
A Scientist Looks at the Pyramids: Engineering evidence connected with the building of the great pyramids suggests conclusions that go far beyond the problems of pyramid design

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Source: *American Scientist*, March—April 1971, Vol. 59, No. 2 (March—April 1971), pp. 210-220

Published by: Sigma Xi, The Scientific Research Honor Society

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Engineering evidence connected with the building of the great pyramids suggests conclusions that go far beyond the problems of pyramid design

The pyramids of Egypt are immensely large, immensely ancient, and, by general consensus, immensely useless. The very dawn of human history and civilization is marked by a set of monuments so gigantic that nothing even faintly approaching their grandeur has ever been attempted again in our cultural orbit. Silent and mysterious, the pyramids have kept their secret for the better part of five thousand years. The mystery surrounding them mainly concerns the purpose for which they were built. It has been suggested that they were observatories, or grain stores, or refuges from the Flood, or depositories of Divine revelations expressed in geometrical terms.

Archaeological evidence, however, leaves no doubt that the pyramids served as funerary monuments for the early pharaohs. Since the only undisturbed sarcophagus, in an unfinished pyramid, was found empty and since all the other tomb chambers had been robbed in antiquity, we cannot be certain that the kings of Egypt were actually buried in them. Possibly the pyramids were only cenotaphs but, even so, their connection with funerary rites and sacrifices is attested by

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contemporary literary evidence. On the basis of this inescapable conclusion the matter has been turned over to the professional Egyptologists whose aim it is to show why an early civilization should have mobilized all its resources and directed its entire labor force at nothing better than a royal tomb.

It is the object of this article to suggest that this generally accepted conclusion may result from faulty logic. While it is readily admitted that the pyramids served as royal mausoleums, it is not necessarily true that this was the only purpose for their construction. In fact it may not even have been the principal purpose.

However, before discussing the problem of why the pyramids were built, something has to be said about the state of Egyptian civilization at that time. Also, a short account of the pyramids themselves has to be given in order to provide the factual basis for our considerations.

The Old Kingdom

Several centuries before the first pyramid was built, the scattered settlements along the Nile Valley seem to have coalesced into two groups: Upper Egypt, situated south of present-day Cairo, and Lower Egypt, comprising the tribes of the delta. Possibly an invading "dynastic race" was responsible for this process, but very little is known about it. Eventually, by conquest and marriage, the two kingdoms were gradually united over a period to which archaeologists allot three or four hundred years, covering the first two dynasties of pharaohs in Egyptian history. The tombs of some of these early pharaohs, which have been excavated by Flinders Petrie and W. B. Emery, are

shallow underground chambers, surmounted by fairly low oblong and rectangular structures. These resemble in shape the low bench in front of the local farmers' houses, called a mastaba, and this term has been adopted by the Egyptologists.

The building material of the mastabas was mud brick and, in order to lend stability to the outside walls, they were made to slope inward at an angle of about 72°, which simply means a tangent of 3. As we shall see, this slope of 3 in 1 was adopted by the pyramid builders for all their buttress walls. Toward the end of the first two dynasties limestone, sometimes well cut and polished, begins to appear as building material for selected features of the tomb. However, there was no gradual increase in size or magnificence leading up to pyramid building. Emery in his description of the fairly modest and badly planned tomb of the last pharaoh of the Second Dynasty remarks on the curious fact that the huge Step Pyramid at Saqqara was built only a few years later.

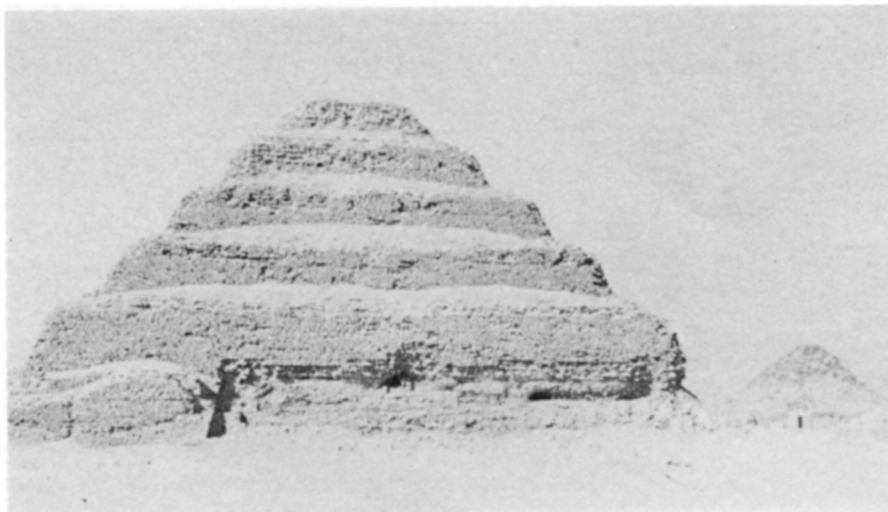
On the other hand, there is no evidence whatever of any technological breakthrough in the methods of quarrying or cutting stone which might account for the onset of pyramid building. All the tools and techniques used by the pyramid builders were in existence well before their time. In fact, the nature of the work involved underwent no change at this time, but the extent of it was subject to a sudden escalation of fantastic proportions.

It appears that the reign of Zoser, the first king of the Third Dynasty with whose name the Step Pyramid is associated, was marked by far-reaching political and social changes. He evidently was the son of an Upper Egyptian king and Princess Nemathap

of Lower Egypt, and there are many indications that this marriage finally sealed the unification of the two kingdoms. It is important and significant that it was not the pharaoh who was credited by the Egyptian historians with building the Step Pyramid but his vizier, Imhotep. To Imhotep is ascribed not only the design of the first stone buildings but also the first teaching of astronomy, magic (science?), and medicine. Egyptian tradition deified him as the supreme sage of all times, and the Greeks equated his worship with that of Asklepios, their god of healing. Imhotep is unique in Egyptian history as being a much venerated personality who was not a king.

The place chosen by Imhotep for Zoser's mausoleum was the desert plateau on the west bank of the Nile above Memphis, the capital of the united Egypt, just south of present-day Cairo. This is the famous Step Pyramid of Saqqara, which to this day dominates the western skyline of the valley. In spite of being about five thousand years old, the building is in a remarkably good state, and only the edge of the lowest step and the smooth casing stones have disappeared. The Step Pyramid gives the impression that six stone mastabas, of diminishing size, have been piled on top of each other, but this is architecturally misleading. Instead, the construction is that of a tower whose masonry is held in place by outer buttress walls of diminishing height. The inclination of the buttresses follows the standard pattern of a 3 in 1 elevation, as used on the earlier mastabas.

The next pyramid was built at Meidum, about 35 miles south of Saqqara, also at the edge of the western desert. This pyramid, which is the only one of the seven great pyramids that is heavily ruined, will become the most important one for our considerations. It was originally planned as a step pyramid, on an even grander scale than Zoser's, but then the plan was changed and the step pyramid was covered with a smooth mantle which transformed the edifice into a true pyramid. The angle of elevation of the sides is $\sim 52^\circ$, and this results in a shape for which the ratio of circumference to height is 2π . This large-scale exercise in squaring the circle may have been chosen for aesthetic reasons or, more probably, it may have had magical significance.



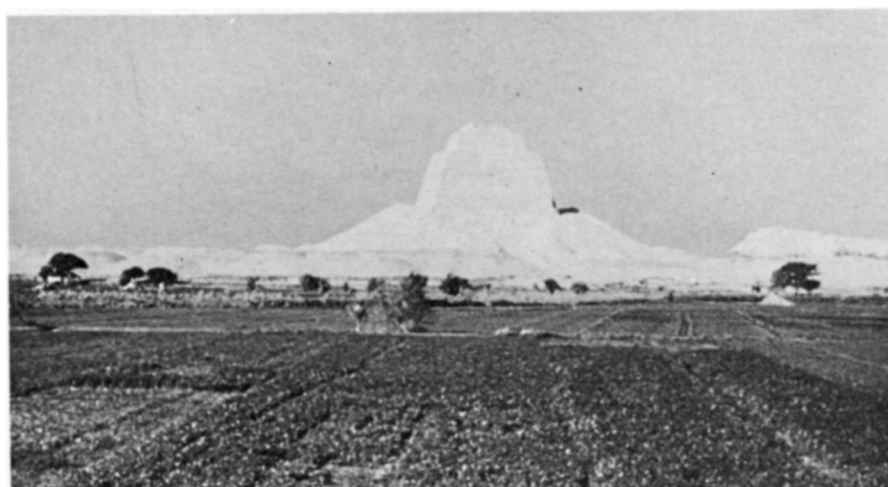
Zoser's Step Pyramid at Saqqara. The shape of the original mastaba can clearly be seen in the ruined lowest step.

It is obvious that the change from the Meidum step structure to the true pyramid took place very late in its construction, when the step pyramid was essentially finished. This is evident from the towerlike structure we see today, in which some of the underlying steps are exposed. These steps had already been given their outer casing, and this casing had even received its final polish when the outer mantle was added. Of the outer mantle only the lowest part, covering the two bottom steps, now remains intact.

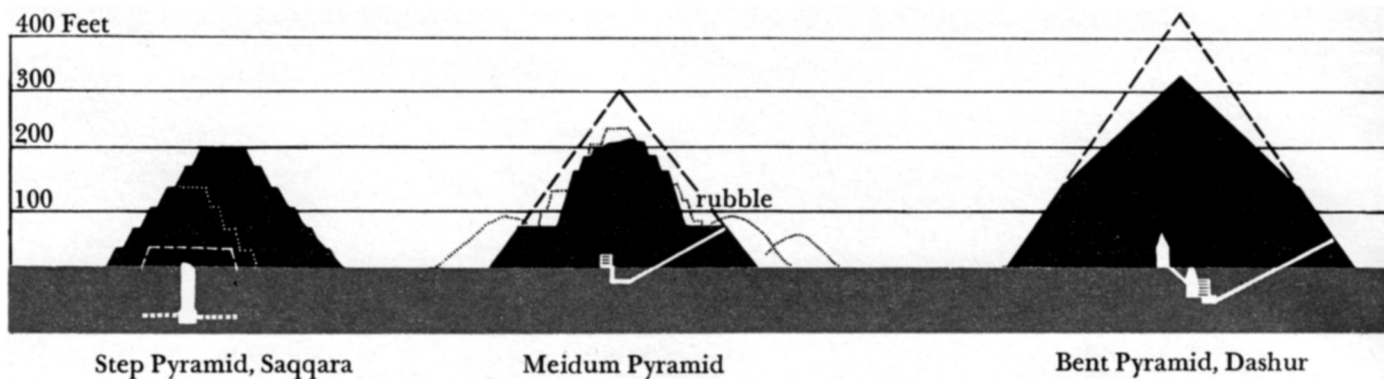
The third and fourth pyramids are at Dashur, just a few miles south of Saqqara. Number three was planned on a still grander scale than its predecessors. It appears to have been designed from the beginning as a true pyramid of 52° elevation. However, when it had reached a third of its intended height the angle of elevation

was lowered to $43\frac{1}{2}^\circ$, which incidentally, makes the ratio 3π . Its curiously stunted shape has earned it the name of Bent Pyramid. Whether this and the other great pyramids also were constructed on top of an underlying buttressed step structure is impossible to say without dismantling substantial parts of them. A certain amount of evidence for the continued use of this basic architectural pattern is provided by the smaller and later pyramids of the Sixth Dynasty, which in their ruined state expose a clearly visible step structure.

Egyptologists have suggested that the change of elevation in the Bent Pyramid was due to the premature death of the Pharaoh, and the need to finish the building in a hurry. This explanation is not very convincing, and again it is a point to which we will return later. The use of a slide rule shows



The ruined pyramid at Meidum seen from the Nile valley. It is surrounded by enormous mounds of rubble formed by the debris of the original structure.



The seven great pyramids of Egypt, drawn to the same scale.

that the amount of masonry saved in this manner is less than 10 percent of the total. Moreover, the next pyramid to be built was designed from the very beginning with the lower elevation angle of $43\frac{1}{2}^\circ$. This fourth pyramid, also at Dashur, is the first one preserved in its true pyramid shape. Unlike its predecessor it has been completely stripped of its white limestone casing and has become known as the Red Pyramid. There is, as we shall see, good reason why the three pyramids following that of Zoser are not associated with the name of a pharaoh.

It is different with the remaining three great pyramids, all at Giza, which are known as that of Khufu (Cheops), Khafra (Chephren), and Menkaure (Mykerinos). The first two of these, numbers five and six in our series, are the well-known colossal edifices overlooking Cairo. They each cover roughly the same area as the Red Pyramid but are much more impressive because they revert to the elevation angle of $\sim 52^\circ$. The third pyramid in the Giza group is, by comparison, a runt, with only a tenth of the cubic content of its predecessor. The pyramid age had come to an end, having

lasted for a little more than a century. Pyramids were still being erected for about a thousand years, but they rapidly became smaller and shoddier, and it is quite clear that with the third Giza pyramid the zest had gone out of pyramid building forever.

From the Meidum Pyramid onward, these structures were all aligned remarkably accurately in the cardinal directions, and they all have entrance passages pointing toward the celestial pole. The arrangement of these internal passages is an absorbing subject but is beyond the scope of this article. Here it must suffice to say that they lead to comparatively small "burial" chambers and that their cross-section is only about one meter square, too low to walk through and just about large enough to admit a dead body.

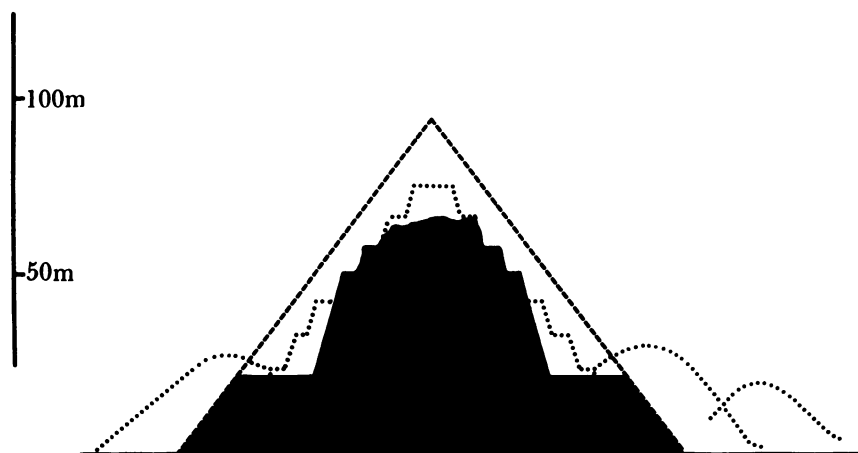
Disaster at Meidum

It should not be thought that I went to Egypt with the intention of finding out why the pyramids were built. On the contrary, as will be presently explained, the final conclusions were drawn quite unexpectedly and much later in a sequence of steps, largely

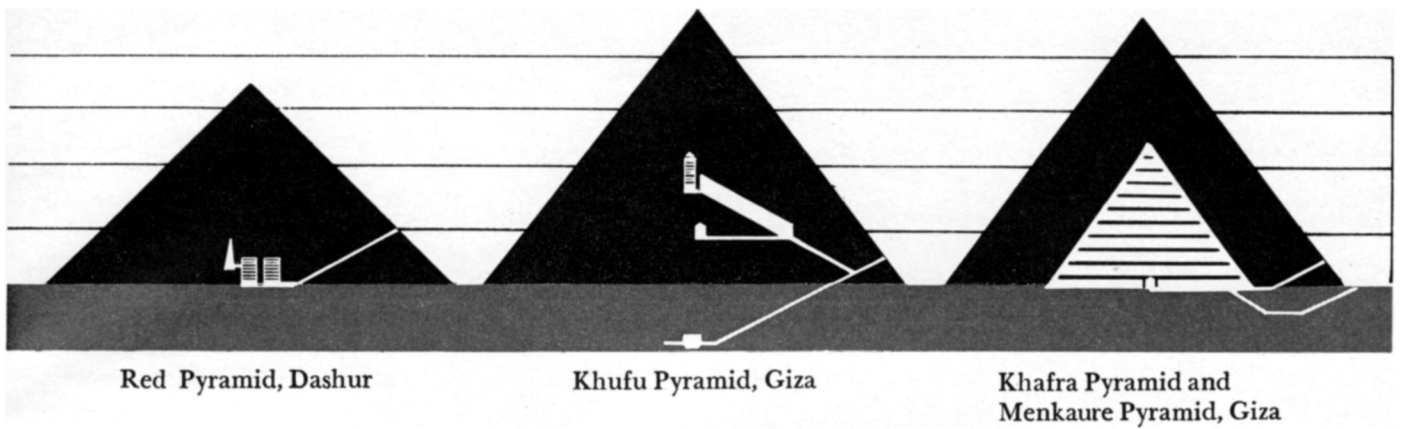
based on the photographic material I had gathered. On my first trip I visited all the usual Egyptian tourist sites, including most of the pyramids. I then became intrigued by the magnitude of technological organization that had been mastered at this early phase in human civilization, and on my second visit I was kindly granted facilities by the Egyptian Antiquities Service for a closer scrutiny and an inspection of the interiors not open to the public.

My first aim was to see the Meidum Pyramid, which is beyond the standard tourist itinerary and is rarely visited. Even in its heavily ruined state it is a most impressive structure: the remaining central core of the step pyramid still rises to a height of over 40 meters. In fact, the disappearance of the outer mantle and some of the lower buttress walls enhances its height, having left a tower with an elevation of 3 in 1. Bands of smooth and rough surface show, as Borchardt has pointed out, that the step pyramid below the mantle was built in at least two stages, each of which had dressed external walls when the next enlargement was decided upon. Egyptologists ascribe the ruined state of the monument to quarrying by later generations, and Flinders Petrie, who made the first survey, mentions that he saw fellahin carting away stones on donkeys.

This again is a problem for the slide rule. The immense bulk of the pyramids will allow severe inroads by quarrymen without showing much effect on the shape of the structure. Most of Cairo's great mosques and essentially the whole city wall were built with casing stones from the Giza pyramids without any noticeable effect on their size. In fact, while Napoleon's companions were climbing these pyr-



The Meidum Pyramid; diagram showing the remaining core and plan of original steps and mantle.



Red Pyramid, Dashur

Khufu Pyramid, Giza

Khafra Pyramid and
Menkaure Pyramid, Giza

amids, he calculated that the stone used in them would suffice to build a wall ten feet high and one foot thick around the whole of France. Keeping this in mind, even whole donkey caravans cannot provide an explanation for the reduced shape of the Meidum Pyramid. Moreover, this pyramid is the only one which never had a large town in its neighborhood where the pillaged stones could have been used.

However, there is no need to search for the stolen masonry since it is still there, surrounding the pyramid in huge mounds of rubble. In fact, a very rough estimate suggests that not much of the original bulk is missing. Equally, it is hardly likely that anyone will have expended immense labor in reducing the pyramid to ruins for no useful purpose. Leaving out willful destruction, we must conclude that the collapse of the Meidum Pyramid was the result of a disaster.

Once this view is accepted, we find ample reason to support it. The prototype at Saqqara had shown that a step pyramid is stable and, indeed, the polished buttress walls at Meidum indicate that two successive phases of a step pyramid at that location, too, had been finished successfully. The disaster evidently occurred when the building was given a novel, and as yet untried, shape by adding the mantle in order to transform it into a true pyramid. Fortunately the existing remains of the pyramid and three successive surveys, by Petrie, Borchardt, and Rowe, permit an excellent reconstruction of this third building phase. After the outer step pyramid was completed, stones were laid onto the steps in order to smooth the shape of the building. At this stage the resulting structure was probably still fairly stable since the weight of these pack-

ing blocks was supported by the buttress walls of the steps. However, then further stones were laid on, beyond the edge of the buttress wall and forming an outer mantle. This addition was evidently required in order to achieve the desired elevation of 52° . At the height of the, at present exposed, second step, the thickness of this outer mantle was about 7 meters and it was completely unsupported by buttress walls. It is most likely that the failure occurred when, during the third building phase, the weight of this unsupported layer was gradually increased.

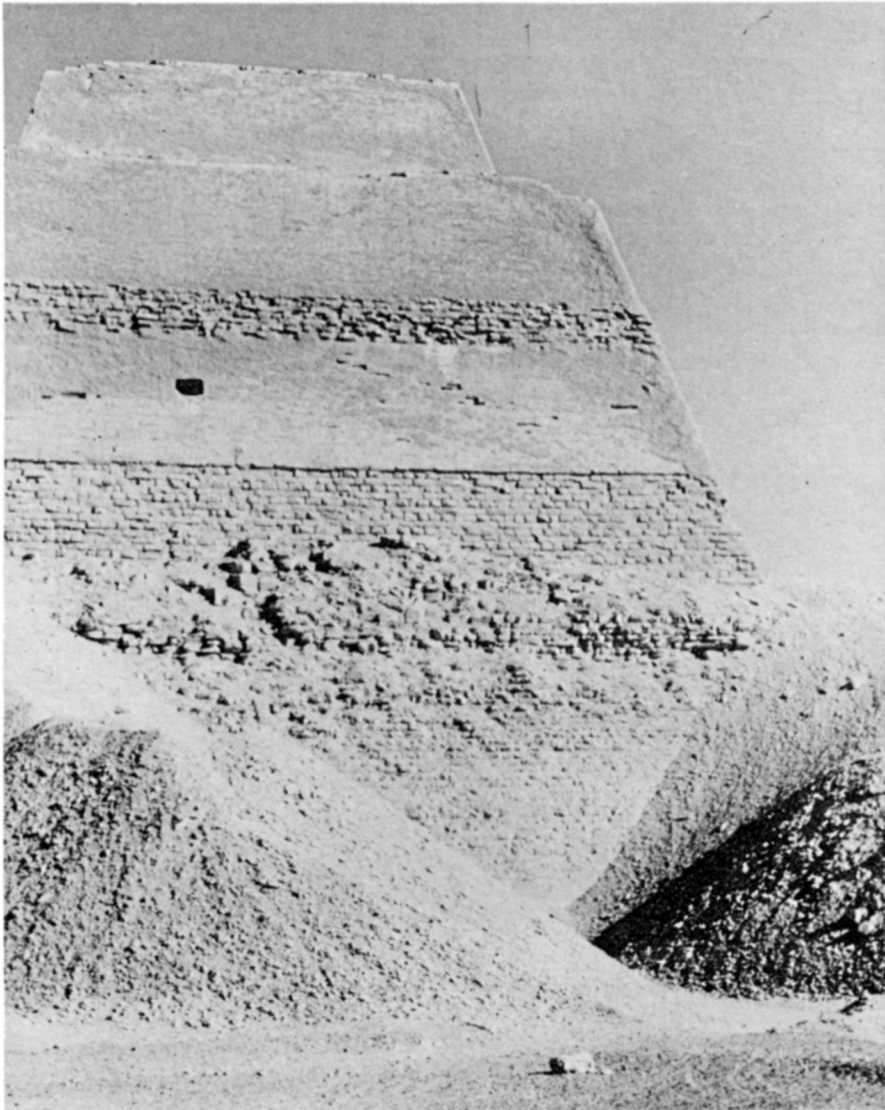
The average pressure at the base of a large pyramid is, at the center, of the order of 50 kg cm^{-2} , with the thrust acting vertically downward. This is high but not destructive for limestone and cannot cause failure if the load is evenly distributed. However, whereas the blocks forming the buttress walls and the outer casing were well squared, this is not true for the bulk of the pyramid masonry. Thus for blocks which, owing to surface irregularities, touch in only a few places, pressure at the joints might rise to $1,000 \text{ kg cm}^{-2}$ or higher, and this is enough to cause limestone to crumble. In fact, there is evidence from inside the passages that some of the pyramids slightly "settled" while building was in progress. This mild bedding down of the masonry would not have catastrophic consequences in an otherwise sound structure, but things were different at Meidum, where the pyramid had two serious architectural weaknesses: the unsupported outer mantle and the smoothed internal surfaces of the buttress walls. These provided no frictional adhesion for the surrounding masonry and thus became dangerous slip planes.

At whichever of these weak features

the original fault on loading developed, the resultant motion of huge masses of stone is likely to have triggered off catastrophic changes at the other as well. The ruin, in any case, shows clearly that an appreciable fraction of the whole pyramid masonry slipped off along the polished inner walls. Moreover, the disaster appears to have occurred with considerable rapidity since the wide extent of the rubble heap testifies to the fact that the slipping mass must have acquired appreciable kinetic energy.

Structural failure in a pyramid will lead to phenomena that are quite different from the collapse of a conventional building. The kinetic energy liberated in the motion of this enormous mass will alter the shape of the individual building blocks in such a way as to encourage further movement, and the whole body of the structure begins to behave like a fluid rather than a solid. In fact, the edifice will undergo changes that are quite similar to plastic flow. Whereas before the catastrophe the thrust was essentially downward, severe structural failure must result in lateral forces that tend to flatten out the affected portions of the edifice. As a result the material will behave very much like a slipping mine tip, a type of disaster which is only too well known.

That pyramids are prone to plastic flow is shown by at least two examples. A later and rather poorly built pyramid, that of Pepi II at Saqqara, had been provided with a strong girdle of limestone completely surrounding its base. Archaeological evidence leaves no doubt that this girdle was added at a late stage in the building operations. It evidently was built as a containing buttress because the pyramid showed a tendency to spread outward under its own weight. The other instance oc-



The remaining core of the Meidum Pyramid shows that two successive phases in the form of step pyramids had been completed before

the outer mantle, giving true pyramid shape to the structure, was added.

curred fairly recently when excavators removed the stone covering from some sections of the largest Mexican pyramid. The core of the structure, built of adobe brick, began to exhibit plastic flow after heavy rain, and emergency action had to be taken.

Once it is realized that the ruined state of the Meidum Pyramid was not caused by later pillaging but was the result of failure during construction, additional evidence for it can easily be found. The memorial stelae in the mortuary temple attached to the base of the pyramid have remained un-inscribed. In addition, the large slabs of limestone forming the corbeled roof of the tomb chamber, although fitted perfectly together, were never dressed. That smooth polishing of internal surfaces was not only possible but customary at that time is shown by the perfect finish of the burial

chamber of an adjacent and contemporary mastaba. This all goes to show that the Meidum Pyramid was abandoned before completion.

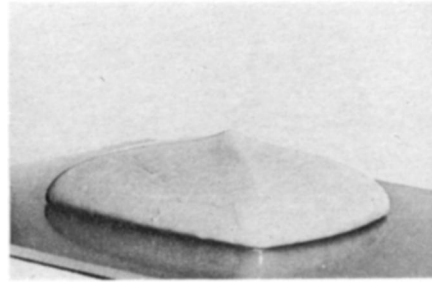
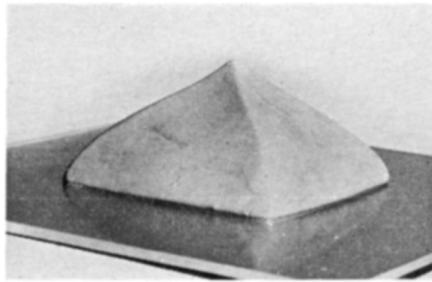
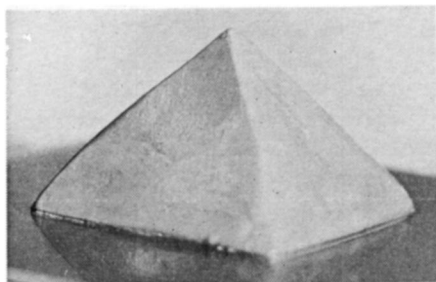
However, the strongest and most interesting evidence for the disaster comes from Dashur. We have seen that the explanation for the curious shape of the next pyramid, the "bent" one, is quite unconvincing. The true reason now becomes apparent through the failure at Meidum. When it occurred, the builders at Dashur immediately took action in order to avoid a similar catastrophe. They reduced the angle of elevation to a less perilous value, making sure that lateral thrust was not likely to develop. In this way, and although they spoiled the appearance of the structure, they were able to complete their task safely. Again playing safe, they built the Red Pyramid from the beginning

at the same lower angle that had proved reliable for the upper part of the Bent Pyramid.

Further proof for this sequence of events is to be found in the peculiar manner of laying the casing stones in the Bent Pyramid. In fact, this peculiarity has puzzled the Egyptologists so much that, for a time, they dated the Bent Pyramid before that of Meidum until other evidence led them to the correct order. At Meidum, as in the Step Pyramid at Saqqara, the blocks forming the buttress walls are laid perpendicular to the face of the wall; that means the courses slope backward into the pyramid at an angle of about 1 in 3. In fact, it is this camber which, by the inward thrust of the masonry, lends added strength against collapse. When at Meidum the outer step pyramid was completed, the tops of the steps were made level, and later, on transformation into the true pyramid, the packing blocks were laid onto them in horizontal courses. Moreover, this horizontal packing was continued in the outer, unsupported mantle, making it easier for failure to occur by the complete absence of inward thrust.

The shape of the Bent Pyramid shows that, when the building plan was altered, the core of the structure must have been completed up to one-third of the intended height and could not be changed. When the Meidum Pyramid collapsed, every possible means had to be employed to save the Dashur edifice from a similar fate. One of these was the lowering of the angle of elevation at the upper levels. The other was to lay the packing and casing stones with an inward camber, similar to that of the buttress walls, thereby providing added inward thrust. Understandably, the Egyptologists who surveyed the pyramid regarded this arrangement of the outer courses as an early method reminiscent of Zoser's first step pyramid. No casing blocks have survived at the Red Pyramid, but the packing stones were laid horizontally. This evidently was considered quite safe in view of the lower angle of elevation.

Having successfully played safe with the lower elevation at the two Dashur pyramids, the Egyptian architects appear to have felt confident that they could again attempt structures embodying the desirable ratio of 2π . The last three great pyramids, all at



Three successive stages in the plastic flow of a pyramid under its own weight. Material and structure of the model were homogeneous, showing merely the action of lateral forces.

Giza, were built at an elevation of 52° and have not only been constructed without disaster but also have stood the test of time successfully. We cannot, of course, know whether novel methods were employed in designing the core, but the external features of the Great Pyramid show clearly what means were adopted to ensure safety. First of all, very much larger packing blocks, of about one meter cube, were used. Secondly, these blocks were very well squared, and these two features counteract the development of plastic flow. Finally, additional inward thrust was provided not by letting the masonry courses slope backward but by making them slightly concave toward the top of the pyramid. This was achieved by grading the size of the blocks in the lower courses so that the edges are somewhat raised with respect of the center of the faces. This last precaution, incidentally, was evidently considered unnecessary after completion of the building since it was not repeated in the two remaining pyramids.

The object of pyramid building

So far our considerations have revealed a large-scale technological failure in the second pyramid the Egyptian architects built and the precautions they took in order to avoid another catastrophe. However, the sequence of events we have traced leads to further conclusions which go far beyond the problems of pyramid design.

Most important of all, the Bent Pyramid had already reached a third of its intended height when its predecessor at Meidum collapsed in the final building stage. This shows that, contrary to accepted ideas, the pyramids were not built consecutively but their

building periods overlapped very substantially. Therefore the concept that a pharaoh, after coming to the throne, built his pyramid in which he was eventually buried and then the next king repeated this process has become untenable. Indeed, as we shall see presently, this sequence of events in any case turns out to be technologically impossible.

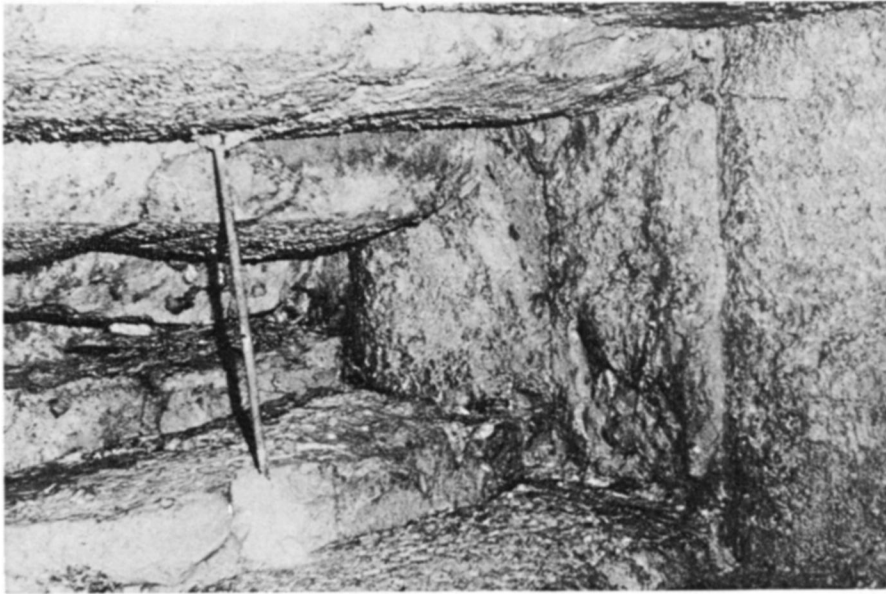
The erection of a pyramid required a very large labor force, probably an appreciable fraction of the whole male population. No contemporary records have been found, and our only information comes from Herodotus, who visited the pyramids two thousand years later. The priests told him that 100,000 men were employed for twenty years in erecting the Great Pyramid, and Flinders Petrie, when making his famous survey at Giza, considered this estimate reasonable. Herodotus mentions shifts of three months' duration but, unfortunately, the relevant passage is ambiguous. It is now generally assumed that these were three months in each year, coinciding with the annual inundation of the Nile, when agricultural work was at a standstill. For these three months, at least, a large part of the whole Egyptian population was employed by the state and became completely dependent on it for their maintenance.

Before considering this last question further, let us turn to the variation of the size of this labor force during the construction of a single pyramid. The work consists in quarrying the stone, shaping the blocks, transporting them to the building site, raising them up, and laying them into place. Most of this is unskilled or semiskilled work, requiring no special craftsmanship. A much smaller number of highly skilled masons, for cutting and dress-

ing the casing blocks, was probably permanently employed. Petrie excavated workmen's dwellings at Giza suitable for housing four to five thousand of these artisans. Again this appeared to him a reasonable number for the work required. In our considerations we will disregard these relatively few skilled men and deal only with the huge seasonal labor force.

In order to finish the immense structure of a pyramid within a reasonable time, the maximum available labor force would be brought to bear on the task. However, throughout construction this would not necessarily be equal to the maximum employable force. The layers near the base require the largest number of blocks to be quarried and transported. As blocks forming these layers can be placed with comparative ease and from all sides, the maximum available labor force would be fully employed for the first few years. Then, as the pyramid is growing, conditions begin to change. Fewer blocks per layer are required, but now access is becoming progressively restricted and slow. This feature is quite independent of the particular system of ramps that was actually used, about which we know little. Accordingly, the employable labor force begins to drop after the first few years of pyramid construction from its constant level, finally tapering off gradually; after the edifice is eventually completed, the labor force would become inactive until, in the following reign, the pattern must be repeated. Then again the maximum number of men is required for several years.

Whatever the state of the Egyptian economy was at the turn of the Third to the Fourth Dynasty, it could never have stood the strain of this employ-



The roof slabs in the burial chamber of the Meidum Pyramid were left undressed.

ment pattern; neither could any other economy since. As pyramid building started, a profound change had to take place in the living conditions of the population, affecting more and more people as the work proceeded. They and their families became completely dependent on the central administration which employed and fed them. At the same time the administration must have made annual levies to obtain the grain needed to supply their workers. These deliveries too had to increase steadily, until in the end an entirely new system of supply and distribution was established. This system, operating for a period of years, would have made a complete break with the previous isolated village economy, ushering in a basically different phase in the life of the whole country. It is quite inconceivable that after twenty years or so,

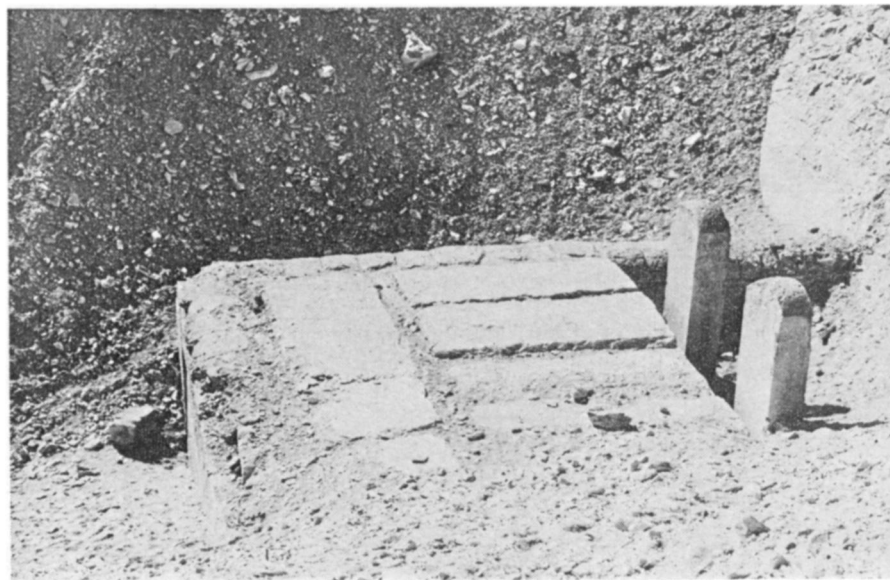
when the pyramid had been completed, the Egyptian economy should have reverted to the old pattern. The change that had been brought about by pyramid construction was far too radical to permit this. The only possibility was to embark on the next pyramid at the time when the labor force on the preceding one was tapering off. Pyramid building became an economic necessity whether or not there was a pharaoh ready to be buried.

The astonishing conclusion that pyramid building was an activity in its own right removes one difficulty which has baffled the Egyptologists for a long time. There are more pyramids than pharaohs. The reason why the Meidum Pyramid, the Bent Pyramid, and the Red Pyramid are known under these names rather than names of

pharaohs is that they all have been tentatively ascribed to Seneferu, the last pharaoh of the Third Dynasty. Unconvincing efforts have been made to invoke obscure names from Manetho's list of kings, referring to quite short reigns in order to solve this problem. With the realization that it was not the pharaoh but the pyramid that led the pace of construction, this problem has disappeared. From the evidence presented earlier in this article we know that the pharaoh, possibly Seneferu, when finishing the pyramid at Meidum, had already built the major part of the next pyramid at Dashur.

When I say that pyramid building had become an economic necessity, I am not suggesting that the Egyptians were caught up in a vortex of architectural activity from which they did not know how to escape. On the contrary, it seems that they had embarked consciously on the construction of these enormous monuments in order to achieve a highly organized political and economic structure of their society. In fact, they invented the state, a form of centralized and efficient organization which up to then was unknown to the human race.

Until then Egypt had consisted of separate tribal units, each with its local god, which were loosely connected by the gradual imposition of a unifying Horus cult. The parents of this falcon god, Osiris and Isis, gave emphasis to the importance of the continuance of life after death, leading to elaborate tombs and funeral rites. The potentialities of this form of religiopolitical federation had probably been exhausted in the course of the first two dynasties. With firm unification at the time of Zoser, the stage had been set for the next phase in the development of society. In this new stage, which we call the state, centralization of power and administration became the key object. It was achieved by the ingenious device of creating a large communal task, engulfing eventually a large fraction of the population: pyramid building.

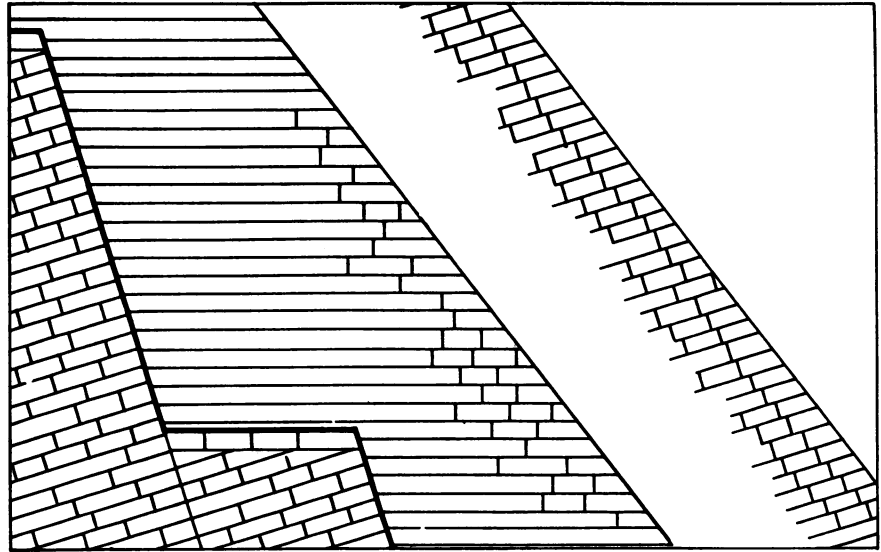


The memorial stelae at the Meidum Pyramid have remained uninscribed. The lower part of the outer mantle which has remained intact can be seen on the left.

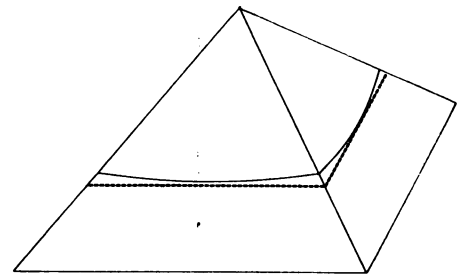
That the pyramid was chosen is not surprising. Heaping up an impressive man-made mountain is the simplest and most basic great communal task that can be imagined. All that is required for its achievement is a worthwhile reason. The existing Osiris cult easily lent itself to an interpretation in which the ascent of the dead pharaoh to the sun was of paramount importance for the afterlife of every member of the community. The pyramid, as is known from contemporary inscriptions, was the means of achieving this ascent.

It would not be very rational to assume that Imhotep, with almost fiendish ingenuity, had worked out this master plan for the creation of the state and then set out on the design of the Step Pyramid of Saqqara. In fact, we know that this was not the case. The original funeral monument that he built for Zoser was a traditional type of mastaba on the west bank of the Nile above Memphis. Its only difference from earlier structures of this type was its greater size and its entirely stone construction. After its completion, this mastaba was twice successively enlarged. It was possibly at this stage that the organization of labor marshalled for this big tomb began to suggest a new economic pattern with desirable political consequences. Again the exploitation of this new scheme was gradual, taking place in two consecutive stages. The first was the erection, on top of the existing mastaba, of a pyramid composed of four steps. It seems that the provision of labor for this great enterprise, far from exhausting the working capacity of the community, was proving very practicable and perhaps economically beneficial. This is shown by the fact that Imhotep was encouraged to enlarge the building still further, increasing its cubic content three times and reaching an even greater height by constructing the final pyramid of six steps.

Details of the subsequent development cannot be discussed in the space of this article but it seems clear that, after two—probably never completed—step pyramids, Seneferu embarked on the true pyramid age with the continual employment of a huge labor force. It seems that now the organization of the centralized state through the drafting of ever-increasing numbers of workers was consciously exploited. It is significant that the main

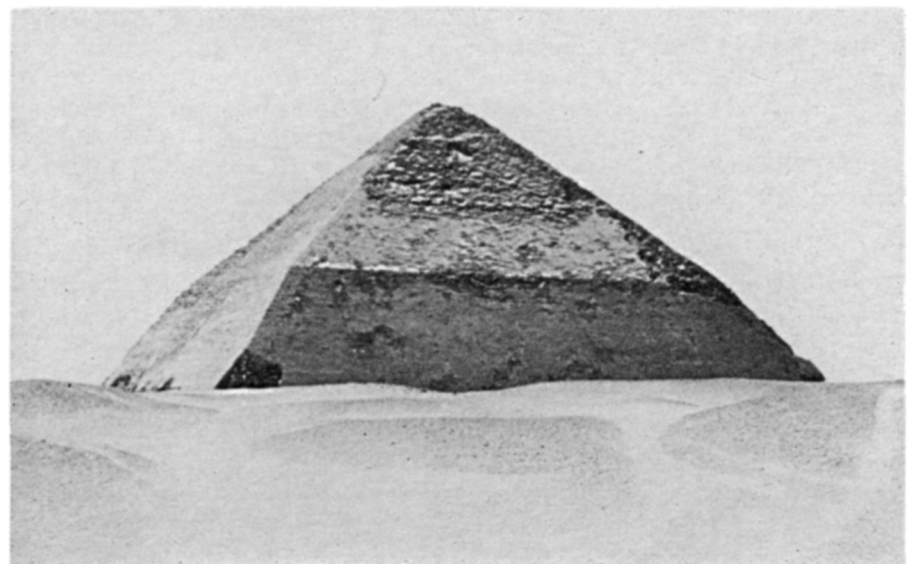


Position of building blocks in the Meidum Pyramid (*left*) and in the Bent Pyramid (*right*). In this diagrammatical sketch the width of the unsupported mantle surrounding the step structure of the Meidum Pyramid is apparent.



In order to achieve greater stability the courses of masonry in the Cheops Pyramid were laid slightly concave toward the apex.

The Bent Pyramid at Dashur.





Very large and well-squared blocks were used in building the Cheops Pyramid.

emphasis was shifted toward numbers and away from skills. The elaborate surrounding walls and subsidiary buildings of the earlier step pyramids were dispensed with and the bulk of the pyramids themselves was continually increased.

Five enormous pyramids were built in less than a century, and then, with the Menkaure Pyramid, this fantastic activity tapered off within a comparatively short time. Pyramid building has achieved its object; the organization of the state had been created. From now on the labor force, accustomed to centralized organization and well disciplined, could be turned to other, economically more rewarding activities within the new state. As for the pharaohs, they still got their pyramids but they now had to ascend to the sun on mud bricks, thinly covered with a limestone casing. Neither did control of expenditure for their monuments allow them to ascend very high.

Space does not permit more than passing remarks on two other problems of the pyramid age: the shape of the monuments and the question of forced labor. That the monument of the communal task had to be a mountain, as steep and as high as circumstances permit, goes without saying. The structure was a mountain and not a building, as is attested by the great

difficulties the Egyptians encountered in providing even a little space inside it. A mountain is something one can ascend, and a passage in the pyramid texts suggests ascent to heaven by a staircase, which may be the meaning of the step pyramid. The true pyramid may suggest ascent along the sun's rays.

Connected with this interpretation was evidently a change in the religious position of the pharaoh, ushered in under Seneferu by the priests of Heliopolis. A conical stone was the emblem of the sun god, and this cult change, exemplified by the alteration of the Meidum Pyramid, may be associated with a closer link of the pharaoh with the god he was supposed to accompany on his daily journey across the sky. This would mean enhanced importance for the whole community of the pharaoh's person and of the part he had to play after death for the well-being of all, in this and the next life. The building of this cult symbol on a stupendous scale must have appeared to the Egyptians as an essential and worthwhile task.

This leads straight to the question of despotic "slavery," to which the pyramid builders are supposed to have reduced their people. Even a serious Egyptologist like Borchardt will interrupt a scholarly dissertation on building ramps to conjure up the

spectacle of exhausted slaves toiling under the whips of overseers. In our age of automatic weapons we are accustomed to large numbers of people being terrorized by a small well armed group. No such disparity existed between worker and overseer five thousand years ago, and in order to enforce unwilling labor, a very sizable army would have had to be employed to control a hundred thousand workers and their disgruntled relatives scattered over the country. Moreover, the workers would have had to be rounded up each year anew, and this subjugation had to last for a century.

This is not very probable, and the alternative, that the work was undertaken willingly, sounds a good deal more likely. When enquiring about the labor force used for large projects in present-day China, I learned that a sufficient number of volunteers is always available. The pay is good, there is a sporting rivalry between work gangs, and when the workers return, they are the heroes of their village, telling evening after evening "how we built the dam" stories. Inscriptions on the pyramid blocks give the name of working groups such as Vigorous Gang and Enduring Gang. Moreover, the cooperative effort of villagers, brought together from a great number of different tribal communities, some with traditional enmity, must have played an im-

portant part in the creation of a centralized state.

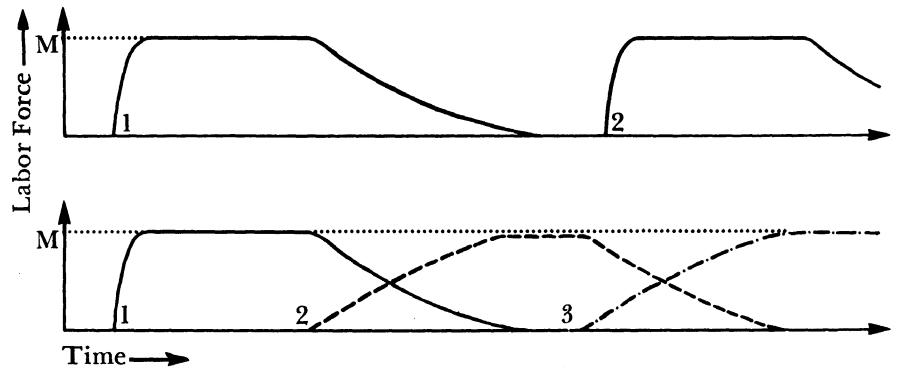
Altogether our analysis suggests that, far from being a period of abject slavery and exhaustion, the pyramid age represented a new form of communal living by common work for the benefit of all. One even may have doubts whether it was spiritual benefit only. Such information as has come down to us indicates that at the time when the pyramids were erected, Egypt's prosperity increased rapidly. Seneferu is credited with building the first sea-going ships that traded along the Syrian coast, and he and his successors established for the first time a hold over territories beyond the Nile Valley, in the Sinai peninsula.

The Mexican pyramids

There exists another set of large pyramids in the world, at Teotihuacan and Cholula in Mexico. It has often been maintained that a connection must exist between the two sets of striking monuments in Egypt and Central America. This I am inclined to believe, but not in the way it is usually suggested. Even if, though that seems unlikely, the Egyptians had navigated papyrus boats across the Atlantic, they would hardly have induced the Mexicans to engage in an activity they themselves had given up two thousand years earlier.

Carbon dating and similar methods show that the great Mesoamerican pyramids were built just before the beginning of the Christian era. There is even greater paucity of information about this period than about the Egyptian pyramid age since no script had been developed. Neither is there any reference in Mexican tradition to the people who built the pyramids. They were overgrown and in ruins when more than a millennium later the Aztecs entered the Valley of Mexico. They thought that the double line of mounds at Teotihuacan, hiding ruined pyramids, were tombs and called it the Avenue of the Dead. They also named the two large pyramids that of the sun and of the moon, but none of these descriptions have any link with the true significance of the monuments, about which we know, as yet, practically nothing.

The Aztecs displaced the civilization of the warlike Toltecs, whose capital was probably at Tula, and it may have



Idealized diagram of the maximum employable labor force as a function of time when building pyramids consecutively (*above*) and with overlap in construction (*below*).

Overlapping construction of the pyramids could be phased in such a manner that the employable labor force is always equal to the maximum available labor force *M*.

been the Toltecs who earlier conquered the people whom we now call Teotihuacanos. What their real name was is unknown and the archaeological research into their civilization is still in its infancy. However, it is worthy of note that in Mexico, as in Egypt, legend ascribes the building of the large pyramids to the inspiration of an outstanding sage who further taught them many of their arts and crafts. He later was deified under the symbol of the plumed serpent, Quetzalcoatl, and Cortez benefited by a tradition that this god would return to Mexico from the east.

Pyramids were still being built when the Spaniards conquered Mexico, but the true Central American pyramid age had come to an end 1,500 years earlier. Again, as in Egypt, the colossal pyramids mark the beginning rather than the height of Amerindian civilization. Their precursors were some fairly modest circular mounds, such as that at Cuicuilco just outside Mexico City. Cuicuilco can be roughly dated because it was partly covered by a flow of lava from the volcano Xitle, which erupted some 2,000 years ago. Pottery found there classes Cuicuilco into Mexico's late Archaic period, characterized by agricultural village communities, each with its own tradition, as is shown by the different styles of the little female idols found in abundance. The mound at Cuicuilco marks the onset of cult ritual, serving a large number of villages. From the little we know, it can be concluded that life in the Valley of Mexico at about 300 B.C. was not unlike that in Egypt under the first two dynasties.

Then, quite suddenly as in Egypt, we find a number of gigantic pyramids,

the largest of which, at Cholula, exceeds in cubic content that of Khufu at Giza. The angle of elevation is lower than in Egypt, because in Mexico the building material was mud brick which was stabilized and protected against heavy rains by a thick mortar made from pounded volcanic stone. Embedded in the mud brick are numerous small idols, which show that the large Mexican pyramids followed immediately upon the mound at Cuicuilco and that the culture was identical with that of the villagers who built the mound. Thus, we have no reason to ascribe the pyramids to the initiative of some conquering race, and we must assume that village settlement in the Valley of Mexico had reached a stage at which it had become ripe for urbanization and centralization of power. Just as the people of the Nile had invented the institution of the state 3,000 years earlier in the Old World, the Teotihuacanos performed the same task in the Western Hemisphere. They, too, achieved the necessary organization of the villagers by creating a labor force for a striking communal task, and again the most obvious undertaking, the building of an artificial mountain, was chosen.

In Egypt the avowed reason for constructing pyramids was to provide the pharaoh with a funerary monument, but the Teotihuacan pyramids were not primarily burial mounds. A number of tunnels have been bored through these mud brick and earth structures and these have not as yet revealed the existence of a tomb although there are indications that one may exist in the Pyramid of the Sun. The main object of the Amerindian pyramid was to provide a stage for a ritual, usually a human sacrifice, to be watched by a



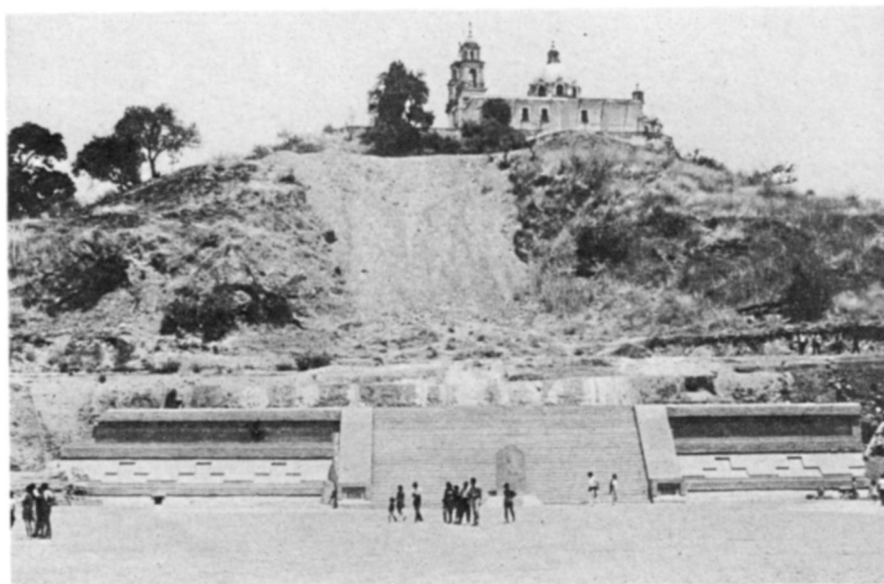
The Pyramid of the Sun at Teotihuacan.

large number of people. The top of the pyramid was always flat, carrying a temple and an altar, an arrangement which already exists on the mound at Cuicuilco and was continued until the Spanish conquest.

It is interesting to note that in Mexico, just as in Egypt, the period of building very large pyramids not only occurs at the onset of urbanization but that it also lasted for a relatively short time. Like the burial of pharaohs, human sacrifice, required to keep the sun alive by feeding it with blood, remained a social activity of essential importance to the population through-

out the Amerindian civilization. Pyramids carrying altars continued to be built, but it was no longer necessary to concentrate large labor forces as a means to create the state. As soon as the basic pattern of the state had been developed, the Mexican pyramids were built no larger than necessary to provide a good view of the spectacle for a large crowd.

Instead, architectural features other than size, and sometimes not compatible with it, were given greater importance. With the continual increase in the number of sacrifices in Toltec and particularly in Aztec times, rapid



Excavation and reconstruction has begun at the large pyramid at Cholula, on which the Spanish conquistadores built a church.

disposal of the victims became necessary. Their corpses were rolled down the pyramid steps, to be received by their captors or buyers for cannibalism, and this purpose was best served by relatively small but rather steep structures. Thus, while retaining their ritual function, the later edifices could be erected by a modest labor force. As in Egypt, no large pyramids were attempted after the early Mexican pyramid age, although in both cases the community became larger and more prosperous, and the technological means were more advanced.

In this article I have purposely left the sequence of conclusions in the order in which they occurred to me. This is to show that I did not approach the subject with any preconceived idea; it developed on the basis of what I consider to be compelling logic. Faced with the same basic material, the scientist and technologist draws different conclusions from the archaeologist simply because he is looking for different things. In doing so, he may occasionally arrive at results that are at variance with the archaeologist's ideas merely because in these particular instances the problems are essentially technological ones.

Naturally, I have discussed some of these ideas with my Egyptologist friends, particularly with Professor Emery of University College, London, the successor of Flinders Petrie, and with Dr. Edwards of the British Museum, whose famous book *The Pyramids of Egypt* is the standard work on this subject. I am much indebted to their helpful advice and I am encouraged by the fact that they have raised no objections to my suggestion of a disaster at Meidum and the subsequent events. Whether Old Kingdom experts in general will accept my thesis that the pyramids were more important than the pharaohs whose names they immortalize remains to be seen.

It might be possible to atone for this heresy by drawing the archaeologists' attention to a small section of Seneferu's world which lies entombed under the rubble at the foot of the Meidum Pyramid. The physicist's analysis of the spread of the debris suggests that the catastrophe was too rapid for people to save themselves in time, and they most probably are still there, after almost 5,000 years, waiting for the excavator's bulldozer.