Application of Building Stone in the Old Kingdom of Ancient Egypt as an Indicator of Changes in Knowledge

Agnese Kukela[1], Valdis Seglins[2], [1-2]*University of Latvia*

Abstract. **The study investigates the construction stages, materials and binder used in the Step Pyramid of Djoser to determine its current state of preservation. This research has allowed identifying 5 different building stone selection stages, marking the development of knowledge on construction materials and their properties. This pyramid is exposed to deterioration processes threatening stability of the structure. Unconsidered restoration strategy just aggravates the situation, but this study would assist in elaboration of appropriate conservation measures.**

Key words: **stone material, stone processing, indicators of knowledge, Ancient Egypt**

I. Introduction

The Old Kingdom of Ancient Egypt (ca. 2686-2160 BC) is notable as a time of rapid changes in the society and also in the building. The skills and knowledge obtained during the Predynastic period regarding the building of complex and multi-level underground tombs were decreasing, yet familiarity with rocks, their properties and treatment features was rather high; moreover, the tools necessary had already been developed. During this period the adobe material production and building abilities improved and starting from the 2nd Dynasty individual construction elements (door openings, columns, flour slabs) were produced of stone. At the beginning of the 3rd Dynasty grand flat-mound tombs (mastabas) were being built reaching 35 000 cu.m in construction volume. The building stone was rarely used, whereas gypsum and adobe plaster of various compositions were applied frequently.

In the architecture of Ancient Egypt mortar mainly fulfilled two functions. It was used as a binding material between the stone blocks and as a sliding material to reduce friction of heavy blocks being put in the position [1]. But, since the quality of shaping of building blocks and their positioning, especially in the body of the structures, was rather low, the mortar, along with a mixture of small pieces of stone was also used to fill the gaps between the blocks.

The use of gypsum mortar is known from the times of the 2nd Dynasty. It mainly consisted of burned gypsum and sand, frequently with chipped limestone. Yet, quality of such plaster was rather low. Moreover, the quality of novel materials used as a binder is even lower and it can be easily distinguished also nowadays.

At the end of the 3rd Dynasty, the time linked with the reign of king Djoser, numerous innovations had been introduced. These innovations concerned large-scale application of building stone and binder of far better quality, and they resulted in construction of previously unthinkable structures. In this sense, the Step Pyramid of Djoser is a unique structure and provides evidence for numerous attempts to implement innovations concerning geological knowledge on building stone available and its properties, binder and its variations for different purposes, thus marking an extremely important stage in the initial development of the silicate chemistry. Furthermore, it also concerns the areas of planning, development of building constructions, engineering calculations, etc. The experiments and innovations promoted rapid diversification of building material. Such improved knowledge was successfully applied to developing the world's major stone construction project – the complex of pyramids at Giza.

II. Geological Structure and Environmental Conditions of the Territory

The Saqqara plateau is situated about 40 km southeast of Cairo on the left bank of the river Nile and rises for 17 – 25 m above modern flood terrace of the river. Starting from the Early Dynastic times this plateau was used as a necropolis which served as such for about 3 thousand years. The tombs were built as underground structures, as well as mastabas and pyramids, their combination and as simple Coptic cemeteries. Nowadays, these are outskirts of the desert with active movement of sand, requiring regular care and maintenance of the monuments located on the plateau. The climate is very dry; rainless period may last for several years, whereas sand storms are very frequent, thus intensifying the deterioration of the monuments.

The Saqqara plateau is formed by middle and late Miocene Mokkatam Formation (separate lower part of Maadi group) as layered and rhythmic lime rocks at shallow sea conditions. The lower part of the rhythm consists of 30 – 50 cm thick massive sandy limestone layer, covered by 10 – 15 cm thick lime marl. These layers are overlaid by up to 10 cm thick layer of marl and argillite. The next rhythm basement layer is sandy limestone or sandstone with carbonate cement, which is not always marked clearly and is followed by less sandy and massive limestone. At the upper section the proportions of layers change and clayey rocks prevail. At the top of rhythm the proportion of the limestone and marl/argillite reaches almost 1:1. The thickness of rhythms is not constant and variations are observed from 0.7 – 1.2 m up to 4 – 5 m.

Sometimes local depressions are visible, where the thickness of clayey rock layer reaches several meters. The general tendency marks the increase in clayey layers thickness towards the south, but to the north these rocks have considerable amount of gypsum. Aforementioned grey and yellowish grey layers of sandy limestone are the main building materials in this area used in construction of the necropolis, and the upper part of the geological section at some parts is exposed to the stem escarpments of the plateau.

The Saqqara plateau is located in the seismically active area, where earthquakes with magnitude of about 4.0 happen yearly. As a result, massive limestone layers are cracked forming a peculiar structure of blocks measuring approximately 0.30 – 0.40 m (Fig. 1).

Fig. 1. Exposed fragment of geological section of Saqqara plateau

Larger intact natural limestone blocks are of rare occurrence. Seismic activities affect the monuments located on the plateau and result in loss of the stability of their structure.

III. Materials and Methods

The study was conducted in the Step Pyramid complex that encompasses several temples, the pyramid and its complicated underground system of galleries and passages embracing the area of 15 ha constructed just in 20 years. The pyramid was built in several stages, gradually progressing from initial square mastaba until forming a four-step pyramid and later a six-step pyramid of rectangular base as it is currently exposed (Fig. 2). This funerary complex has been robbed, rebuilt and reconstructed already starting from antiquity times. Therefore, it is hard to identify the time of particular construction or restoration. In the search for cheep building materials, the construction and finishing materials of the pyramid's complex were stolen; temples and subsidiary buildings were partially ruined.

Therefore, starting from the year 2005 our study was mainly focused on the investigation of the Djoser's pyramid, which was rebuilt to a lesser extent.

The pyramid is not available for any kind of direct studies. This caused limitations for choosing the research methods and possibilities for instrumental and analytic evaluation of many characteristic values.

For this reason, several sets of photographic documentation of the pyramid's facades and fragmentary verification of the data obtained applying non-destructive methods on site were used as a main source of information.

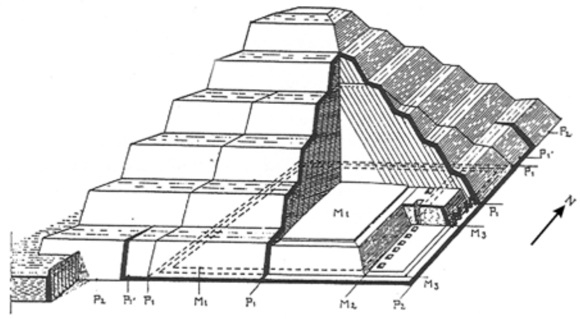

Fig. 2. Schematic representation of stages in building the Step Pyramid [2]. M1, M2, M3 – initial mastaba rebuilding stages; P1, P2 – pyramid rebuilding stages

For the needs of the study, the 3D geospatial model of the pyramid was created using MicroStation V8i software [3], allowing supplementation of this model with numerous levels of specific information. One of such layers contains data on typical forms of weathering of the pyramid stone material and its weathering intensity [4]. Detailed identification of weathering forms was carried out on samples areas verified on site with further manual interpretation of high resolution photographic documentation. The state of preservation or damage due to weathering of exposed surface of the stone blocks of each façade of the Step Pyramid was assessed. Additionally, the types of binding mortar and its preservation were identified [5].

The quality of building blocks used in the various phases of construction of the pyramid was also appraised. A number of criteria to evaluate the quality of building blocks were set, such as size of the blocks (diversity and variations) and uniformity of the material chosen (selection of stone material of same composition and properties), treatment of surface of the blocks (unprocessed, tooled edges, processed edges, smoothed surface), pre-processing of the blocks enhancing their quality (removal of the layers of clayey rocks easily affected by weathering). Potential sites of ancient stone material extraction were studied as well. Such sites are eastern and north-eastern escarpments of Saqqara plateau partly accessible for visual examination with numerous ancient tombs located there. Such examination enabled the authors to compare the results obtained with the data of the other studies on quality of the stone material used in the construction of the pyramids [6,7].

IV. Results and Discussion

The appraisal of the quality of stone production and assessment of weathering of stone blocks has allowed distinguishing previously identified construction stages of the Step Pyramid [8] and characterise them applying aforementioned criteria (Table 1).

The summarisation provided in the table below denotes that during the construction of the Step Pyramid two major steps in extraction and application of building material have been made.

TABLE 1

CHANGES IN THE QUALITY OF STONE MATERIAL AT DIFFERENT STAGES OF CONSTRUCTION OF THE STEP PYRAMID

Characteristics of stone blocks	Main construction stages of the Step Pyramid (according to Lauer)				
	M1	**M2**	**M3**	**P1**	**P2**
Sizes of the blocks, frontal part, m	Approx. 0.45-0.70	Approx.0.25-0.50	Approx. 0.45-0.80	Approx. 0.50-1.20	Approx.0.70-1.40
Variations and diversity in size of the blocks	Large number of variations. Sizes of the blocks vary often.	Blocks of approximately same size, variation in size up to 50%.	The data does not suffice.	5-6 different standards of size, small stones and angular rocks used for filling the splits and larger joints.	Only some standard sizes are used; blocks of other sizes are used rarely.
Uniformity of the material chosen	Very high diversity of material, weathered and heterogeneous stone blocks are used frequently.	Large number of blocks with different properties.	The data does not suffice.	Several materials similar in their properties.	Selection of the material of the same or similar composition and properties.
Treatment of the surface of the blocks	Unprocessed	One or two edges of the stone blocks are tooled, adjusting them for transportation or particular place of laying in the masonry.	The data does not suffice.	Tooled edges of the stone blocks with no additional smoothing of the surface.	All the edges of the stone blocks are processed; surface of almost every block is evened.
Pre-processing of the blocks	The stones were not processed before lying.	The edges of the stone blocks are chopped off rarely.	The data does not suffice.	The stone blocks were given shape without detaching low quality material.	Inappropriate layer of clayey rock removed from almost each stone block.

At first, during the initial stages of the construction there was a transition from the coincidental gathering of stones in the vicinity (M1) using large volume of mortar to bind the stones, towards intentional search for appropriate construction blocks (M2) at the nearest plateau escarpment. Most likely such transition was initiated by practical consideration, since the desert, surrounding the Saqqara plateau, has limited volume of scattered stones. Therefore, the search for alternative source of building material on the escarpments of the plateau is very logic. The presumption that for the needs of the construction the quarry was laid out in the vicinity of the construction site is not reasoned. The evaluation of the building blocks utilised in the construction of the pyramid reveals that almost none of these blocks have the same or a similar composition. Moreover, part of the building material, before laying in the masonry, was already affected by continuous weathering processes.

The other essential step is the transition from the material of diverse quality (M2/M3) to the application of blocks of one particular type (P1). The quality of such blocks still is not high, the sizes of the blocks differ, but the stone material has similar composition and properties. It implies the existence of centralization of extraction and development of mining; yet, similarities in quality of the material extracted imply the implementation of appropriate geological investigation prior to extraction.

From a perspective of production of necessary building resources these are fundamental changes, ensuring the choice of high quality building material that is undergoing quality control and is utilised in monumental buildings, nowadays still justly called the Wonders of the World.

However, after a detailed analysis of weathering traits of the surfaces of each stone block on the facades of the Step Pyramid, some additional aspects have been uncovered. These studies have revealed traces of gradual changes in the quality of building block applied during the latest stage of the pyramid construction (P2). The sizes of the blocks are more precise, and the surface of the blocks is quite even; the blocks are homogeneous and without the layer of low quality clayey rocks. According to these traces, it is possible to identify several stages of the construction of later six-step pyramid (P2). These stages can be traced in all the facades of the pyramid from down to up following the course of the pyramid construction.

During this construction stage, at the lower part of the pyramid, while forming the first step, the quality of stone blocks is contrasting. At some areas these blocks are similar to those used during the previous construction stage (P1), yet the material of higher quality and of scrupulous choice is dominant. These blocks are tooled from all the sides. However, just on some of the images of photographic documentation there are visible traces of surface treatment. These are most characteristic features for the first two steps of the pyramid construction (Fig. 3).

The building material used in the construction at the base of the western façade of the Step Pyramid requires special attention. Recently, the seventh or the lowest step of the pyramid was uncovered (Fig. 4). The existence of this step has been unknown until recent years, and there is no such step at least at the southern façade of the pyramid.

The stone material utilised in the construction of this base or “0” step is different. By its composition, this limestone is sandier than the one used further.

Fig. 3. Characteristic quality of the blocks laid in the lower part of the Step Pyramid (southern façade).

The stone blocks are tooled accurately, and surfaces are evened; the blocks are bond with little amount of adobe-gypsum mortar. Sizes of the blocks differ, and at least 3 types of sizes can be distinguished.

Unfortunately, it is impossible to detect the time period, when this masonry was laid and whether this really was a part of the step of the pyramid or just a support wall.

In the middle part of the Step Pyramid (mainly its third and fourth steps from below) the quality of building blocks is much higher (Fig. 5). These blocks are comparatively uniform, tooled, but with uneven surfaces (at this construction stage it is compensated with a large amount of adobe mortar). This building stage is rather contrasting – there are remarkable differences in amount of mortar applied to bond the building blocks and in the placement of the blocks and quality of such work. Most likely this denotes the existence of different teams of workers with different level of knowledge and qualification.

Fig. 4. Building blocks used at the base or "0" step at the western façade of the Step Pyramid

At the final stage of the construction of the Step Pyramid, when two upper steps are being built, the quality of building stones is for that time outstanding (upper part of the fifth step and sixth step).

These blocks are tooled accurately, processed from all the sides, at least part of these blocks has additionally evened surfaces, and the clayey rock layer is removed.

Fig. 5. Building blocks used in the fourth step of the construction of the Step Pyramid (southern façade)

The sizes of the blocks are very regular; therefore, the amount of mortar applied is quite little and does not exceed 3-5% of the building volume. Without a special analysis, it could be concluded that the blocks have been fit and adjusted to form a monolith.

Many scholars [2,8,9] denoted that the Step Pyramid after its completing had a fine limestone casing. Some of the casing support elements at the base of the pyramid are still visible. Unfortunately, all these elements have been replaced and, thus, it is impossible to verify their authenticity, since the prior reconstruction work has not been documented.

Currently, tooled white and light grey fine grained limestone blocks from Tura (ancient quarry site on the opposite side of the Nile) can be distinguished.

The lime-gypsum mortar binding these blocks most probably is the result of reconstructions. The composition of the stones is similar to the material used in the casing of other pyramids in the vicinity. Such limestone was also used in casing of the pyramids at Giza necropolis (Fig. 6).

Fig.6. The Pyramid of Khafre at Giza with the remains of casing from Tura-Maasara quarry

The same can also be assumed regarding the Step Pyramid of Djoser. However, there are not enough data at our disposal to give a detailed description.

The very existence of limestone casing of the Step Pyramid is a significant finding for our study allowing us to make several important conclusions. This denotes the high level of skills of ancient masons to produce comparatively thin and homogenous stone slabs, transport them, including crossing of the Nile, and apply them onto the vast area of the pyramid facades. The other substantial conclusion can be made regarding the geological knowledge of that period. The casing of just one such pyramid, applying high quality stone slabs requires a prospect to be discovered, investigated, evaluated and verified with at least simple technological tests. Since this monument was designed as a tomb for the king, no deflection was permitted.

Presuming that the time of the construction of the Step Pyramid was approximately 20 years, the final stage of the construction (P2) would take not more than 5 years. Even nowadays such research for appropriate building material would be hard to perform, especially since the actual construction work was already in progress.

The binding material used in the construction of the pyramid requires special discussion. Currently, the loss of binding material is the main threat to the stability of the whole structure. Studies revealed [5] that at the various stages of the construction of the pyramid, not only building blocks, but also mortar of different quality was utilised. Thus, the particularities of deterioration processes of the mortar differed as well. Paradoxically, during the latest stage of the pyramid construction (P2), when the quality of building stones is high, the quality of mortar applied is rather low. The sand - lime (gypsum) mortar with high content of washed alluvial sand was used. The sand was washed insufficiently and still contained a lot of silt and clay components. The admixture of gravel size particles was also considerable and resulted in decrease of quality of mortar affected by weathering. The only possible way how this peculiarity could be explained is assuming that the final stage of the pyramid construction was accomplished in hastiness and mortar of more appropriate quality did not suffice. Thus, the fissures, loss of lime mortar and, finally – loss of cement mass can be currently distinguished. These are widely spread features and can be easily identified in all the facades of the pyramid.

V. Conclusions

The versatile studies of the world's most ancient stone building – the Step Pyramid of Djoser – not only provided new substantial data on preservation and reconstruction of this monument, but enabled us to make several significant conclusions on the changes and development of the knowledge of ancient builders during the construction of the pyramid.

The studies of the facades of the pyramid allowed identifying several construction stages of this monument, featured not only by architectural form of this tomb, but also by the mortar applied and the way the construction blocks were processed. These distinctions can be identified and assessed comparatively by evaluation of the state of preservation of building material, studying particular weathering types and their intensity.

The quality of the material utilised for the building of the pyramid clearly denotes gradual raise of geological knowledge on raw construction materials. The results of the study reveal the presence of changes regarding the requirements towards quality of the building material and evidence on regularity of the material supply from particular quarry site during all building process. Taking into account the scale of this monument, such development of knowledge on location and extraction of building material of appropriate quality is cogent. This could also be attributed to the development of stone processing and technique of mortar production, thus marking an important stage of development in the history of Ancient Egypt.

Although the aforementioned information indicates rapid growth of the level of geological and engineering knowledge, it can not be assumed that these abilities have emerged spontaneously or have been adopted from other cultures. Most probably this historical stage was broader, but convincing evidence still has to be found.

References

1. **Arnold, D.** *Building in Egypt: Pharaonic stone masonry*. New York, Oxford University Press, 1991. p 316.
2. **Verner, M.** *The Pyramids*. The American University in Cairo Press, 2004. p 495.
3. **Seglins, V., Kukela, A., Kalinka, M.** Geovizualization of stone material weathering data for geoarchaeological studies. ***In:*** *Proceedings of the International Multidisciplinary Scientific Geo-Conference Surveying Geology & mining Ecology Management,* 2011, vol. II, p 401-407.
4. **Kukela, A., Seglins, V.** Study of the historical monuments: from the photography to the digital spatial model. ***In:*** Proceedings of the 53rd International Scientific Conference of Daugavpils University. (in print).
5. **Kukela, A., Seglins, V.** Assessment of weathering of construction blocks and mortar in historical monuments. ***In:*** IOP Conference Series: Materials Science and Engineering, IOP Publishing. (in print).
6. **Klemm, D., Klemm, R.** *The stones of the Pyramids. Provenance of the Building Stones of the Old Kingdom Pyramids of Egypt.* German Archaelogical Institute Cairo Department. Walter de Gruyter Gmbh, 2010. p 167.
7. **Clarke, S., Engelbach, R.** *Ancient Egyptian construction and architecture.* Dover Publications, New York 1990 [1929]. p 242.
8. **Lauer, J.P.** *Histoire Monumentale des Pyramides d'Égypte, vol.1: Les Pyramides à Degrés (IIIe Dynastie),* Cairo, Institut Français d'Archéologie Orientale, 1962. p 402.
9. **Lehner, M.** *The Complete Pyramids*. The American University in Cairo Press, 2004, p 256.

Agnese Kukela, Dr.geol. stud., Researcher of the Department of the Applied Geology at the Faculty of Geography and Earth Sciences at the University of Latvia. She is the author of several scientific publications in the fields of stone material weathering studies and assessment of Cultural Heritage stone monument preservation state. She is an Assistant Lecturer at the study course "Geoarchagology".
Address: 10 Alberta Street, Riga, LV-1010, Latvia
Phone: 67331766, Fax 67332704
e-mail: agnese.kukela@lu.lv

Valdis Seglins, Professor, Dr.geol., Head of the Department of the Applied Geology at the Faculty of Geography and Earth Sciences at the University of Latvia. He is the author of more than 200 scientific publications in the fields of geology, geophysics and stone monuments of the Cultural Heritage. He has the lecture courses of "Quaternary Geology", "Applied Geology", "Economics Geology", "Geology of Europe" and "Geoarchaeology".
Address: 10 Alberta Street, Riga, LV-1010, Latvia
Phone: 67331766, Fax 67332704

Agnese Kukela, Valdis Segliņš. Būvakmens izmantošana Senajā valstī Ēģiptē kā zināšanu izmaiņu indikators.
Pasaules materiālās kultūras mantojuma apzināšana un novērtēšana ir tikai neliela daļa no pasākumiem, kuri ir nepieciešami šo pieminekļu aizsardzībai un saglabāšanai. Visai ievērojama daļa no minētajiem pieminekļiem ir veidoti no akmens materiāla un to būvniecībā ir tikušas izmantotas saistvielas, kas laika gaitā zaudē savas sākotnējās īpašības. Saistvielas zuduma vai to īpašību maiņas dēļ tiek būtiski apdraudēta daudzu izcilu pasaules kultūrvēstures pieminekļu stabilitāte un tie apdraud ne tikai apmeklētājus, bet arī to restaurācijas un konservācijas darbus. Viens no šādiem pieminekļiem ir Džosera pakāpienveida akmens piramīda Ēģiptē. Valdnieka Džosera piramīdā par saistvielu ir izmantoti dažādi mākslīgi veidoti maisījumi un šo saistvielu izmantojums dažādās piramīdas daļas nav vienmērīgs un vizuāli tās gandrīz nav atšķiramas. Tādēļ pašreizēji ir iespējams novērtēt tikai saistvielas saglabāšanās pakāpi, kas tika vērtēta kā dēdēšana. Pētījums ļauj droši vizuāli diagnosticēt 5-6 dēdēšanas paveidus un novērtēt tos vairākās intensitātes klasēs. Minētā tipoloģija ir izstrādāta vairākos parauglaukumos izvērtējot piramīdas visas fasādes. Detalizēti pētījumi norāda, ka piramīdas būvniecības gaitā vienlaicīgi ir tikušas izmantotas dažāda sastāva javas, tomēr nav zināmi šādas izvēles iemesli, jo apzināta ir tikai fasādes ārējā kārta nelielā dzijumā. Ņemot vērā, ka objektā nav iespējams veikt tiešus instrumentālus pētījumus un ņemt paraugus analītiskiem pētījumiem, izstrādātā klasifikācija ir izteikti empīriska un nav universāla, tomēr tās ir nozīmīgs atspaids konservācijas projektu izstrādei.

Агнесе Кукела, Валдис Сеглиньш. Применение строительного камня в Древнем Царстве Египта как индикатор изменений знаний.
Разведывание и оценка Всемирного культурного наследия составаляет лишь небольшую часть мероприятий, необходимых для охраны и сохранения этих памятников. Большая часть этих памятников построены из камня. В постройке этих сооружений использовался связующей материал, который со временем теряет свои качества. Утрата связующего вещества или изменения его свойств порождают серёзную угрозу не только для стабильности большинства памятников культурного наследия, но и для посетителей, а так же для работ по реставрации и консервации. Одним из таких памятников является каменная ступенчатая пирамида царя Джосера в Египте. В этой пирамиде связующим веществом служат разные искуственно созданные смеси. Однако их использование в разных частях пирамиды неравномерно и визуально практически неразличимо. Поэтому в данный момент определить оценить только степень их сохранности, оцениваемую как выветривание. Ход исследований позволил визуально идентифицировать 5-6 различных видов выветривания разной интенсивности. Разработанная типология была апробирована на нескольких тестовых участках по всем фасадам пирамиды. Детальные исследования показали, что в ходе строительства пирамиды одновременно был использован раствор разного состава. Однако причины такого подхода не известны, так как была обследована только внешняя часть фасада на небольшой глубине. Учитывая, что в исследованиях данного объекта невозможно производить инструментальные замеры и брать образцы для аналитических исследований, разработанная классификация являеться эмпирической и не универсальной. Однако данная классификация может оказать существенную помощь при разработке реставрационных проектов.