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The surprising truth behind the construction of the Great Pyramids

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February 17, 2009

Abstract

How the Great Pyramids of Giza were built has remained a mystery. The seminar deals with the hypothesis that some parts of the pyramids were cast *in situ* using granular limestone aggregate and an alkali alumino-silicate based binder [1]. The hard evidence for this idea is provided by comparing limestone samples from pyramids and samples from nearby sites using scanning and transmission electron microscopy. The pyramid samples contain microconstituents with significant amounts of Si in combination with elements, such as Ca and Mg, in ratios that do not exist in any of the potential limestone sources. The microscopic structure of the pyramid samples also suggests that the material from parts of pyramids is a man made precipitate rather than natural stone.

Contents

1 Introduction

How the Great Pyramids of Egypt were built has remained an enduring mistery. Attempts to fit the historical and physical evidence into a coherent whole have all failed. The prevailing model of construction is one in which blocks of limestone were cut in local quarries, cut to shape using copper tools, transported to the pyramid site and then hauled up ramps and put in place using wedges and levers. This "carve and hoist" hypothesis, based on accepted models of Egyptian life of the time, has a number of problems, biggest of those are:

1. Khufu's pyramid contains about 2.3 million blocks, averaging 2.5 tons each, with average dimensions of $1.3\text{m}\times1.3\text{m}\times0.7\text{m}$. Some of these blocks are placed in tiers whose edges closely conform to the pyramidal envelope, although the tiers vary from 0.5m to 1.25m in thickness with abrupt changes in the thickness of proximate tiers, which implies high precision surveying, management and craftsmanship in forming and placing these massive blocks.

(a)

(b)

Figure 1: (a) Edge of a gash in pyramid, made with gunpowder in 19th century by an overly eager explorer. The outer casing blocks mach perfectly, implying they were cast while core blocks appear carved. (b) Seam between two outer casing blocks. The seam is neither straight nor smooth yet the two neighbouring blocks fit perfectly. (picture taken from [9])

2. Casing blocks which covered the pyramids closely correspond with each others shape on all contact surfaces. The currently remaining casing and backing blocks fit as close as 0.05mm across their entire adjacent vertical faces in some areas as well as their flat outer surfaces' angle to produce the precise outer slope of the pyramid. The backing stones were frequently shaped to fit exactly to the shape of the rear face of the casing block This would make the work on pyramid with just the cut stones practically impossible with technology of that time. Even more unnecessary considering the fact that those areas would be covered for eternity and that the construction of the pyramids needed to be reasonably fast to be finished before the pharaoh died.

In the 1980's, Davidovits [2] proposed an alternative theory. This theory proposes that the pyramid blocks were cast *in situ*, with a wet mix of limestone particles and a binder put into molds, which in time hardened into concrete with the macroscopic appearance and properties of native limestone. According to Davidovits, the concrete is made by mixing kaolinitic (clay-like) limestone with lime, plant/wood ash and water. The water separates the clay from the limestone and the basic solution, resulting from the lime/ash dissolves the alumino-silicates. With time the alumino-silicates react with the alkali hydroxide to form sodium/potassium poly-silico-oxo-aluminates which function as a binder.
The egyptologists agree that while the main bulk of pyramid core blocks were made from Giza limestone, the outer and inner casings were made from a much finer grained limestone. The comparison of casing samples with samples from different sites in the vicinity of the pyramids showed that the casing samples are distinct enough from samples from nearby sites to rule out the possibility that the casing stones originated from there.

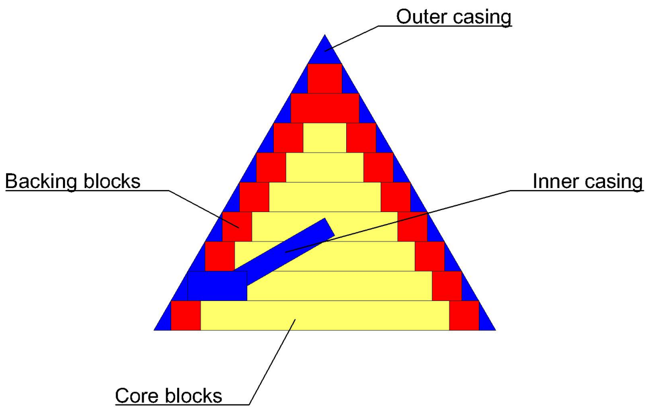

Figure 2: Pyramid schematic: Inner and outer casing is not natural limestone i.e. they must have been cast. Backing blocks were probably cast while core blocks were not.

2 Experimental procedure

In total, 11 samples from 8 areas were analyzed, namely

- Outer casing of Khufu Pyramid
- Inner casing of Khufu Pyramid
- Several sites with natural limestone in the vicinity of the pyramids

The samples were cut in thin slices and polished, which is a standard procedure in analyzing materials. The use of water was avoided to prevent the solution and/or reprecipitation of water soluble salts. The micrographs had a thin coating sputtered onto their surfaces to make them more conductive and prevent charging. The samples were then observed using scanning and transmission electron microscopy. Most observations were of internal surfaces, free of external contamination.

3 Research methods in materials science

3.1 Electron microscopy

An electron microscope is a type of microscope that uses electrons to illuminate the specimen and create an enlarged image. All microscopes have resolution limit due to the wavelength of particles they use. For example, optical microscopes use visible light with wavelengths between 400 and 700nm. The best resolving powers of high quality microscopes are thus about 200 nanometers. The electron microscopes use electrons with energies of few thousand eV. For example, electron with energy of 3600 eV has a (relativistic) wavelength

$$\lambda_e \approx \frac{h}{\sqrt{2m_0E(1+\frac{E}{2m_0c^2})}} = 0.02nm$$

which would theoretically result in resolution of 0.01nm. However, construction details decrease resolution of the microscope, which reduces resolving power of a standard electron microscope to about 1 nm. [3]

3.1.1 Scanning electron microscopy (SEM)

Scanning electron microscopy is a type of electron microscopy which utilizes a beam of high energy electrons to image the sample surface. The electrons interact with atoms in the sample, producing signals that contain information about the sample surface topography, composition and other properties. Structure of a scanning electron microscope is shown in figure 3:

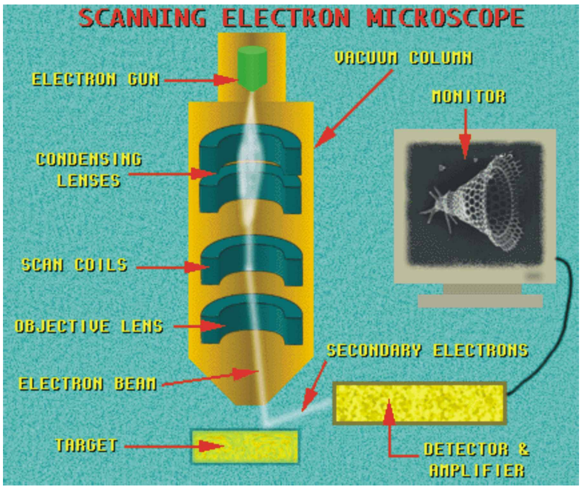

Figure 3: Scanning electron microscope (picture taken from [4])

The electron gun thermionically emits electrons with energies up to 40 keV. The electrons are focused by condenser lenses to a spot about 0.4nm to 5nm in diameter. This primary beam then passes through scan coils, which deflect the beam so that it scans in a raster fashion over the area of sample surface. When the primary electron beam interacts with the sample, the electrons lose energy by random scattering and absorption in specimen, extending from about 100nm to 5μm into the sample. This depth depends on the electron energy, the atomic number of the specimen and the density of the specimen. The energy exchange between the electrons and sample results in the reflection of electrons by elastic scattering, emission of secondary electrons by inelastic scattering and the emission of electromagnetic radiation. Each of those can be detected by specialized detectors. Particularly significant to sample analysis in our case were the backscattered electrons, providing composition data on samples. Also important are electrons reflected by elastic scattering, which provide data on the topography of the samples. [4]

3.1.2 Transmission electron microscopy (TEM)

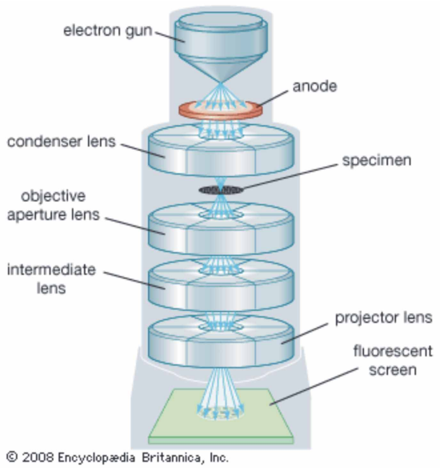

Figure 4: Transmission electron microscope (picture taken from [11])

Transmission electron microscopy is a type of electron microscopy where the electron beam is transmitted through an ultra thin specimen, interacting with specimen as they pass through. Simply put, the transmission electron microscopy operates on the same basic principles as the light microscope but uses electrons instead of light. At high resolutions, however, one must also consider the diffraction, which can provide us with a tool to analyze the crystalline structure of the specimen. [5]

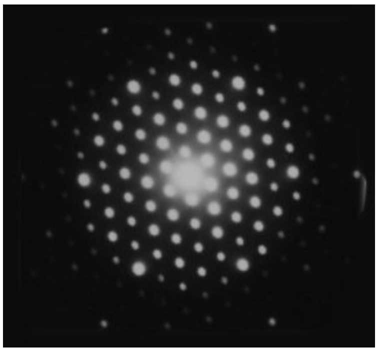

Figure 5: Typical diffraction pattern of a crystalline specimen (picture taken from [12])

3.2 Other methods

It is worth noting that materials research employs several other techniques that do not include electron microscopy. The materials can be tested for their mechanical properties (elastic and shear modulus, Poission's ratio etc.) thermal properties, electrical and magnetic properties etc. Common materials research techniques also include resonance (nuclear magnetic resonance, information on atomic and chemical structure of materials), X-rays (X-ray spectroscopy - information on elemental composition, X-ray scattering - information on microstructure), ion beams (elemental composition, impurity distribution, analysis of trace elements, high sensitivity measurements of light elements) and others. Unfortunately, in-depth explanation of these methods is beyond the scope of this seminar. [5, 6, 7, 8]

4 Results

4.1 SEM

(A) Natural Stone: In all natural samples, microstructural analysis in the SEM indicated that the predominant phase was a porous calcite ($CaCO_3$) that contained halite (mineral form of NaCl), silica, that is, a phase wherein the O/Si ratio was 2:1 and the concentration of every other element was $<0.05\%$. All samples also contained an organic substance, rich in C and O, found in various shapes, mostly at grain boundaries This substance was also found in the form of a thin coating that covered many of the phases identified in the natural limestone, such as calcite, halite and $CaCl_2$.
In short: all samples of natural stone contained calcite, silica, halite, an organic substance plus some smaller amounts of other impurities, all in irregular structures, which is a typical limestone structure.

(B) Outer Casing: In the outer casing microstructure, at least six different microconstituents and/or phases, labeled M, G, D, T, Q and O were identified. Region Q is most likely calcite, region O is reminiscent of the organic phases observed in the natural limestone. Region D is most likely dolomite. Higher magnification SEM micrographs of region M (Figs. 3 (b) and (c)) indicate a complex microstructure. In many locations, small rhomboedric crystals roughly 2 μm in diameter are visible. Based on their morphology it is reasonable to assume the cubes are single crystals. The chemistry of these particles shows they contain Si, apparently in solid solution in dolomite (region D). The importance of this observation is that Si is not known to dissolve in dolomite in nature. The most intriguing, however, is the region T. This thin strip contains very little Ca, is mostly considerably hydrated (lot of OH groups) and is not known to exist in calcite naturally.

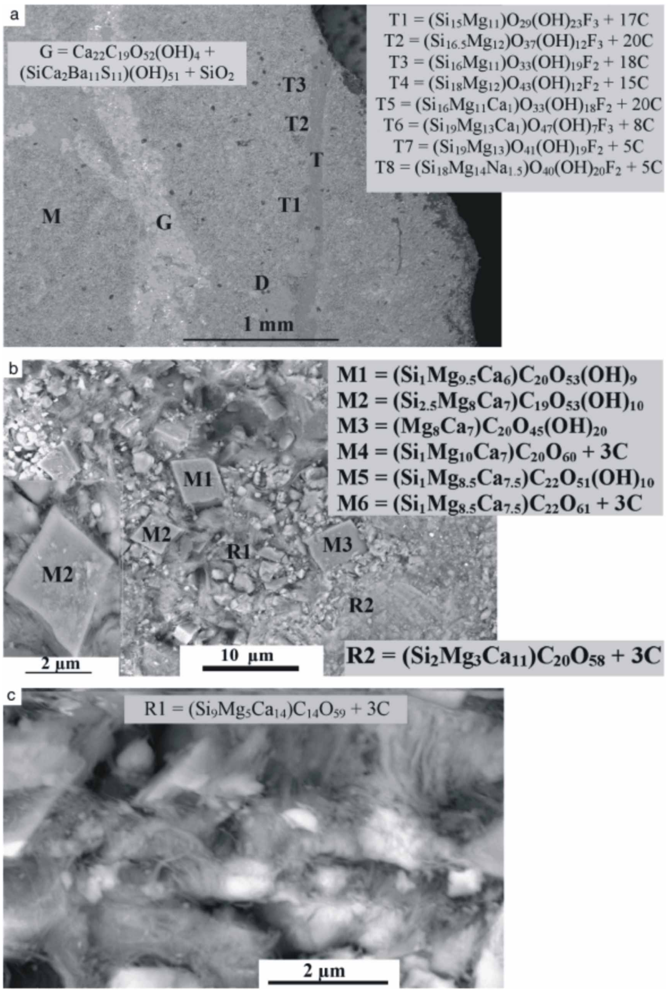

Figure 6: Backscattered scanning electron microscopy micrographs of outer casing sample at low magnification (a), higher magnification of region M showing small cuboid particles (b) even higher magnification of region R1 (c). Structure in (b) and (c) is very complex and unlike natural stone. (picture taken from [9])

	Ca	Mg	Si	Al	O	C
1	5	8	36	2	25	25
2	8	20	28	2	41	1
3	2	11	18	0.0	54	15
4	<1.0	27	61	2	8.5	2

Table 1: Elemental analysis of outer casing samples. The analysis reveals that , in addition to well crystallized calcite and dolomite regions, regions containing Mg, Si, O and sometimes Ca were also found. [1]

(C) Inner Casing: The microstructure of the inner casing is characterized by a matrix phase and two distinct microconstituents. The matrix phase is comprised of exceptionally pure $CaCO_3$, while the microconstituents include a great deal of S and Si and lack C and Ca at the same time. Figure 7 shows micrograph of a region of inner casing sample together with elemental maps of the region. The regions containing Ca are clearly visible, surrounded by regions rich in S and Si, but poor in Ca.

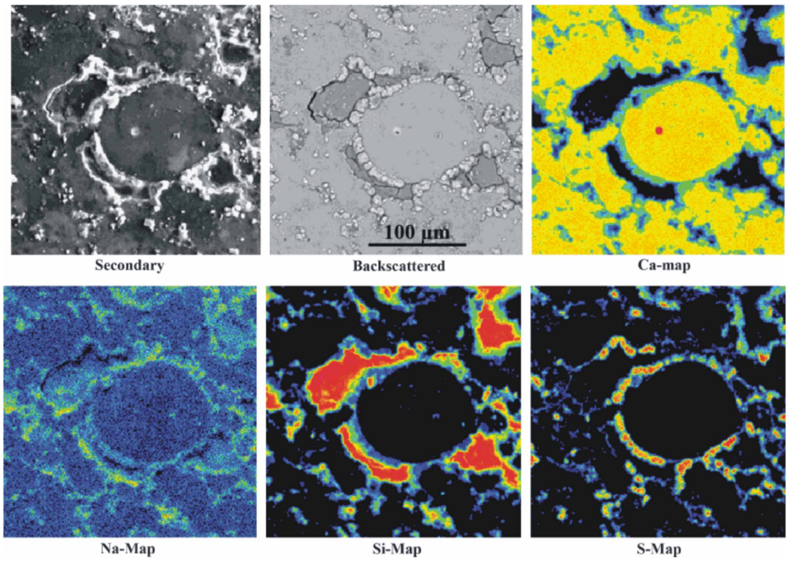

Figure 7: Scanning electron microscopy micrographs and elemental maps of bulk of inner casing sample showing (a) secondary and (b) backscattered images, rest of images represent elemental maps. (picture taken from [9])

	1	2	3	4	5	6	7	8	9	10	11
C	2.5	6.3	2.5	2.3	4.2	4.2	2.9	19.4	20.6	3.7	3.6
O	65.8	65.3	64.8	62.8	69.8	61.4	65.4	60.5	58.7	63.6	64.5
Na	1.4	0.7	1.4	1.0	0.8	1.1	1.4	0.3	0.6	0.9	0.9
Si	2.4	2.9	2.4	7.9	8.1	3.4	6.3	0.5	0.2	31.0	29.3
P	0.9	0.6	0.9	0.8	0.7	1.1	0.9	0.4	0.4	0.3	0.6
S	14.2	13.0	14.2	12.5	8.6	14.7	12.0	0.3	0.3	0.3	0.5
Ca	13.9	11.2	13.9	12.7	7.7	14.0	11.1	18.9	19.0	0.1	0.2

Table 2: Elemental analysis of inner casing samples regions, similar to those in Fig. 7. In addition to areas with 1:2 ratio of Si:O (columns 10 and 11, areas with almost pure SiO_2) and areas with Ca:C:O ratio of 1:1:3 (calcite $CaCO_3$ region, columns 8 and 9), both areas containing almost no other elements, there are also regions with abundance of S, Si, Na and P (columns 1-7) [1]

4.2 TEM

The TEM scans have shown that the outer casing samples were either amorphic or nanocrystalline, which corresponds to relatively rapid precipitation.

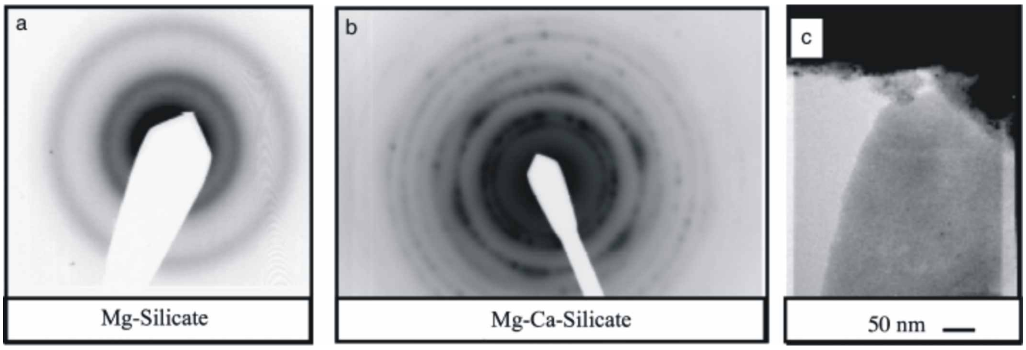

Figure 8: Selected area diffraction of select outer casing samples confirming that they were either amorphous (a) or nanocrystalline (b), (c) shows TEM micrograph of a typical region examined (picture taken from [1])

5 Discussion

5.1 Ubiquity of Si between calcite particles

According to Davidovits, the pyramid blocks are made of calcite aggregates held together with a silica based binding phase. If this theory is correct, Si should be ubiquitous in the "grain boundary" areas, i.e., the areas between the calcite and other aggregates. Based on data, the ubiquity of Si is clear, it was found in T, M and R regions in outer casing samples, and together with S and Ca or P in the inner casing sample. Most of these regions also appear to be hydrated to some extent. As Si is a common geologic element, it is not surprising that it is found everywhere, but its presence in combination with elements and structures that have not been yet observed in nature certainly is. This implies the pyramid material to be aggregate with silica binding phase. However, probably the most compelling evidence that Si is in solid solution in calcite or dolomite are the small cuboid precipitates shown in Fig. 3 (b). From their size and morphology, it is quite clear they are single phase, i.e., with Si in solid solution.

5.2 Presence of moisture

Most of the casing samples appear to be hydrated. However, it is important to emphasize again that neither calcite nor dolomite is known to form hydrates in nature, and that only the "calcite" in the grain boundary areas is hydrated, neither the aggregates in the samples nor the natural limestones contained any water of hydration. In short, the only part of the blocks that was hydrated was the binding material. Supporting the hydration is the fact that when the Great Pyramid was opened in 820 AD, the interior chambers were reported to be encrusted with salt, which is consistent with damp and porous rock. Even today, the pyramids are not dry. For example, the electromagnetic sounder experiment of 1974, intending to map the interior of the pyramids, failed because of high moisture of the pyramid stone. A simple explanation would be that various ions found in the microconstituents were at some time present in solution and precipitated or reacted together relatively fast to form the glue necessary to fabricate the synthetic stone. In this scheme, some of the added water would end up bound in the stone as observed. Under such conditions, the resulting microconstituents would tend to be amorphous and/or nanocrystalline, which corresponds with TEM observations.

5.3 "Common sense" evidence

Careful examination of the visible pyramid blocks on the Giza plateau suggests that most, especially in the core, have been carved. Some, near the surface, including the casing, appear to be cast.

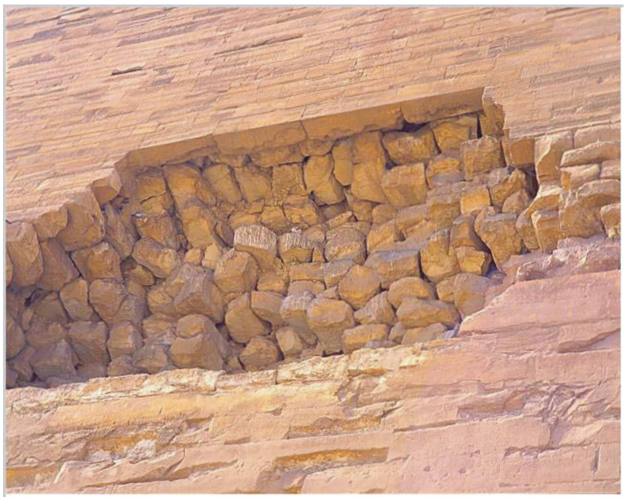

Figure 9: Gash in Snefru Pyramid. Snefru Pyramid was built few years before the Great Pyramid probably utilizing same construction techniques.In this picture you can clearly see the (rough) carved interior and smooth outer casing (picture taken from [9])

6 Conclusion

The simplest explanation for the presence of many different microconstituents, some of which appear to possess chemical compositions and morphologies not found in the natural stone, is that the various ions were in solution and precipitated relatively fast. This makes a very impressive implication that the blocks from pyramids were created by ancient egyptians and have endured through millenia, while the best concrete that our civilization is currently capable to produce, only lasts for about 150 years. Apparently the ancient egyptians were much better at materials science and chemistry as was theorized before. Supporting this theory is the recent casting of blocks closely resembling the ones in pyramids [10]

However, one of this seminar's primary intentions was also to illustrate how far physics can reach in helping provide scientists in material science with tools for their analysis, who, when equipped with such tools can in turn help archeologists uncover some more fascinating data about our past.

Furthermore, results acquired in the research of the pyramidal material could lead us to making concrete that is much more durable than the best known concrete while reducing the pollution from the production by as much as 90%.[10]

References

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