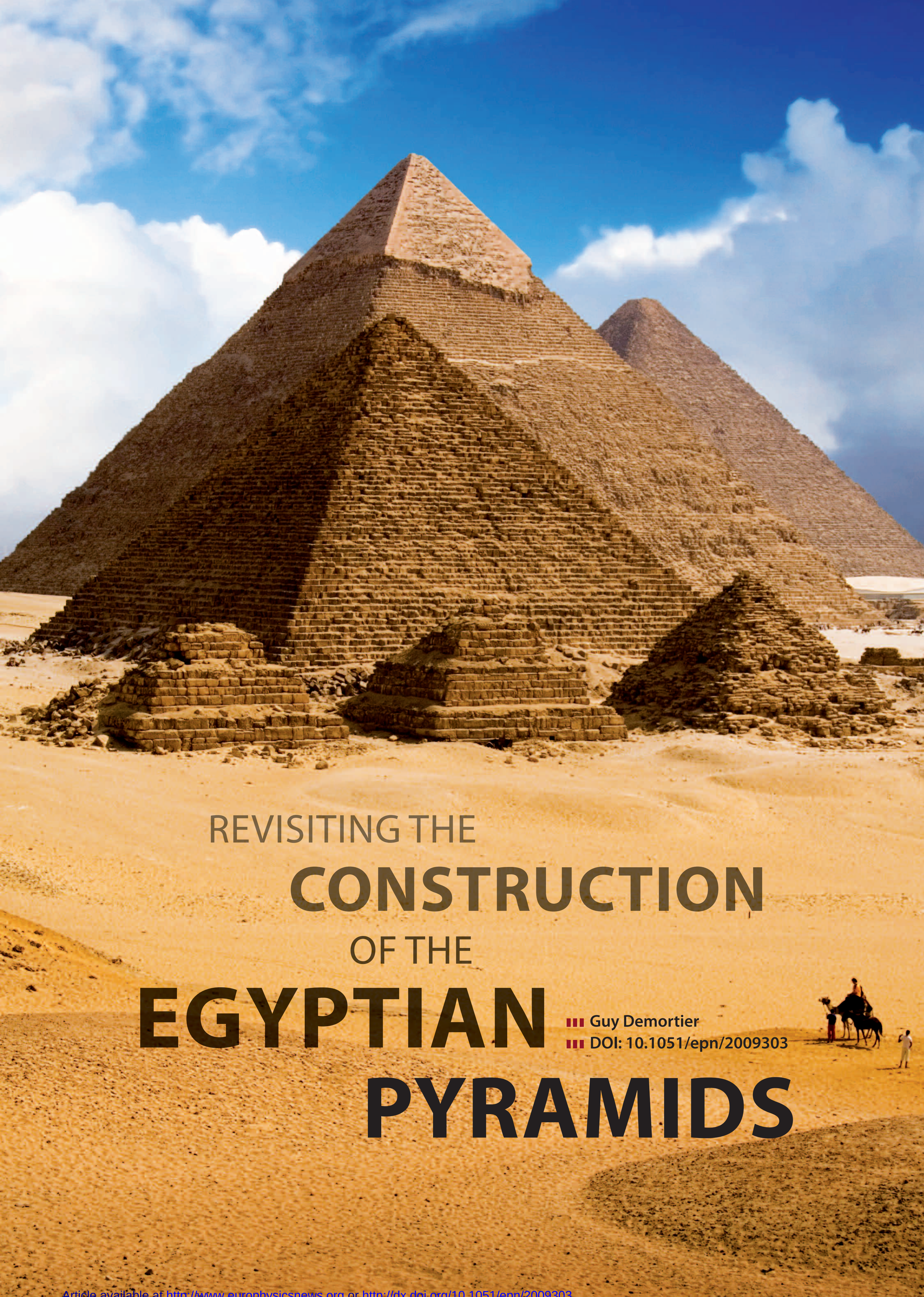

REVISITING THE CONSTRUCTION OF THE EGYPTIAN PYRAMIDS

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The Kufu pyramid, with a volume of 2,7 10^6 m^3, was completed over a period of 20 to 30 years. From this one can estimate a daily rhythm of 300 to 400 blocks, each having an average volume of 1 m^3. This means one block put at the right place every 2 minutes. To achieve this goal, 1 m^2 of block face would have to be hewn every 20 seconds! What a performance, with tools made of stone or with soft copper! The construction of the pyramid of Kufu took 2,5 10^{12} J. In other words, 1m^3 of material was to be lifted up by 1m every 3 seconds! This assumes an efficiency of 100% (but who would guarantee that every small lift was never repeated?). Hoisting huge blocks of more than two tons with rudimentary means at this rate, even with 1200 teams of 15 men working simultaneously on 1200 blocks at the 60 000 m^2 surface of the monument, is an impossible task. Remember that wheels and pulleys did not exist at the time.

When looking (fig. 1a) at the vertical faces of the blocks visible today (but initially underlying the casing blocks which were totally removed), one sees irregularities in the shapes but a remarkable close fit. It is surprising that these blocks have been so "poorly cut" but are so perfectly joined. This close fit would have been more easily achieved if the blocks had been hewn with perfect parallelepipedal shape! Furthermore, great precision in this juxtaposition seems useless because these blocks were originally hidden under the casing anyway. The blocks also appear more porous at their top part than at their bottom, but this feature cannot be explained by some erosion of natural limestone. Surprisingly, when the Kufu pyramid is seen from the air (especially from a helicopter which blew the dust when flying close to the top of the pyramid- fig. 1b), one clearly sees that the horizontal surfaces of the blocks are flat. Presently, casing blocks are only present at the top of the Kafra pyramid (fig. 2).

In many books on Ancient Egypt, no distinction is made between techniques used in the Ancient Kingdoms (4500 years B.P) and the New Kingdoms (3000 years BP). During the New Kingdom and later, big monuments were made with moderate-size stones kept close to each other by dovetails (fig. 3). Nothing similar is visible on the pyramids. Compared with the 147 m of the Kufu pyramid, the height of the monuments of the New Kingdom does not exceed 20 m. We have calculated that the construction of the pyramid would have required 20 times more work than the Ramesseum (built 1200 years later). The Ramesseum and the Kufu pyramid cover the same surface at ground level, and thus they would require the same number of workers to make the comparison pertinent. Considering that the works on monuments at different periods are so different and that the structures of the block assembly are very different, we conclude that the materials could be also different.

In 1978, the French chemist Joseph Davidovits rejected the generally accepted technique of carving and hoisting stones. He proposed that the building method involved the moulding on site: blocks were made of a kind of concrete whose basic binding compound was natron: a sodium carbonate extracted very close to the site of Giza. The binder was obtained by some chemical reaction leading to a geopolymer (a name given by Davidovits). It is a poly-sialate containing an alkaline nucleus: sodium from natron. Natron, lime and water form caustic soda, which reacts with aluminous limestone to yield the basic geopolymer [1].

▼ **FIG. 1a:** Irregular vertical faces of the blocks of the Kufu pyramid

▶ **FIG. 1b:** Flat horizontal faces of the blocks of the Kufu pyramid

Ion beam Analysis of the material

X-ray fluorescence and X-ray diffraction [1] have shown that the blocks consist of limestone (85 to 92%) associated with a binder. Additional analyses were performed by PIXE (Particle-Induced X-ray Emission), PIGE (Particle-Induced gamma-ray Emission) and by NMR-Spectroscopy for structural characterization [2] in laboratories of Namur and Lecce. One of the pyramid's samples appeared to be made of a central compact structure embedded in a material of different composition. The central part is identified as natural limestone but the outer part contains a large amount of F, Na, Mg, Al, Si. The concentration ratios in the binder relative to the core are 7,5 for F, 8,5 for Na, 12 for Mg, 2 for Al and 21 for Si. Furthermore, a significant signal of As in the outer part may be attributed to some additional ore which could be scorodite. This mineral ore containing arsenic was 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. Recent measurements at the Tandetron of the University of Lecce on a large number of samples confirm the previous results and, for several samples, a very high content of P, S and/or Cl (up to 10%). The high concentrations of Na P, S and Cl are attributed to the use of natron and the presence of Mg, Al and Si to the use of the Nile alluvium to obtain the binding medium.

We have also fabricated the binder based on the geopolymer formula. 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 chemically highly basic (pH = 10 - 11). The NMR spectra of several samples of Kufu pyramid indicate that the tetrahedral Al content is 10-15% of that obtained for the pure synthetic mixture. Si-NMR leads to the same conclusion. This binder exhibits a very fine adherence with small gravels.

More recently, Barsoum, Ganguly and Hug [3] compared a number of pyramid samples with six different limestone samples from quarries of their vicinity. The pyramid samples contain micro-constituents with appreciable amounts of Si in combination with Ca and Mg, in ratios that do not exist in any of the potential limestone sources. The intimate proximity of the micro-constituents suggests that, at some time, these elements had been together in a solution. Furthermore, between the natural limestone aggregates, the micro-constituents (with chemistries reminiscent of calcite and dolomite which are not known to hydrate in nature) were hydrated in the pyramid samples. The ubiquity of Si and the presence of submicron silica-based spheres strongly suggest that the solution was basic. Transmission electron microscope confirmed that some of these Si-containing micro-constituents were either amorphous or nano-crystalline, which is consistent with a rapid precipitation reaction.

▲ **FIG. 2:** Casing blocks at the top of the Kafra pyramid

Many additional arguments are in favour of a mode of construction based on agglomeration. These include: **(a)** the chaotic organisation of shells in the blocks, with respect to their parallel alignment in natural stones in the quarries around Giza, **(b)** the high water content measured by the transmission of electromagnetic waves, **(c)** traces of mortar, mostly at the base of the blocks.

The walls of narrow channels, with a cross section of 20 cm x 20 cm, starting from the Queen's chamber and investigated by R.Gantenblink's robot [4], clearly indicate that they were not carved: There is no gap between the walls and the ceiling of this conduit, and there are no protrusions in the walls and the ceiling. The only irregularities have a hollow (concave) shape. A carving procedure would have given both convex and concave irregularities in equal amounts. When thinking about a moulding procedure, the apparent cavities could be understood by some loss of material during the de-moulding.

1 m^3 of block material would have to be **lifted up** by **1m** every **3 seconds!**

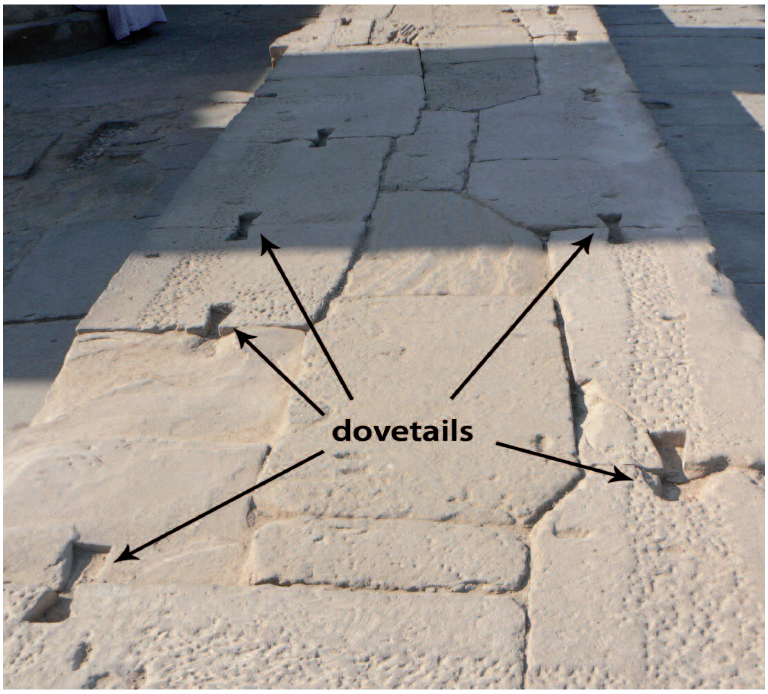
Manpower for the construction of the pyramid

The moulds could have been made of grooved small boards fitting into one another (fig. 4). These 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 of the blocks of the Kafra pyramid as reported by Davidovits [1]. The irregularity on the blocks in the Kufu pyramid would be due to possible "accidents" during the removing of the planks of the mould after the solidification of the liquid binder. We could imagine that these 'accidents' in de-moulding were intentional, to favour the link between the adjacent blocks with no need of dovetails. The height of a single block depends on the height of the shortest plank of the mould. The upper surfaces of the blocks are flat, as can be seen in fig. 1b. The modular width of the blocks depends on the number of small planks constituting the board.

The solid ingredients, brought in bow nets, were poured into the mould that had been made waterproof by the application of a mortar to waterproof the base of the mould. Instead of having teams pulling blocks weighing several tons, the workers transported the ingredients by small loads (25 kg) not requiring wide ramps. These hypothetical ramps would have badly supported the extensive heavy carriages during more than twenty years at a rate of 300 to 400 huge blocks per day. With the moulding technique, workers saved their energy by only bringing loads upwards, passing them from man to man on successive pyramid levels, without having to climb the monument. Thus, lifting the ingredients could be achieved with an optimal efficiency. By contrast, in the case of heavy hewn blocks the efficiency would have been extremely low, due to the necessary up and down movements when manipulating heavy charges. In addition, the fabrication of (static) moulds requires much less wood than the fabrication of (moving) hard sledges. Indeed, wood is rare in Egypt.

To complete the whole construction in 25-30 years, six workers would transport 1 m^3 of small pieces of limestone each day from the quarries to the building site; one worker would lift 40 kg of ingredients every minute (limestone rubble, water, binder) to the height of one single step (1m or less), two workers were dedicated to the supervision of each mould and kneading during the pouring of ingredients. No more than 2300 workers would be present simultaneously on the surface of the pyramid. The distribution of the manpower is illustrated in fig. 5 [2].

▼ FIG. 3: Dovetails on external blocks of monuments of New Kingdom



The procedure was described in ancient reports.

Herodotus (V^{th} century B.C.) 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 were raised by means of machines fabricated with ***short*** *wooden pieces…* ***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…"*

This description supports the following explanations:

a) Short wooden pieces cannot be associated with long beams of levers necessary for the lifting, but could be the planks of the mould,

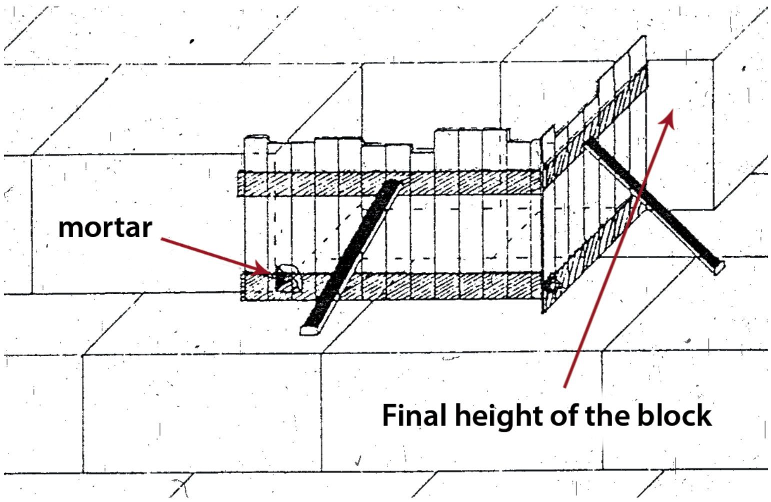
b) The completion of the pyramid began with the installation of the **facing blocks at the summit**. In order to make sure he would be well understood, Herodotus adds in the next sentence that the builders continue on the following floor, downwards, to end with the one that touches the ground. These facing blocks are still present today at the top of Kafra's pyramid (fig. 2) and they hold firmly together even after more than four millennia. They have obviously 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 for the building and not for food. In the sentence which closely follows this statement, Herodotus argues about the supplementary cost for food, tools and clothes. Garlic and onion, then, must have a direct link with ingredients occurring in the manufacture of blocks.

According to J. Davidovits two of the three ingredients appear in the text of the Famine Stele, dedicated to Pharaoh Djezer and its architect Imhotep [1]: "hedsh" (disaggregated stone smelling like **onion**) and "tem-ikr" (mineral containing arsenic identified by our PIXE measurements) which has the characteristic smell of **garlic**.

Recent and future investigations

On April 2, 2008, an announcement appeared in the Boston Globe to prove once again that the cement pyramid theory is not going away. Linn Hobbs (professor of materials and nuclear sciences at MIT) and his students have tested the theory by making a "Mini Great Pyramid". **"In fact, the very idea has been so controversial that you can't get research funding, and it's difficult to get a paper through peer review"**. Building a small-scale model of the pyramid using the materials and methods the Egyptians may have used is far more than just an educational exercise for the students. "Like any other investigation of ancient technologies, you can only get so far by speculating, and even only so far by looking at evidence. To go the rest of the way, you have to do the thing yourself. You have to get acquainted with the materials." says Linn Hobbs.



▲ **FIG. 4:** Mould model

The enigma is certainly not completely solved and our next investigations would include: (**a**) dating of straw in mortars by C^{14} accelerator mass-spectrometry, (**b**) comparison of plants growing on the pyramid and in quarries: differences would appear if some basic ingredient is used for the moulding, (**c**) investigation of the differences between the perfectly preserved blocks of the edges of the casing blocs of the pyramid of Kafra and the more damaged ones in the central part… if we have some opportunity to obtain the required material. ■

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▼ **FIG. 5:** Step on pyramid