CHAPTER 8

Khufu's Pyramid: The Return to a Steep Angle

After Khufu ascended the throne, the construction of his pyramid was almost certainly considered immediately.

I believe that within the king's circle and among the ruling elite, the ideal forms envisioned were those his father Sneferu had desired but ultimately failed to realize: a true pyramid with a 51.5-degree slope—achieved by adding casing stones to a step pyramid—and the original 54-degree design of the Bent Pyramid before its change in angle.

Although the Red Pyramid was completed, its gentle, hill-like profile may have felt insufficient to those who sought "a taller and more sharply pointed monument"—a form that embodied what a royal pyramid ought to be.



Fig. 8-1. The Pyramid of Khufu (photographed in August 2008)

A crucial point often overlooked is this: While the Bent Pyramid appears today as a conspicuously "failed" structure due to its mid-construction change in angle, the Step Pyramid at Meidum—despite its outer casing having already begun to deteriorate and collapse even in antiquity—would not have appeared as the bare core we see today. At that time, it likely still retained the external form of a true square pyramid, allowing observers to see directly a pyramid with a 51.5-degree slope.

This ability to see the Meidum Pyramid in its near-original form is, in my view, extremely important.

The overwhelming impact of Khufu's Pyramid is not felt in distant photographs, but when one stands at its base and looks upward. The sense of looming pressure—almost a physical force—is directly tied to the slope angle. There is a profound difference between slopes below 45 degrees and those above 45 degrees, a difference that cannot be captured by the mere numerical gap of eight degrees.

Anyone with skiing experience will understand this intuitively: Once a slope exceeds 45 degrees, skiers often describe it as a "cliff" or a "wall." Even a small numerical difference can produce a dramatic change in human perception.

This sense of pressure—of being overwhelmed—is precisely what makes a pyramid effective as a monument of royal authority. In a sense, it is the very metric by which a pyramid's value is judged.

I have stood at the base of the mausoleum mound of China's First Emperor and at the Pyramid of the Sun in Teotihuacan. Both are undeniably massive, yet neither produced the overwhelming impact I felt beneath Khufu's Pyramid. The difference lies in the slope: both the First Emperor's mound and the Pyramid of the Sun have relatively shallow angles, and thus the impression they create is fundamentally different.

If Khufu and the elites of his time stood beneath both the Meidum Pyramid and the Red Pyramid, they would have experienced—viscerally—the stark difference in pressure and intimidation produced by their respective slopes.

The Meidum Pyramid is thought to have been about 90 meters tall.

The Red Pyramid is taller at 104 meters, yet if the Meidum Pyramid still retained its true-pyramid form in Khufu's time, standing at its base would likely have made it feel taller and more imposing than the Red Pyramid.

Compared in this way with the Meidum Pyramid, or with the lower portion of the Bent Pyramid, the Red Pyramid may well have struck observers as lacking the force expected of a monument to royal authority. This visual and psychological consideration may have been among the factors behind Khufu's decision to return to a steep slope.

However, Khufu's design specifications—52 degrees and a height of 146 meters—were extraordinarily demanding.

A note on terminology is in order here. Egyptological literature conventionally describes the slope of Khufu's Pyramid as "51 degrees," apparently by simply dropping the minutes rather than rounding them. I depart from this convention and use "52 degrees" throughout this book. Petrie's own survey of the casing stones (The Pyramids and Temples of Gizeh, 1883) reports a mean angle of 51°52′ ± 2′—within measurement error of 51°50′. Rounded to the nearest whole degree, this is 52, not 51, and I see no reason to perpetuate that imprecision here.

It is often assumed that the Bent Pyramid, the Red Pyramid, and Khufu's Pyramid represent a straightforward technological progression. I do not believe this. Rather, the path leading to Khufu's Pyramid was a zigzagging line shaped by alternating priorities.

The Bent Pyramid, whose drastic mid-course design change was forced by structural instability, served as a cautionary example. The Red Pyramid, built with a safer construction method and a conservative slope, embodied a design philosophy centered on safety margins. Khufu's Pyramid, by contrast, represented a return to a steep angle and an unprecedented height—a bold specification that broke from the conservative trend.

1. Selecting Giza as the Construction Site—The Limestone Bedrock

Faced with such extremely demanding design specifications, the

pyramid project must have begun examining concrete measures immediately.

The project team's greatest concern would undoubtedly have been the steep slope angle, which directly translated into increased ground pressure at the base of the pyramid.

Since uneven ground conditions were the direct cause of the "bend" in the Bent Pyramid, the selection of a suitable foundation was the most critical issue. By this time, the project members were already aware that the ground at Dahshur was weak. It is therefore highly likely that the engineering side strongly advocated relocating the construction site.

The site ultimately chosen as a candidate was Giza, located roughly 26 km north-northwest of the Red Pyramid. The area is a raised plateau where limestone bedrock is exposed at the surface, making it appear to be an ideal location with strong, stable bedrock.

Moreover, because Giza is a plateau, the pyramid would have been visible from great distances. In ancient Egypt 4,500 years ago—when the surrounding landscape was far less obstructed than today—the pyramid would have been visible from an even wider area.

According to the study by Hader Sheisha and colleagues, a branch of the Nile—what modern scholars call the "Khufu Branch"—once flowed close to Giza. This would have made it possible to transport materials by water.

Most decisive of all, however, was that the primary construction material—limestone—could be quarried directly at the site.

The Red Pyramid is estimated to have required roughly two million limestone blocks. By that stage, the project team must have fully recognized that transporting such a vast quantity of stone was a major logistical challenge.

Khufu's Pyramid required 2.3 million blocks. Although its height is 1.4 times that of the Red Pyramid, the total number of blocks increases by only a factor of 1.15 due to the geometry of a square pyramid. Even so, a 15% increase is a significant burden.

The greatest advantage of Giza was that the main construction material—limestone blocks—could be sourced locally. In fact, there is

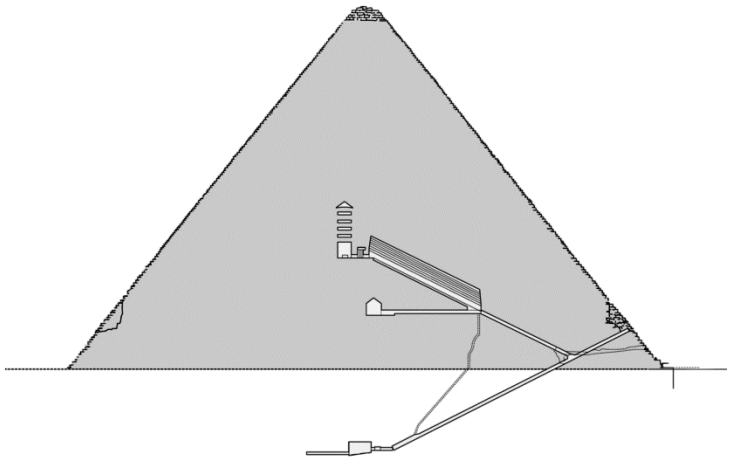

Fig. 8-2. Internal Structure of the Pyramid of Khufu (traced from Howard Vyse, Operations Carried on at the Pyramids of Gizeh)

evidence that Giza had already been used as a quarrying site during Sneferu's reign.

The quarry sites used during Khufu's reign still survive today in areas such as the so-called Central Field, located immediately south of Khufu's Pyramid—so close that it can practically be considered adjacent.

For a project involving such an enormous volume of stone, the advantage of having extremely short transport distances was decisive.

Another important factor was that high-quality limestone for the casing stones came from Tura, across the Nile. Transporting these stones required crossing the river and using water transport.

Dahshur lies upstream from Tura. Therefore, transporting casing stones from Tura to Dahshur by boat would have required sailing against the Nile's current. It is possible that, instead of rowing upstream, the stones were ferried across the river and then transported overland to Dahshur.

In any case, during the construction of the large pyramids at Dahshur, this must have been recognized as a major logistical challenge.

From this perspective, choosing Giza—located downstream from Tura—as the site for an even larger pyramid was a rational and strategically sound decision.

2. Bedrock Investigation and the "Mysterious Subterranean Chamber"

In Operations Carried on at the Pyramids of Gizeh (1837), the joint work of British explorer Howard Vyse and engineer John Shae Perring, a cross-sectional diagram of Khufu's Pyramid depicts not only the structures now known as the King's Chamber, the Queen's Chamber, and the Grand Gallery, but also a deep underground chamber referred to as the "Subterranean Chamber."

In The Great Pyramid Passages and Chambers (1910), John and Morton Edgar published numerous drawings and photographs of the Subterranean Chamber. The walls remain roughly hewn, the floor is unpaved, and the chamber itself is about the size of a 25-meter swimming pool. In one corner, there is a vertical shaft resembling a well.

Even from the photographs included in their book, it is clear that the rear portion of the chamber is in an unfinished state. For a long time, this led to speculation that the chamber represented an "unfinished burial chamber" or that construction of a room intended for religious rituals had been abandoned. However, none of these interpretations gained broad acceptance, and the chamber remained an unresolved "mystery."

What makes this unfinished chamber particularly strange is that while the rear portion remains incompletely excavated, the entrance area shows signs of finished wall-cutting. It is highly unnatural for workers to cut the entrance walls while excavation at the far end was still underway, as this would cause severe interference in the workflow. The preserved state therefore suggests that excavation at the rear was halted first, and only the entrance-side wall-cutting continued afterward. This, however, makes the chamber's purpose even more difficult to understand.

According to Operations Carried on at the Pyramids of Gizeh in 1837, the Subterranean Chamber appears to lie almost directly beneath the central axis of the pyramid.

A descending passage, running from true north toward true south at an angle of 26 degrees and a width of roughly 1.6–2 meters, extends for more than 100 meters. At a depth of about 30 meters below ground level,

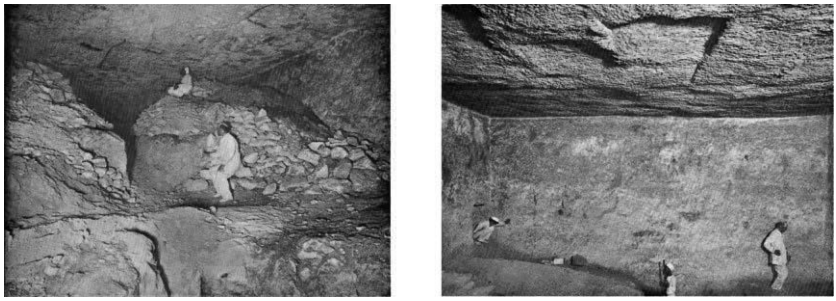

Fig. 8-3. Rear (left) and front (right) views of the Subterranean Chamber (from The Great Pyramid Passages and Chambers, John & Morton Edgar, 1910, public domain)

the passage becomes horizontal, and the chamber lies beyond this point. The surface of this passage (beneath the masonry) lies inside the pyramid's base perimeter. Since it is structurally implausible that the builders carved a passage downward through already-laid masonry, the excavation of this passage must have begun before the first course of stones was set, and the passage was extended downward as construction progressed.

The slope of this passage—26 degrees—is shared by the descending passages of many pyramids, corresponding to a gradient of 50%. This strongly suggests that the passage was excavated from the outset with the explicit intention of reaching a chamber 30 meters below ground.

Even though Giza had been selected as the construction site, the project members—drawing on their experience with the Bent Pyramid—must have been deeply concerned about whether the bedrock could withstand the enormous ground pressure of such a massive pyramid. It is reasonable to assume that they conducted what we would today call a geotechnical boring survey. Exposed bedrock outcrops are weathered and cannot be evaluated solely from the surface. The thickness of the bedrock cannot be known from surface inspection alone, nor can one determine whether the rock is uniform or contains micro-fractures, voids, or other features that could compromise stability. A thorough bedrock

investigation would have been indispensable.

This is common sense even today: large structures require geotechnical surveys, and in earthquake-prone Japan, even ordinary residential houses cannot be built without one.

At this point, I asked myself:

If I were a member of the pyramid project, where would I want to investigate the ground most thoroughly?

Naturally, the most critical point would be the location of maximum ground pressure—the point directly beneath the pyramid's apex, the exact center of the structure.

Then it struck me:

There is a "mysterious subterranean chamber" located 30 meters below the center of the pyramid.

Although I still consider the possibility that the chamber may originally have been intended as a burial chamber, I began to suspect that it might also be related to bedrock investigation.

However, for a chamber to serve as a geotechnical test site, it would need to be located precisely beneath the center. If it were 10 meters off, one could confidently say it was not intended to examine the central ground conditions. Even a deviation of 5 meters would only allow a weak argument that it "might" have been intended for that purpose.

In recent years, laser-based measurement technologies have greatly improved the precision with which the internal structures of Khufu's Pyramid can be mapped.

These measurements have revealed the exact positional relationship between the Subterranean Chamber and the pyramid's center point, as shown in Fig. 8-4.

The north–south centerline of the pyramid passes almost directly through the middle of the Subterranean Chamber. The northern wall of the chamber—the wall on the passage-entrance side—is parallel to the east–west centerline and lies 1.94 meters south of it.

In other words, a person standing on the pyramid's north–south axis can look straight ahead and observe the bedrock located 30 meters below

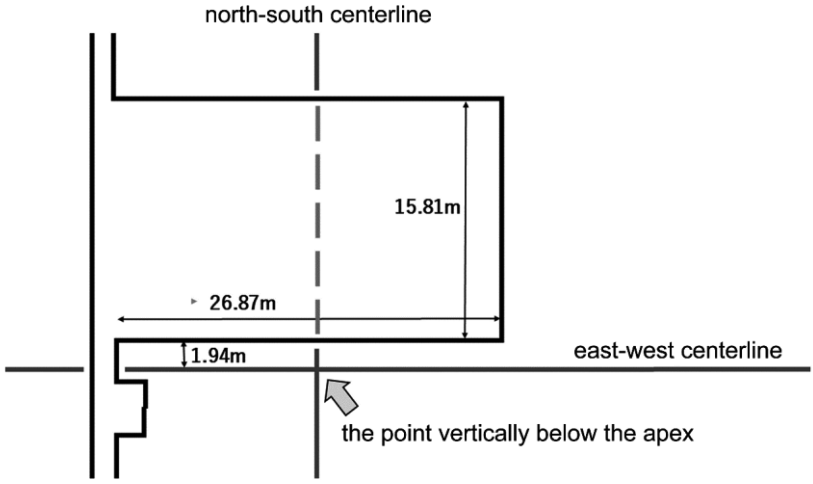

Fig. 8-4. Positional relationship between the Subterranean Chamber and the north–south and east–west centerlines (created with reference to khufupyramid.dk)

the east–west axis, as if viewing a large screen directly in front of them.

This led me to consider that the chamber was not merely a test pit excavated to examine the bedrock down to a depth of 30 meters, but also a monitoring post used throughout the entire construction period to observe whether the steadily increasing ground pressure—caused by the accumulation of millions of stone blocks—was producing any harmful effects on the underlying rock.

The features they would have monitored likely included:
cracks forming on the chamber walls
small steps or displacements in the rock layers
falling grains of sand from the ceiling
unusual sounds caused by damage within the bedrock

Although the northern wall is actually offset 1.94 meters from the east–west axis, this deviation is understandable. In ancient Egypt, two points separated by more than 100 meters along a narrow descending passage could not be observed directly; they had to rely on rope-based surveying. Moreover, the passage descends at 26 degrees, making precise

measurement extremely difficult.

Even in Operations Carried on at the Pyramids of Gizeh in 1837, the diagram shows a slightly different positional relationship, with the center point falling inside the chamber. This means that even 19th-century measurements carried errors exceeding two meters.

The personnel responsible for continuous monitoring were likely lower-ranking administrators. Since the chamber functioned as a worksite, there was no need to pave the floor or finish the walls and ceiling. In fact, leaving the ceiling roughly hewn would have made it easier to detect falling particles or other signs of instability.

In one corner of the chamber is a vertical shaft resembling a well, but its purpose remains unexplained. Given its location, it clearly was not intended for drawing water.

Because the chamber is carved into limestone bedrock, groundwater would have been a serious threat. Water can weaken limestone, dissolve it to form cavities like those in karst terrain, or seep through micro-fractures—any of which would indicate instability. The mere presence of groundwater seepage would imply the existence of continuous fine cracks.

When all of this information is considered together—the chamber's precise location beneath the pyramid's center, the presence of the unexplained vertical shaft, and the unfinished yet functional nature of the space—it becomes increasingly plausible that this chamber served as a monitoring post. Its purpose may have been to detect abnormalities in the bedrock directly beneath the pyramid's center and to ensure that groundwater did not infiltrate the area during construction.

However, this hypothesis would collapse unless the depth of the vertical shaft matched the maximum historical water level of the Nile. Although various surveys of the Giza Plateau exist, many lack clearly defined elevation reference points, and for a long time I was unable to confirm the necessary data.

This changed when I examined the study by Dr. Gamal Younes and colleagues, The pyramid builders' waterways: Reconstructing the ancient

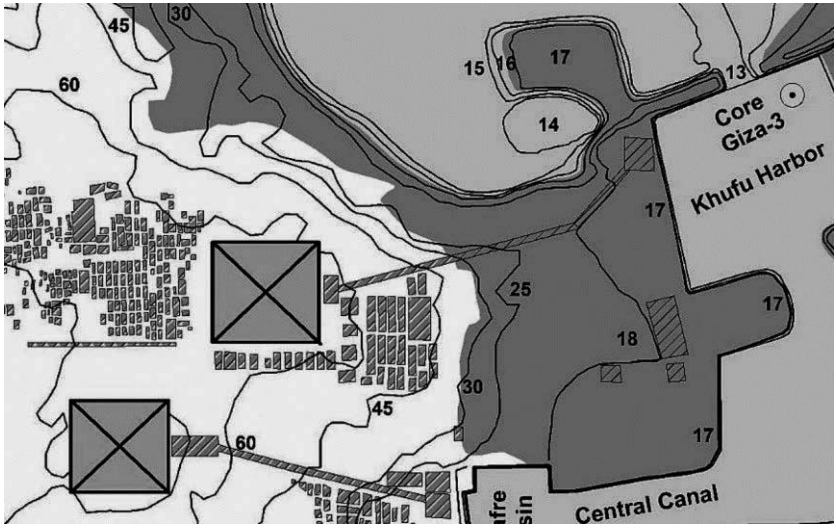

Fig. 8-5. Contour map of the area surrounding the Pyramid of Khufu, showing zones where Nile alluvial mud remains (shaded areas)

topography of Khufu's Pharaonic Harbour at Giza, Egypt. Their maps show that the Pyramid of Khufu stands at an elevation of 60 meters plus α, and that the alluvial mud deposited by ancient Nile floods reaches the 30-meter contour line.

Since the Subterranean Chamber lies 30 meters below the pyramid's base, excavating the vertical shaft an additional depth of α from the chamber floor would have reached the maximum flood level of the ancient Nile. In other words, by digging this shaft, the builders could confirm whether the bedrock beneath the pyramid had ever been eroded or weakened by past extreme floods.

Furthermore, the fact that the chamber itself is located at a depth of 30 meters means that it was deliberately positioned above the highest historical water level. This suggests that the chamber was intentionally placed as deep as possible within the bedrock while still remaining above the maximum flood elevation—a depth chosen with clear purpose.

As construction progressed and millions of stone blocks accumulated, the ground pressure at the pyramid's center would have increased

steadily. If any harmful effects on the bedrock had been detected, it would have served as a warning that a crisis similar to the near-collapse of the Bent Pyramid was unfolding. For the project members, continuous monitoring would have been essential.

One might question whether ancient Egyptians possessed a "monitoring mindset" comparable to modern engineering practice. Yet the existence of Nileometers, systematic astronomical observations, and other long-term measurement traditions suggests that continuous monitoring was entirely natural within ancient Egyptian culture.

The pyramid project members were deeply concerned about vertical ground pressure. Today, with modern structural mechanics and material science, we know that the ground pressure beneath Khufu's Pyramid is approximately 120 tons per square meter, and analyses show that the limestone bedrock at Giza has more than sufficient bearing capacity to support this load (Hemeda, S., and A. Sonbol. 2020. "Sustainability Problems of the Giza Pyramids." Heritage Science 8: 8.).

Therefore, the monitoring post 30 meters underground likely detected no abnormalities throughout the construction period.

However, the Egyptians of 4,500 years ago had no way of knowing this safety margin. Their anxiety about ground pressure must have been constant.

3. The Struggle with Gravity Load Distribution

One of the most distinctive features of the Pyramid of Khufu is the complexity of its internal structure. This includes not only the Grand Gallery and the elaborate gravity-relieving systems above the King's Chamber, but also the unused Queen's Chamber and the numerous voids that have been discovered in recent years.

From the perspective of technical project management, the internal spaces of Khufu's Pyramid can be broadly divided into two categories.

The first category consists of the Queen's Chamber, the Grand Gallery, the King's Chamber, and the gravity-relieving structures—spaces that

were ultimately not used for their presumed original purposes. These appear to represent a heavily reinforced safety-oriented design philosophy, in which every conceivable idea was incorporated during the planning stage (see Fig. 8-2).

Technically, the pyramid employs three major structural methods:

1. corbelled construction
2. gabled roofs
3. flat ceilings formed by massive stone beams

Among these, corbelled construction involves stacking stones so that each successive layer projects slightly inward, creating the necessary space for passages or chambers and resulting in a high ceiling. This technique was used in the burial chambers of Sneferu's Bent Pyramid and Red Pyramid, and in Khufu's Pyramid it appears most prominently in the ceiling of the Grand Gallery.

The Grand Gallery itself is a structure whose design intent is difficult to understand. In the Dahshur pyramids, corbelled vaulting clearly served to protect the burial chamber. But the Grand Gallery is merely a passageway. It is unclear why such an enormous gravity-relieving structure was required for a space that is not a chamber.

From its spatial relationship with the Queen's Chamber and the horizontal passage leading to it, I suspect that the Grand Gallery's

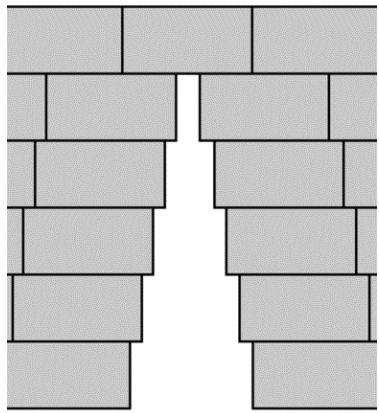

Fig. 8-6. Conceptual diagram of the corbelled construction



Fig. 8-7. The massive gabled structure above the original entrance of the Pyramid of Khufu (photographed in 2008; the lower area with tourists marks the looters' tunnel now used as the modern tourist entrance)

gravity-relieving design may originally have been intended to protect the Queen's Chamber and its approach. In other words, the Grand Gallery may have begun as a structural solution for a chamber that ultimately went unused.

The next major structural method is the gabled ceiling. In Old Kingdom Egypt, the true arch—developed in Mesopotamia and later widely used in Roman triumphal arches—was not yet known. Thus, the gabled ceiling was the established method for resisting vertical gravitational loads. I believe that Khufu's Pyramid represents the earliest known use of this technique in a pyramid. Gabled ceilings appear above the Queen's Chamber, at the uppermost tier of the gravity-relieving system above the King's Chamber, and above the original entrance.

The massive gabled stones above the entrance are particularly striking. In Fig. 8-7, the presence of tourists provides a scale reference, making the enormous thickness of the stones immediately apparent—and they are

laid in two layers. When one stands before this structure, it conveys not a sense of rational minimalism but rather an unmistakable intention to pursue the maximum possible safety, regardless of cost. To me, the gabled stones themselves feel like a silent declaration:

"Beyond this point lies a space that cannot be governed by rationality alone."

Another technique is the flat ceiling supported by thick stone slabs or beams, a method commonly used for passage ceilings. In Khufu's Pyramid, the ceiling of the King's Chamber is formed by massive granite beams, and above them an additional gravity-relieving system was constructed.

It seems unlikely that the builders rigorously evaluated whether such complex structures were strictly necessary. Rather, they appear to have taken every possible precaution in advance to counter vertical gravitational loads. This attitude resembles the approach taken in the Red Pyramid, where safety was prioritized over economic efficiency, resulting in the conservative 43-degree slope.

In Khufu's Pyramid, the burial chamber appears to have shifted progressively upward during the design process—from the initial subterranean chamber, to the unused Queen's Chamber, and finally to the King's Chamber.

A second group of internal features consists of the numerous voids whose shapes and locations lack consistency. These were not part of the original design; rather, they appear to be ad-hoc responses to problems encountered during construction. Their irregular forms, lack of pattern, and unclear purposes suggest that the builders were forced to create additional spaces as they adapted to unforeseen structural issues. These voids seem to be evidence that the struggle against gravity load—and the unintended side effects of that struggle—exceeded the assumptions made during the design stage.

Several well-known structural problems occurred during the construction of Khufu's Pyramid, including the cracking of the granite beams in the King's Chamber and the jamming of the granite blocking system in the ascending passage.

The cracking of the King's Chamber beams refers to the fractures visible in the granite ceiling beams. The French architect Gilles Dormion proposed that the gravity-relieving chambers were hastily added in response to these cracks. However, because the relieving chambers lie directly above the King's Chamber, his theory would require the beams to have cracked before any weight was placed above them—an implausible scenario. Consequently, his hypothesis has not gained support among specialists. The gravity-relieving system was almost certainly part of the original design, intended to distribute the vertical load of the overlying masonry.

The "jamming of the ascending passage" refers to the granite blocking mechanism installed within the Grand Gallery, which became stuck during operation and had to be compensated for with packing stones.

I believe that the jamming of the granite blocking system in the ascending passage was a typical side effect of the project members' extreme fear of vertical loads. Because of this fear, they installed a large gravity-relieving structure above the Grand Gallery. A gravity-relieving structure, by definition, redirects vertical pressure into horizontal pressure. This horizontal pressure can deform the joints between structural elements. I consider the malfunction of the blocking system to be a consequence of this effect.

Given the enormous scale of the gravity-relieving structure above the Grand Gallery, it is likely that the resulting horizontal stresses produced distortions over a wide area. Recent muon-radiography studies have revealed a large void above the Grand Gallery. I do not believe this void was created by the horizontal stresses; rather, it seems to have been an emergency space intentionally created to prevent further propagation of strain.

In other words, the excessive use of gravity-relieving structures—driven by the designers' fear of vertical loads—may have generated horizontal stresses that adversely affected the pyramid's outer regions, particularly the casing stones.

As discussed in Chapter 7, the lower portion of the Bent Pyramid

employed inward-tilted masonry, which produced enormous vertical pressure at the center. This, in turn, imposed excessive load on the weak ground beneath, nearly causing structural failure. In response, the upper portion of the Bent Pyramid adopted horizontal masonry, a method that was then carried over into the Red Pyramid. Khufu's Pyramid also employs horizontal masonry as its basic structural principle.

However, even horizontal masonry produces horizontal stress when subjected to massive vertical loads. This may seem counterintuitive, but stone is not a perfectly rigid body; under pressure, it undergoes slight deformation.

When a vertical load is applied, the stone compresses slightly in the vertical direction and expands laterally. This is analogous—on an extremely small scale—to how bread dough flattens and spreads outward when pressed from above. Although stone deforms far less than dough, the principle is the same: vertical compression produces horizontal expansion, and thus horizontal stress.

The same applies to gabled ceilings, which also generate horizontal thrust.

In a pyramid, the interior is densely packed with masonry, so the horizontal stress is transmitted outward. This outward pressure contributes to cracking and detachment of the casing stones.

It is characteristic of Khufu's Pyramid that multiple, fundamentally

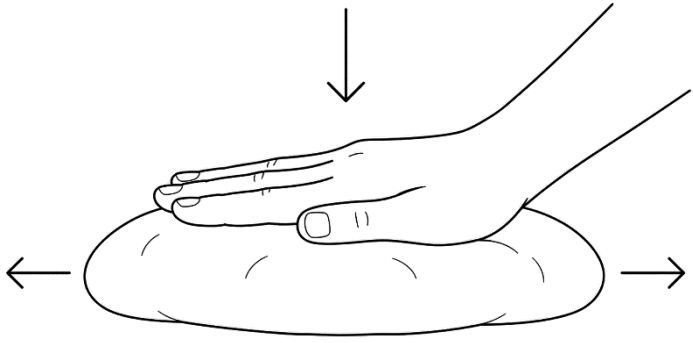

Fig. 8-8. Bread dough spreads sideways when compressed from above

different methods of resisting gravitational loads—corbelled vaulting, gabled ceilings, and massive stone-beam flat roofs—were used simultaneously.

This suggests that the pyramid was not the work of a single brilliant designer, but rather the product of a team of engineers, each with deep expertise in different structural techniques, working together to solve unprecedented challenges.