shells in natural stones, (b) the high water content (about 13%) of the whole pyramid measured by the transmission electromagnetic waves, (c) traces of mortars mostly at the base of the blocks, play in favour of another way of construction: not natural hewn and hoisted stones but the agglomeration of natural limestone using a binder... which contains natron, alumino-silicates and certainly water. All ingredients have been transported in small quantities, dropped in moulds installed progressively onto or

on the side of blocks which were previously moulded.

2. The chemistry of the binder

In the 70s, Davidovits [1] proposed that the great pyramids were made of a kind of concrete whose basic binding element was natron: a sodium carbonate. Natron was indeed widely extracted from a region of the North of Egypt, on the left bank of the Nile, very close to the site of Giza. The binder is obtained by some chemical reaction giving rise to a geopolymer (name given by Davidovits to a class of x-polysialates, x being an alkaline nucleus, in particular sodium) [4]. Natron, lime and water form caustic soda, which reacts with aluminous limestone to yield the basic geopolymer. A mineral ore containing arsenic (scorodite or olivenite) is added to produce sodium arsenate acting as an activating ingredient that could have been used in various concentrations to control the speed of the hydraulic setting. The invention is attributed to Imhotep, the architect of the pyramid of the Pharaon Djeser.

3. Physico-chemical analyses

In addition to the analyses carried out by Davidovits with X-ray fluorescence [5] and X-ray diffraction, which showed that the blocks mainly consisted of limestone (85–92%), we have also performed investigations on a little number of samples from the Cheops' pyramid: elemental analysis was performed by ion beam analyses, PIXE and PIGE and structural characterization by NMR-spectroscopy.

By using the PIGE–PIXE techniques (proton induced gamma-ray emission or X-ray emission) we have determined the elemental content of small fragments. The light elements F, Na, Mg, Al, Si were quantitatively determined by using PIGE [6], and K, Ca, Fe and other trace elements by using



Fig. 4. Details of small fragments of the pyramid. Parts a and b from an inside block: a limestone nugget (left) coated with a linking material (right). Part c: fragment of a casing block with an inclusion of shell. Part d: yellow geopolymer cement reproduced at LARN using the recipe of Davidovits showing the fine granulation and its adherence to small gravels.

PIXE [7]. A small sample from the Cheop's pyramid is made of a central compact structure containing mainly limestone with traces of other elements (Fig. 4(a)). The outer part (Fig. 4(b)) contains a large amount of F, Na, Mg, Al, Si, indicating that a material to aggregate the limestone has been used [8]. The ratios of concentrations of F, Na, Mg, Al and Si in the coating relative to the bulk are given in Table 1. Except for Al, those ratios are much more greater than one, indicating a complete different structure. The high

Table 1		
Intensity radios (coating/bulk)		
F	7.5	
Na	8.5	
Mg	12	
Al	2	
Si	21	

concentration of sodium is certainly due to the use of natron for the binder. The PIXE spectra of Fig. 5(a) and (b) illustrate the low content of calcium in



Fig. 5. Comparison of PIXE spectra from the central part of limestone (part a of Fig. 4) and the external binding material of Fig. 4(b). The X-ray energies (horizontal) are given in keV.

the coating relative to the bulk. Furthermore, the significant signal of As in the coating may be attributed to some additional ore which could be scorodite as more extensively discussed below. In addition to PIGE and PIXE measurements which allow us to have insight to the elemental composition, the nuclear magnetic resonance spectroscopy (NMR) of Al²⁷ and Si²⁹ enables us to determine the type of synthetic medium (basic pH) and to differentiate a natural environment (neutral pH) from an artificial one. We have then fabricated the binder based on the geopolymer formula of Davidovits [1]. The NMR-spectra of Al and Si on this modern synthetic material shows typical

resonances assigned to Si $[Si(OSi)_4]$ and Al (tetrahedral) in this synthesized material which is highly chemically basic (pH around 10). The NMR spectra (Fig. 6) of several samples of Cheops' pyramid indicate that the tetrahedral Al content is 10-15% of that obtained for the pure synthetic mixture reproduced in our laboratory and which exhibits a very fine adherence with small gravels (Fig. 4(d)). This value of 10-15% of the NMR signals is in direct relation with the amount of geopolymeric binder and, consequently, also related to the original water content of the blocks (Fig. 6(a) and (b)). Si-NMR leads to the same conclusion (Fig. 6(c) and (d)).



Fig. 6. Comparison ((a) and (b)) of Al-NMR spectra obtained with the pure binding material (the one shown between gravels of Fig. 4(d)) and some powder from the small sample of the pyramid of Cheops. Corresponding Si-NMR spectra are given in parts (c) and (d). The horizontal scales give the frequency displacements in parts per million.

4. Manpower for the construction of the pyramid

The moulds could have been made of grooved small boards fitting one into the other in the way of modern wooden floors. The fixation by two crossbars of the first and of the last small board of the mould (and only these two boards), as represented in Fig. 7, allows the intermediate small planks to slide in a movement going from the top downwards to prevent any leakage in the region of contact with the block of the inferior step. These small boards have probably the width of an Egyptian palm (1/7 of cubit, about 7.5 cm). The construction of the moulds with a definite number of small boards explains the modular width reported by Davidovits for the blocks of Chephren's pyramid [1]. Davidovits mentioned this modular dimension (an integer of a reference board width) for the blocks of Chephren and not those of Cheops because blocks of Chephren have a more regular dimension. This second pyramid of Giza would have profited from the experience acquired during the construction of the first pyramid at Giza: the Cheops pyramid. Those blocks of Chephren have then a higher quality in their finish.

The irregularity noticed on the blocks in the Cheop's pyramid would be due to possible "accidents" during the removing of the planks of the mould after the solidification of the liquid binder. Any loss of building material occurring during demolding would have been corrected by a partial covering of the demolded block with the next mould. With this method, the hardening of the



Fig. 7. The model of moulds made with narrow planks (one palm wide for each plank).

new block provided a close fit with the precedent, even though this last one had lost its surface regularity during the demolding.

A system of two boards constituted of a variable number of one palm wide small planks was sufficient for the constitution of a mould: the lower blocks (b), the side blocks (c) and the leaned blocks (d) provide the other four faces that insure the tightness of the volume in which the mixture is poured. This procedure explains the modularity noticed for the widths of all the blocks in Chephren's pyramid and also the close fit between the irregular blocks in the pyramids of Giza, even the one of Cheops. The height of a single block depends on the height of the shortest plank used in for mould. The modular width of the blocks of the Chephren's pyramid depends on the number of small planks constituting the board. Blocks illustrated in Fig. 8 (2nd level of Cheops' pyramid) have a shape, which cannot be explained logically by the carving technique. On the contrary, the trapezoidal shape could have been obtained if one or two side planks of the mould were accidentally inclined before the solidification of the mixture (Fig. 8(a)) or deformed along the length of each narrow plank of only one palm wide (Fig. 8(b)). The width of the central block of this last figure is only 20 cm at top and bottom and 40 cm in the central part. A crazy task if we think it could have been carved!

The solid ingredients brought in bow nets are poured into the mould that has been made waterproof by the application of a mortar. This mortar is applied to the internal base of the mould. The mortar, already visible today, is mainly present at the base of the blocks. As for moulding a block, liquid ingredients are first poured, waterproofing is necessary at the bottom of the mould. The solid ingredients introduced in this liquid are limestone aggregates brought from the immediate neighbourhood of the construction site.

If one considers that spherical aggregates of the same diameter are poured into a cubic vessel, voids between the spheres would represent 26% of the volume (an easy calculation in crystallography). Accordingly one may estimate that a mixture of solid ingredients having statistically any dimension and any shape will fill about 50% of the voids, owing to the fact that small aggregates will



Fig. 8. Blocks of the pyramid of Cheops: (a) a trapezoidal shaped block; (b) very irregular narrow block: 20 cm wide at top and base, 40 cm wide in the middle.

partially fill the space between large aggregates. Consequently, the mixture consisting of solid aggregates occupies 85–90% of the volume of a mould. The rest is the reactant mixture containing water, natron and different alumino-silicates as stated by Davidovits and confirmed by the PIGE and PIXE analyses.

Instead of having teams pulling blocks weighing several tons, the workers transported the ingredients by small loads (of 25-50 kg each) that do not require any wide ramp (that anyway would badly support the extensive heavy carriages during twenty years at a rate of 300-400 blocks of one cube meter per day). Workers could also save their energy by taking the load and bringing it upwards, passing it from man to man, without having the need to climb the pyramid with their load. Any transportation of a small charge would give rise to a maximum efficiency. In the case of heavy hewn blocks, the efficiency would have been extremely lower. The fabrication of moulds (static structure of $0.5-2 \text{ m}^2$) would require at least 100 times less wood (wood is indeed rare in Egypt) than the fabrication of sledges: less quantity of wood for a (static) mould than for a (moving) sledge and shorter time of use for moulds (one day) than for sledges (several days ... or even several weeks).

Assuming that the aggregates were extracted from quarries close to the building site and distant

by at most 3 km from Cheops' pyramid (as may still be seen in the surroundings today), we have estimated the cadence of the construction and the number of workers occupied on the site in the following way:

- (a) 6 men are bringing one cube meter of ingredients per day, from the nearby quarries to the bottom of the pyramid (400 kg per man per day);
- (b) for the lifting of ingredients from the plateau level to the desired step, we estimate that the cadence would represent 1 m³ of material to be lifted by each worker during 1 h from one step to the next one above. Bearing in mind that the height of the steps varies from 100 cm to 50 cm when one passes gradually from the base to the top of the pyramid, there is a progressive decrease in the yield from the bottom to the top. This performance is completely similar to the one accomplished today if we have in mind that modern associated mason have to transport 7000 kg of bricks, sand or cement up to a 3 m floor per day.
- (c) two workers are dedicated to the maintenance of each mould: survey of waterproof of the plank assembly of the boards, kneading during the pouring of ingredients.

Using this model one obtains the results summarized in Fig. 9. One notices that the 8th step is reached after 1 year, the 54th after 10 years, the 90th after 17 years. This last one corresponds to the position of the funeral King chamber and confirms the inscription written in a hieroglyph at that place: 17th Year of Pharaoh's reign.

One also observes that a maximum of 11,000 workers were necessary at the beginning of the construction; this is the moment when the area of one step of the pyramid is the largest. The total activity diminished with the height. However, the lifting of the ingredients towards the summit is made with the manpower distributed on the entire area; each worker passing on the materials from step to step. The activity on the whole surface of the steps will never exceed 2300 workers (lifting and maintenance teams). Each team of four workers had therefore 100 m² to allow them to work without any space constraint. Exchange of work between "transporters" and "lifters" during all the time of the construction may also be considered.

With this model, the total duration for the construction would be 26 years, but the period could be easily reduced to 20 years by increasing the activity on the construction site from the 15th year onwards, or by increasing the amount of personal by 30% during the whole duration of the construction. By doubling the number of men, one could also think to allow them to stay at rest one other day or compensate interruption due to climate troubles.

5. Ancient descriptions and illustrations

In a well-documented report on the construction of the pyramids, Herodotus (Vth century BC) reports:

This pyramid was made, as I am going to say, in terraces that some name steps, and others small altars. When the base had been built, the rest of stones was raised by means of machines fabricated with short wooden pieces; the force of a machine acted from the ground until the level of the first tiers at first: once transported there, the stone was put on a second machine, which was fixed there. From there it was risen on the second tier, and on a third machine. There were as many rows of terraces, as there were machines. It is possible however that there was only a single portable machine: in this case, it was taken up from tier to tier, having brought up there the stone. It is indeed necessary to report these two processes as they were said to me.



Fig. 9. Manpower for the construction of the pyramid of Cheops.

The summit of the pyramid was finished before the rest; and afterwards they completed the parts in the following tier, and one ended by the lowest, by the one that touches the ground. It was written in Egyptian characters, on the pyramid, how much was spent for garlic, onions and parsley for the workers. As I well remember it, the text (that the interpreter explained to me) means that the sum amounts to sixteen hundred talents of silver (58 tons of silver!). If these things cost so much, what did they spend in metallic tools, in foods and in clothes, since they took the time that I have mentioned to build this edifice without even counting, in my opinion the time for quarrying the stones, their transportation and the construction of underground excavations?

The description supports the following explanations:

- (a) *short* wooden pieces cannot be long beam of levers necessary for the lifting, but could be the planks of the mould,
- (b) the completion of the pyramid began with the installation of the *facing blocks at the summit* first. In order to be sure he would be well understood Herodotus insists in the next sentence with the following statement: the builders then continue on the following floor, downwards, to end with the one that touches the ground. These facing blocks are still present today at the top of Chephren's pyramid and they hold firmly even after more than four millennia. They have then evidently been put in place at the top first,
- (c) garlic, onion and parsley cannot be understood as food supply for the workers. A comment on the cost of these ingredients provides us with a hint on the nature of the materials used and not of food. In the sentence which closely follows this statement, Herodotus argues about the supplementary cost for food, tools and clothes. Garlic and onion have a direct link with ingredients occurring in the manufacture of blocks. According to Davidovits [1] two of the three ingredients appear in the text of the Famine Stele [1] describing the "Revelation of Imhotep": "hedsh" is a disaggregated stone smelling

like onion and "tem-ikr" is a mineral containing arsenic which has the characteristic smell of garlic and garlic stone could be scorodite as observed by the PIXE results on the coating of the small aggregate of Fig. 4(b). The famine stele relates to the description of various skills of Imhotep, the architect of the Pharaon Djerer, who describes the procedure to make some kind of concrete (see Appendix A).

(d) underground excavations cannot refer to open air quarries but could be associated with excavations in mines located on the left bank of the Nile in the northern region close to Giza to extract natron. The name of this region is already today: Ouadi Natrum.

This method of construction based on a moulding technique is explicitly described on a painting of the tomb of Rekhmire dating from the XIIth dynasty (Fig. 10). Various operations are



Fig. 10. A bas-relief of the Rekhmire's tomb illustrating the procedure of moulding large blocks.

illustrated on it: loading of ingredients in bow nets (on the left), transport and pouring upright into a mould (in the top centre); one plank of the mould is maintained vertically by a civil servant (in the bottom centre). Contrarily to some modern transcription, the original painting does not show any modular structure in this large block that some scholar had interpreted as an assembly of bricks.

6. Proposals for future investigations

To put an end to the debate involving partisans and opponents of the construction method based on agglomeration, we suggest to increase the physico-chemical analyses by increasing the study of samples, but in addition, by carrying out several simple experiments such as:

(a) the critical study of the slope for each of the three Giza's pyramids, compared with the lower slope of an anterior pyramid like the one of Snefrou. We think that the slope is connected to the type of building material used for the construction. Civil engineers know the relation existing between slope and ingredients that constitute a heap of material. The longevity of the pyramids is, in our opinion, rather linked to these technical data than on computation of "magic" numbers;

- (b) the datation of straw in mortars taken precisely at the bottom of the blocks. The determination of the C¹⁴ content by accelerator mass-spectrometry would require a minimum sampling;
- (c) the removal of some blocks for the observation of an internal face. The presently visible faces underwent climatic erosion which eliminated any imprint of board or ... carving marks;
- (d) the study of the well fitted faces of the blocks similar to those shown on Fig. 8 should reveal whether their faces adhere or not. Traces of adhesion would show that the central block of Fig. 8(a) was moulded before the complete solidification of the two adjacent blocks;
- (e) the sampling of small size fragments and their elementary analysis in terms of elements of light atomic weight, using modern techniques and their quantitative comparison with the contents of these same elements in the limestone found in the neighbourhood of the site;
- (f) a further study of texts, especially in hieroglyphs, and their interpretation by an interdisciplinary team: philologists, historians, archaeologists, with the help of physicists and chemists to comment on scientific interpretation;



Fig. 11. The ceiling of the pyramid of Ounas already showing the traces of the limits of the moulding planks (photograph of Demortier from a TV show).

(g) the reconstruction of blocks of a size similar to those of the pyramids by moulding and carving techniques under the control of independent experts. Moulding of blocks has been made on the site of Geopolymer Institute of Saint-Quentin (France) in September 2002 and July 2003. One hour after pouring the material in the mould, the solidification was sufficient to remove the planks.

7. Evidence of moulding process

The shape of the walls and the ceiling of the narrow channel starting from the Queen's chamber of the Cheops pyramid was discussed in the first paragraph of this paper and it is evidently not made by a carving procedure (see Fig. 3).

In addition, was the ceiling of the Ounas' pyramid (dating from one century after the one of Gizeh) also obtained by moulding? Is the feature displayed on Fig. 11 not a new piece of evidence?

8. Conclusions

Among all proposals dealing with the method of construction of the great pyramids at Giza, Joseph Davidovits' method suggesting the use of the agglomeration technique with limestone aggregates that were extracted very close to the construction site, is by far the most plausible. On the basis of selected texts, illustrations and physical and geographic facts, we have shown that the construction with blocks that were extracted, hewn and transported was an impossible task, whereas the method of moulding blocks explains the entire procedure.

Measurements by PIGE (F, Na, Mg, Al, Si), PIXE (Ca, Sr, As and other elements) and NMR (Al²⁷ and Si²⁹ present in non natural but man made ingredients) give first scientific evidences for this proposal.

We also provide a model describing how moulds could have been assembled and used for the production of individual blocks. The transport of materials in small quantities poured on the place where the mixture rapidly solidifies. We propose some simple tests to continue this investigation, which could be undertaken by a multidisciplinary team, in order to put an end to the various speculations and debates around the "Mystery of the Pyramids".

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Appendix A

We have also to refer to writings on Hieroglyphs and in particular to the "Famine Stele" discovered in the region of Elephantine in 1889 by Charles Wilbour [1]. One part of this inscription refers to the importance of the god Khnum: the god of potters and to the universal knowledge in sciences of Imhotep who was the architect of the Pharao Djeser whose reign dates one century before the one of Cheops.

Let us reproduce here one part of the translation of the content of this Famine Stele (the origin of this name refers to the largest part of the description of the role of Djeser in the solution of wide famine periods in Ancient Egypt) and having reference to the role of Khnum to initiate the construction of huge monuments.

On the east side (of Elephantine) are numerous mountains containing all of the ores, all the crushed (disaggregated) stones (aggregates) suitable for agglomeration, all of the products people are seeking for building the temples of the gods of the north and south, the stables for the sacred animals, the pyramid of the king, and the statues to be erected in the temples and the sanctuaries. Moreover, all of these chemical products are in front of

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Khnum and surrounding him... In the middle of the river is a wonderful place where on both sides people are processing the ores, ... learn the names of the gods which are in the temple of Khnum, ... Learn the names of the stone materials which are to be found eastward, upstream of Elephantine: *bekhen, mtay* (weathered granite), *mhtbtb, regs, hedsh* (disaggregated onion stone), ... *prdn,* ... teshi (disaggregated stone) ... Learn the names of the rare ores located in the quarries upstream: gold, silver, copper, iron, lapis lazuli, turquoise, chrysocolla, red jasper, *ka-y* (radish stone), *mnu, esmerald, tem-ikr* (garlic stone), and also *neshmnet, ta-mehy, heaget, ibehet, bekes-ankh*, green makup (malachite), black antimony and red ochre...

The onion stone (hedsh) and the garlic stone (tem-ikr) are to be related to the description of Herodotus. Chemical signature of this garlic stone (probably scorodite) is to be found in the identification of arsenic by PIXE (see Fig. 5) in the coating of the small fragment of Fig. 4(b).

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