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Construction of the Great Pyramid with pulley-like systems using counter-weights on sliding-ramps

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The construction method of Khufu's Great Pyramid remains debated. Several theories have been proposed that implicate construction-ramps and a layer-by-layer bottom-to-top growth progress. Regrettably, none provides satisfactory explanations how to lift blocks weighing up to ~60 tons and for the tremendous pace to place blocks every ~1 min. Here, a radically different proposal for the construction of the Great Pyramid is presented, where blocks were lifted using pulley-like systems fueled by sliding counterweights down sliding-ramps. One pulley-like system and three sliding-ramps are still visible today, assigned as the Antechamber, and as the Grand Gallery, Ascending Passage, and Descending Passage, respectively. The construction proposal based on analysis of the pyramid's architecture and masonry, is physically advantageous and can explain the fast construction. The proposal offers explanations for the recently discovered voids, and for structural features such as the course height variations, the concavity and the central furrow of the pyramid faces.

When Herodotus, arguably one of the first historians, traveled to Egypt in ~450 BC, he was equally in awe of the Great Pyramid, built ~2600 BC, as any modern-day tourist. As any intellectual, he asked himself the question: how did they build the Great Pyramid? Herodotus apparently talked to locals and priests, trying to get information about the construction process. He noted in his 2nd book of the Histories series, called Euterpe, that they used machines, that the construction took 20 years, and that they finished the highest parts first[1] (Citation S1). The construction duration of ~20 years matches roughly the length of Khufu's reign, 23 years according to the Turin king list. Some modern-day Egyptologists suggested that the construction could have taken only ~10 years[2,3], but the recent discovery of the Wadi El-Jarf papyri indicates that pyramid construction lasted until the very end of Khufu's reign[4,5]. However, Herodotus also reported that the amount of onions and leeks provided for the workers was noted on the pyramid—it is thus unclear if Herodotus got reliable information about the pyramid construction in ~450 BC. A likely scenario is that with the decay of the Old Kingdom at the end of the 6th Dynasty and the beginning of the first intermediate period, ~2200BC[6], knowledge about the construction of the Great Pyramid was lost, thus ~4200 years ago.

In numbers, the Great Pyramid of Giza, *aka*. King Khufu's pyramid has a height, h, of ~146 m, a side width, w, of ~230 m, and thus a volume, $V_{(total)}$, of ~2,574,467 m^3 (following $V_{(total)} = w^2h/3$). Most of the pyramid is built of limestone blocks. Overall, the blocks in the lowest courses (def., stone block layers as visible today on the pyramid without casing) are larger, with dimensions of about 1 m × 2.5 m × 1.5 m, and heavier, ~10 tons, than the blocks in the higher layers, with dimensions of about 1 m × 1 m × 0.5 m, and weight of ~1.3 tons[7,8]; though the block height distribution is much more irregular and decays in height sections[8]. The average block weighs ~2.5 tons, and an estimated ~2.3 million blocks were used to build the pyramid[7]. The total construction time can be estimated by adopting a duration of ~20 years and a ~16-h work-day, assuming an excess number of workers that could work in shifts as long as daylight was sufficient. If workers were called for state's service during the inundation season only, ~4 months, i.e., 120 days per year, it yields ~2,304,000 min (20 × 120 × 16 × 60), while if work is considered to have advanced all year, i.e., 360 days, at identical intensity, it yields ~6,912,000 min (20 × 360 × 16 × 60) of construction time. Thus, the blocks had to be placed at a pace of 1 block per minute to 1 block every 3 min. If one were to consider a shorter, ~10 years, construction period[2,3], blocks had to be placed between every 30 and 90 s. The limestone originated from a quarry just ~500 m south of the Great Pyramid[7]. To a lesser extent, for the casing, white Tura limestone from ~10 km across the Nile was used[7]. Finally, to a much lesser amount, ~3000 m^3, or ~8000 tons, thus ~0.1% of the total volume, the pyramid is constituted of granite from Aswan, ~1000 km up the Nile[7]. It is of the Aswan granite that the King's Chamber was built, using blocks of size up to ~8 m × ~1.5 m × ~2 m, weighing ~60 tons[7,9,10].

It should however be noted, in contrast to our preconception of the pyramid structure, the inner masonry is quite chaotic. Indeed, while the exposed interior faces of the major architectural elements display millimeter-precision fittings between blocks, and the outer casing stones were equally well fitted as can be concluded from the remaining casing stones on the

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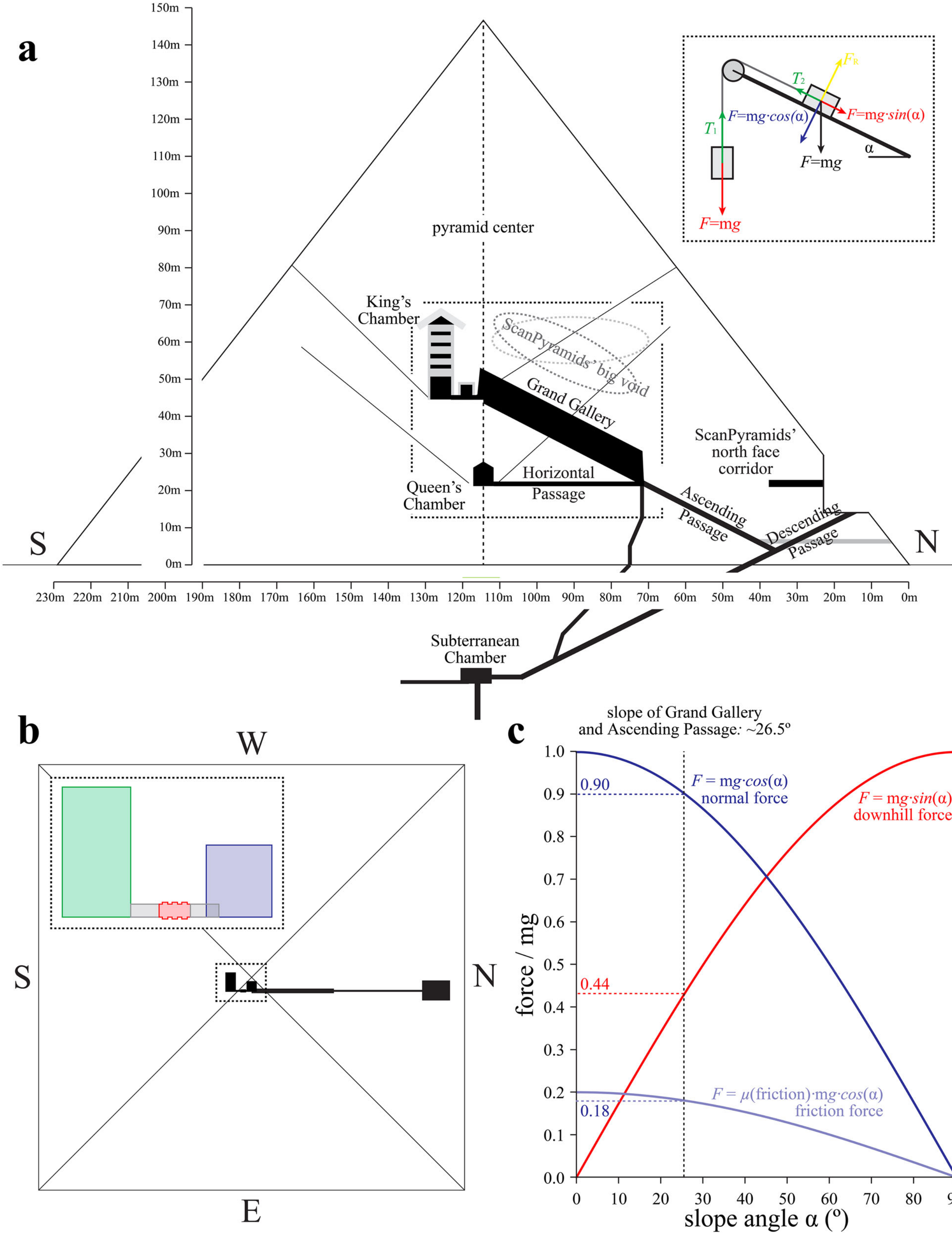
pyramid North face, the outer mantle was of good quality, but where the stone arrangement in previously inaccessible regions can be accessed and inspected, the masonry is found a rather random arrangement of bigger and smaller blocks interspersed by even smaller boulders and mortar[8,9,11,12]. The internal masonry structure can be seen when entering the pyramid through Al-Mamoun's tunnel[13], or when inspecting the large crevasse that Vyse dynamited into the south face[11,12].

While excavations on the Giza plateau provided invaluable insights into the living conditions of the pyramid workers[14], and the finding of logbooks of a ship crew revealed some of the organizational aspects of stone transport from Tura[5], no documents from Khufu's times were found that explain how the pyramid was built. Thus, modern-day Egyptologists ask themselves the same question as Herodotus, and propose various theories for the Great Pyramid's construction[2,3,15–21]. The generally accepted theories rely on construction-ramps on which stone blocks mounted on sledges were pulled up the growing pyramid, constructing the pyramid rather symmetrically, layer-by-layer and bottom-to-top[22], though construction based on levering has also been proposed[23]. The appeal of construction-ramp models is their simplicity. Construction-ramp models rely on brute-force, i.e., calling for a quasi-unlimited contingent of workforce, combined with limited engineering, i.e., building a ramp and dragging blocks up the ramp—they do not call for an unknown technical innovation. However, the use of construction-ramps, in most general terms, runs into three major problems: (i) *The physics is unfavorable*: There are two force components that need to be provided to pull a block up a ramp, a force to lift the block, $F_{(\text{lifting})} = mg{\cdot}\sin(\alpha)$, and a force to overcome the friction between block, i.e., the sledge it is on, and the ramp, $F_{(\text{friction})} = \mu_{(\text{friction})}{\cdot}mg{\cdot}\cos(\alpha)$; where m is the mass of the block, g is the gravity on earth, 9.8 m/s^2, α is the inclination angle of the ramp, and $\mu_{(\text{friction})}$ is the friction coefficient of wood on mud-brick, ~0.6[24] (see Fig. 1c). The friction force scales with the cosine of the slope angle. The cosine function is flat for small angles; it only decreases from 1 to 0.9 for ramps ranging from 0° to 25°. In contrast, the lifting force scales with the sine of the slope angle, and the sine function increases almost linearly for small angles. Thus, the lifting force rises from 0 to 0.42 for ramps ranging from 0° to 25°. Therefore, steeper ramps demand much greater effort. This is why many ramp models propose rather flat ramps, e.g., ~10%, i.e., ~5.71°. For such a slope, the cosine is 0.995 and the sine is 0.1. Thus, to keep the lifting force low on a flat ramp, the ramp must be long, i.e., ~10 times the height it needs to reach, and the friction force remains high. (ii) *The large length of ramps and absence of archeological traces*: As a consequence of the ramp having to be flat, ~10%, to be operable (see point (i)), the final ramp must be ~10 times longer than the pyramid working height, thus ~1.5 km in its final state. However, for a large linear or bent ramp of that length, there is limited space on the Giza plateau, as the major limestone quarry is just ~500 m south of the Great Pyramid[7], and the volume of such a ramp would be multiple times the volume of the pyramid. No archeological remains of such a ramp have been found. (iii) *The slowness to operate on spiral ramps*: To circumvent the problems of ramp length and volume (see point (ii)), several spiral ramp models have been proposed, where the length of the ramp is distributed by winding the ramp up the pyramid. However, it is impossible to design a 1.5 km long ramp around a pyramid with base width 230 m. Therefore, spiral ramp models usually propose steeper ramps, with even less favorable physics, and, given the decreasing side-length of the pyramid at higher height, increasing slope with increasing height. Spiral ramp models come in two flavors, where the ramp is either a mud-brick ramp built on top of the pyramid faces, i.e., external ramp[15,22], or the ramp is part of the pyramid, i.e., integrated or internal ramp[20,21]. Necessary features of spiral ramps, in general, are that they are narrow and have corners. As a consequence, spiral ramps around the pyramid are only practicable by pulling blocks up in single file. However, in a single-file model, no work-unit can advance faster than the slowest work-unit. In addition, all spiral models (to accommodate the ~1 km length) include ~20 corners spiraling up the pyramid, where the blocks have to be rotated by 90°. In these operations, work-units are necessarily stalled, which means that all work-units behind them are also stalled. Once a corner block is rotated, the work-unit cannot move out of its position unless all blocks and corner blocks ahead have moved (Fig. S1). In other words, since there are always several blocks in corner positions stalling the entire file, and since the slowest corner block rotation plus the delay time to start moving all blocks behind it define the pace for each work-unit advancement—single-file spiral ramp models are mostly standing, and it seems highly unlikely that single-file spiral ramp models could reach the pace to place 1 block every ~1 min. In addition, most construction-ramp models do not provide solutions to how the largest and heaviest blocks were transported up the pyramid. Finally, mixed models comprising straight and spiraling ramps have been proposed[18]. The general problems of ramp models have been discussed[18], indicating that ultimately modern-day Egyptologists might agree that the solution to how the Great Pyramid was built is yet to be found (further discussion of construction-ramp models, Text S1).

Inspection of the pyramid in side- (Fig. 1a) and top- (Fig. 1b) view, reveals clustering of King's Chamber, Queen's Chamber, and Antechamber close to a common vertical axis, however, without superposition of these elements[2,25] (Fig. 1a, b, inset). While the Queen's Chamber is centered in the North-South axis (Fig. 1a) it is off the East-West axis center (Fig. 1b). Note, the Queen's chamber is not considered to have been planned as a burial place for a queen, but to represent either an abandoned plan as the king's burial chamber[3], or as a serdab for the King's Ka statue[16]. The Descending Passage, Ascending Passage, and Grand Gallery are parallel to the North–South axis but shifted to the East by ~7 m (Fig. 1b). The ~10.5 m long King's Chamber, reaches the center of the East-West axis but is still largely on the East side, and substantially displaced, ~11 m, to the South of the North–South axis center (Fig. 1a, b). The clustering without superposition, combined with the absence of coherent and harmonious alignment and placement of the major architectural elements with the general pyramid geometry, indicated to me that these architectural elements likely were structurally and constructionally related—and that their locations were the result of technical compromises. If the pyramid had been built using construction ramps and layer-by-layer bottom-to-top, why would these major architectural elements not be placed in the most meaningful locations in the pyramid, e.g., the central axis? Of course, mystical reasons can be invoked, declaring that the factual placement was deliberately chosen and meaningful, but these sound like reverse-engineered answers to questions that were not appropriately addressed. In contrast, I propose that the placement of all architectural elements is the result of compromises and constraints imposed by the construction process.

Here, I propose a model of the Great Pyramid's construction that is radically different from previous models, as it does not call for any construction-ramps on which blocks were pulled up but relies on pulley-like systems using counter-weights on sliding-ramps. In addition to the assessments of the clustering without superposition and odd positioning of the major architectural elements, the construction model proposed here evolved from the following observations: First, I recognized that the Grand Gallery had all signatures of a sliding-ramp useful for force-generation, that Grand Gallery and the Ascending Passage formed one continuous sliding-ramp with identical orientation, slope, and width, where the Ascending Passage represents a linear extension of the Grand Gallery, or inversely, that the Grand Gallery represents a linear prolongation of the Ascending Passage during construction. Second, I recognized that the Antechamber structure could be interpreted as a pulley-like system, rather than as a portcullis system, which is its general assignment. Based on these observations, I propose that the Antechamber served as a pulley-like system to lift blocks, fueled by the force generated by counter-weight sliding down the Grand Gallery and the Ascending Passage. The pulley-like system/sliding-ramp model has substantial physical advantages over construction-ramp models (Table S1). Further, the model explains the arrangement of the King's Chamber, Queen's Chamber, and Antechamber, and the linearity of all passages. Also, the model, extended to the entire pyramid, provides interpretations for the recently discovered voids, i.e., Scan Pyramids' big void[26] and Scan Pyramids' north face corridor[27,28], for structural oddities like the girdle masonry of the Ascending Passage, the linear arrangement of masonry blocks in the Horizontal Passage to the Queen's Chamber[8,9], as well as the concavity[29], the central furrow[30] and pattern of course-heights[8] on the pyramid faces, the morphology of the shafts



emerging from the Queen's and King's Chambers, etc. (Table S2). Conversely, many structural features of the pyramid provide support for the model. In summary, the model performs better than other models from a physical perspective and provides explanations for so-far unexplained structural observations, for the fast construction pace, and for how 60-ton heavy blocks could be lifted 70 m high in ~2600 BC.

Results

The Ascending Passage and the Grand Gallery were sliding-ramps for force generation

First, I noticed that the Grand Gallery (Fig. 1a), built of blocks that are inserted into the pyramid at the angle of inclination of the Grand Gallery itself[9], could represent a sliding-ramp for counter-weights for force generation

Fig. 1 | General layout of the Great Pyramid's internal structure and physics of a counter-weight sliding down a sliding-ramp with the characteristics of the Grand Gallery and the Ascending Passage. **a** Side-view (North–South) of the Great Pyramid with internal structures, i.e., King's Chamber, Queen's Chamber, Grand Gallery, Ascending Passage, Descending Passage, Horizontal Passage, Subterranean Chamber, as labeled. Recently discovered structures, i.e., Scan Pyramids' big void (proposed, gray dashed lines) and Scan Pyramids' north face corridor (confirmed), are also labeled. Note, Grand Gallery and Ascending Passage form a continuous sliding-ramp. Inset: Schematic of forces related to a hanging block and a block on an inclination of ~26.5° (see main text, Movie S1). **b** Top-view of the Great Pyramid with internal structures, i.e., King's Chamber, Queen's Chamber, Grand Gallery, Ascending Passage. Note that the Grand Gallery and Ascending Passage are in a continuous straight line. Note the concentration, but not superposition, of King's Chamber, Antechamber and Queen's Chamber close to the pyramid center. Black represents hollow spaces in **a** and **b**, granite structures of King's Chamber and Antechamber are shown in gray. Inset: Arrangement of King's Chamber (green), Antechamber (red) and Queen's Chamber (blue) (drawing based on: Fig. 2 in Perring et al. The Pyramids of Gizeh, from Actual Survey and Admeasurement, London 1939[25] and Fig. 26 in Romer, The Great Pyramid: Ancient Egypt Revisited[2]). **c** Forces generated by a counter-weight of mass, *m*, in the earth's gravitation, *g*, as a function of sliding-ramp slope. The Grand Gallery and Ascending Passage slope angle, ~26.5° (1 cubit over 2 cubits, 50% slope; the Descending Passage has the same slope), is indicated by the vertical dashed line, and the components of downhill-, normal- and friction-forces by the horizontal dashed lines.

(Fig. 1a, inset). This had been suggested before, though in a different functional context[20]. Interestingly, these authors have readily provided evidence such as scratches and traces on the Grand Gallery side walls that indicate its possible use as a downward sliding-ramp for weight carrying sledges[20]. According to the model presented here, the South (upper) face of the Grand Gallery gives into a pulley-like system that is exposed to the South and to incoming blocks on the ground level, to lift them vertically up (see *"The Antechamber was a pulley-like system"*). In this context, it is important to note that the blocks of the Grand Gallery's south wall are not intercalated with the blocks of the East and West walls, as the blocks of the North wall are[20], indicating that the Grand Gallery was open on the South face until the later stages of pyramid construction. Second, the Grand Gallery and the Ascending Passage have the same direction, the same slope of ~26.5°, i.e., 1 cubit over 2 cubits, ~50% slope, and the same width[8], which I recognized as manifestations that they were one and the same sliding-ramp (see *"Construction of the pyramid core"*). Indeed, the area that is seen today at the interface of Ascending Passage and Grand Gallery, i.e., at the foot of the Grand Gallery and the beginning of the Horizontal Passage to the Queen's Chamber, has been described and analyzed in detail[9,31], and its interpretation appears quite consensual: Large cutouts in the sidewalls allowed the insertion of beams to support a platform that would connect the central ramp of the Grand Gallery and the Ascending Passage. A ~18 cm lowering of the Grand Gallery ramp at its lower end and a protruding ledge at the Ascending Passage's upper end are further indicators that a wooden bridge connected the two ramps[9].

The physics of such a sliding-ramp (Fig. 1a, inset) with an angle, α, of ~26.5°, is described as follows: A counter-weight of mass, m, pulls downhill with a force, $F_{(\text{downhill})} = mg\cdot\sin(\alpha)$, giving $0.44mg$ (Fig. 1c, red line). The component of the gravitational force that is normal to the slope, i.e., the force that pushes the mass onto the ramp surface (Fig. 1a, inset), scales with the cosine of the ramp angle, $F_{(\text{normal})} = mg\cdot\cos(\alpha)$, which is $0.90\cdot mg$ (Fig. 1c, dark blue line). Importantly, the normal force component is multiplied by the friction coefficient, $\mu_{(\text{friction})}$, to give the friction force, $F_{(\text{friction})} = \mu_{(\text{friction})}\cdot mg\cdot\cos(\alpha)$. The surface of the ramp is flat and smooth stone in the Grand Gallery and the Ascending Passage, and the object that was sent down the sliding-ramp was likely a wooden sledge, on which the downhill-sliding counter-weight was loaded. The friction coefficient between wood and stone, $\mu_{(\text{friction})}$, is between 0.2 and 0.4[24]. Conservatively, a friction coefficient of $\mu_{(\text{friction})} = 0.2$ is used here, but Hemiunu might have used a lubricant on the stone surface on which the sledge runners slid, which might have yielded an even lower friction coefficient. Anyway, the estimated friction force is $F_{(\text{friction})} = 0.2\cdot mg\cdot 0.90 = 0.18\cdot mg$ (Fig. 1c, light blue line). Thus, in such a system, the down-sliding weight could directly lift 0.44 times its own weight, and the friction is rather low.

The Antechamber was a pulley-like system

Second, I noticed that the Antechamber, situated on a platform between the top of the Grand Gallery and the King's Chamber and generally interpreted as a portcullis system as a last line of defense against intruders[8,9,22,31], could instead represent a pulley-like system (Fig. 2). Based on earlier, detailed drawings and measurements[9,31] (Fig. S2), a 3D-drawing of the structure was made (Fig. 2a, b).

The assignment of the Antechamber as a pulley-like system is likely the most challenging part of this proposal, as it represents a radical re-interpretation of a structure. Arguments putting into question the structure's assignment as a portcullis system, and favoring its reassignment as a pulley-like system, are the following:

First, and most importantly, the Antechamber's assignment as a portcullis system is questionable because it is non-functional unless one is to add additional blocking elements[9,17,32]: Indeed, the three supposed portcullis stone slabs had initially to be held at a height of ~1.1 m above the floor, the height of the two short passages on both sides of the Antechamber—to allow transport of the dead king and other goods into the chamber—before they were lowered[33]. However, upon lowering the slabs, space is freed up above the slabs, and robbers could climb over them, destroy or tilt away the third slab, or attack the South wall[17]. It appears difficult to accept that the architect who succeeded to build the Great Pyramid designed a faulty portcullis. Functional portcullis systems of different designs had been built before in Sneferu's pyramid[22]. In addition to the above-mentioned flaw, the railings in the side walls that were supposed to hold the portcullis slabs in place protrude from the walls by only ~8 cm, and robbers would only have had to chisel one of them away, and the portcullis could have been angled out.

Second, a portcullis system at this level of the pyramid would arguably be useless: The pyramid had functional closure mechanisms, e.g., coverage of the entrance and the plug blocks in the Ascending Passage[8], which are still unbroken. It appears therefore unreasonable that the pyramid builder had the illusion that tomb robbers that succeeded to break into the sealed pyramid, overcome the plug blocks, and make their way up to the tomb chamber, would be stopped by three stone slabs.

Third, the supposed portcullis system was difficult to maintain while the king was alive: According to general models, the portcullis granite slabs had to be mounted during pyramid construction, as the slabs should not easily be removed. This means that from the day the supposed portcullis system was built, to the day the pyramid was finalized, or a later day when the king died, the stone slabs had to be held in the up-position. Since the Antechamber is located at ~43 m height and was therefore likely completed after about half of the pyramid building time, this would represent between 5 and 10 years. The general portcullis system model comprises wood-logs inserted in the semi-circular indentations at the top of the portcullis (Fig. 2b) over which ropes were tightened to hold the slabs in place[33], and to further secure the slabs, additional wood-logs would have been placed under the slabs[9]. These precautions, however, should not have hampered the king's burial ceremony. Thus, the system might have gone awry at any time between its installation and burial.

Fourth, the 4 rope guidance grooves in the South-wall have each a diameter of ~10 cm (Fig. 2a, b), which seems in numbers and in suggested rope diameter an excessive design to hold portcullises. Thus, while these grooves are generally interpreted as rope guidance grooves in a portcullis system[8,9,31], their number and characteristics point towards a pulley-like system that can carry the heaviest loads. However, the rope guidance grooves per se do not need to be reassigned.

Fifth, the rope guidance grooves in the south wall are ~2.65 m in height, extending by ~94 cm above the position of the wood-logs, which is

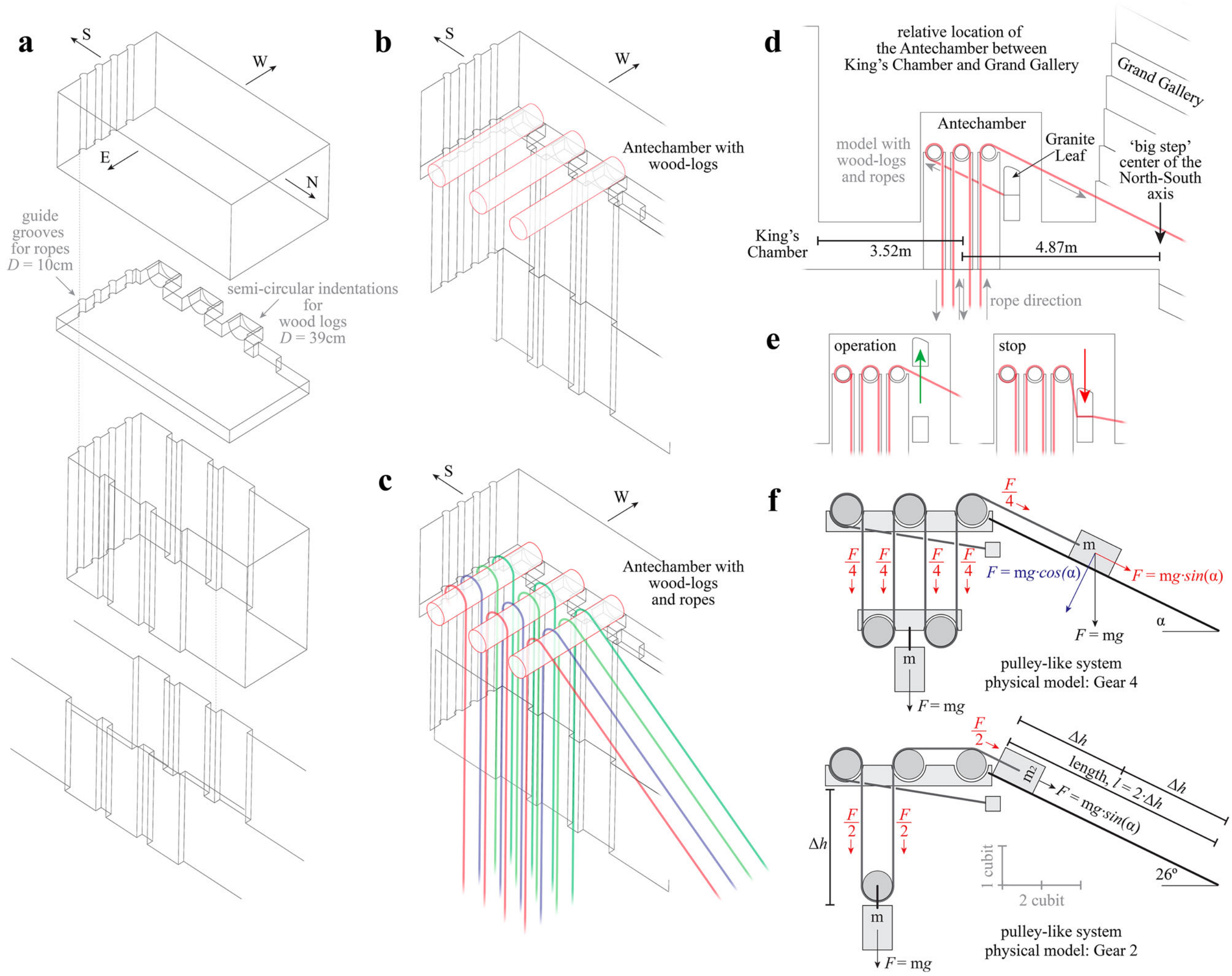


Fig. 2 | The Antechamber was a pulley-like system. **a** 3D-representation of the Antechamber with the different levels with individual architectural features superposed for clarity (3D-drawing based on measurements and representations from: Plate X in Piazzi Smyth, Our Inheritance in the Great Pyramid. 3rd, new and enlarged edition. London 1874[31], and Tavola 7 in Vito Maragioglio, L'Architettura delle Piramidi Menfite, Part IV, Roma 1965[9]). **b** 3D-representation of the Antechamber with wood-logs, looking onto the South- and West-walls with the North and East walls omitted for clarity. **c** 3D-representation of the Antechamber with wood-logs and a hypothetical arrangement of ropes. Given the four rope-guidance grooves in the South-wall, a system of 4 parallel ropes (colored red, blue, yellow and green) is suggested. The use of 4 parallel ropes distributes the heavy weight of the blocks, up to ~60 tons, to be lifted. **d** Relative location of the Antechamber pulley-like system with regard to the Grand Gallery and the King's Chamber. Note, the perfect fit of the rope(s) (red) descending from the first wood-log with an identical slope as the Grand Gallery, 26.5°, into the sliding-ramp. The 'big step' at the South side of the Grand Gallery (black arrow) is in the center of the North-South axis, and above the center of the Queen's Chamber. Defining the center wood-log as the center of the pulley-like system, the center of the mechanism is ~4.87 m South of the 'big step' at the end of the Grand Gallery and ~3.52 m North of the King's Chamber. Illustrating the pulley-like system in the current architectural setting may appear contradictory; however, the Grand Gallery's upper end and the floor of the Antechamber were open until the later stage of construction. **e** Use of the upper slab with the boss of the Granite Leaf to stop rope movement during counter-weight reset in the Grand Gallery, when the pulley-like system was operated in gear 4. **f** Possible configurations of ropes in the pulley-like system: To effectively divide the pulling force by a factor of 4, in order to lift the ~60 tons heavy blocks, the pulley-like system might have been operated in gear 4 (top), while for the majority of 'normal' building blocks, the pulley-like system was likely operated in gear 2, where in order to lift a block by height Δh, the length l of rope to be pulled is $2{\cdot}\Delta h$, perfectly matched with a sliding-ramp with slope 1 cubit over 2 cubits (Movie S1).

nonsensical in the setting of a portcullis system, because ropes would never have passed above the wood-logs (Figs. 2c and S2).

Sixth, the three semi-circular indentations, ~39 cm in diameter, on top of the west wall are generally interpreted to support wood-logs in a portcullis system[8,9,31]. Their diameter appears excessive to hold single portcullis slabs. However, the semi-circular indentations as wood-log supports per se do not need to be reassigned for the interpretation of the structure as a pulley-like system. Indeed, the ensemble of the grooves in the South-wall and the semi-circular indentations in the West-wall are generally interpreted to form a system of support and guidance for ropes that are wrapped around wood-logs for holding hanging weight, in a portcullis system as generally assumed[22], or in a pulley-like system as proposed here (Fig. 2c).

Seventh, the first wood-log, positioned at ~2.86 m height and ~4.17 m from the Grand Gallery, is perfectly positioned for a rope to pass over the Granite Leaf and extend down into the Grand Gallery at a ~26.5° angle, clearing the rope ~1 m above the big step of the Grand Gallery, and aligning the rope ~1.5 m above and parallel to the Grand Gallery floor (Fig. 2d).

Eighth, the assignment of the Antechamber as a pulley-like system provides a meaningful assignment for the Granite Leaf to secure the pulley-like system and to fix the other end of the ropes. Indeed, the boss on the north face of the upper part of the Granite Leaf[8,31] was probably used to lever the upper part of the leaf up for the frequent exchange of ropes (Figs. 2d, and S2). Alternatively, the upper Granite Leaf may have served to squeeze the ropes between the upper and lower slabs and block the mechanism (Fig. 2e): This is the likely mechanism to stop the advance or return of the ropes, when workers had to reset the counter-weights in the Grand Gallery sliding-ramp during operation of the pulley-like system in a high gear that needed extended rope length to be pulled, as will be detailed below.

Ninth, the Antechamber is of terrible workmanship, unworthy of an architectural element. Petrie described the Antechamber masonry as rough and course and testimony to how badly the masons could work[8] (Citation S2). The fact that the Antechamber masonry is so astonishingly rough and coarse[8], is indicative that the structure was not an architectural element, but a working tool. However, as the Antechamber pulley-like system is deep in the heart of the pyramid and had to be operational until the later stages of construction, it could not be removed.

Tenth, despite the portcullis system being the general assignment of the structure over the last 200 years, there is—to the best of my knowledge—no consensus, how the mechanism worked, beyond that it implicated wood-logs and ropes. The structure is not directly interpretable as a portcullis system, and entire elements, e.g., the Granite Leaf with its boss or the excessively high rope guidance-grooves, remained unexplained.

Eleventh, the Antechamber is almost entirely made of granite, even the parts that would only be accessible when the system was already broken, e.g., the South-wall. The fact that the sturdiest stone was chosen for the entire structure is suggestive of it representing a working tool that needed to withstand heavy loads.

Twelfth, the Antechamber is neighbored on both sides by platforms, ~3.52 m in direction of the King's Chamber and ~4.87 m in direction to the Grand Gallery, as measured from the central wood log, i.e., the center of the pulley-like system (Fig. 2d). These spaces, not really necessary for a portcullis system, appear well-positioned and of adequate size to space the pulley-like system from its neighboring architectural elements and to receive the newly lifted blocks to either the South or North side.

Thirteenth, further evidence in favor of the Antechamber being a pulley-like system comes from the inspection of its floor. The floor of the Antechamber was indeed a major concern regarding the feasibility of the model, as, if the Antechamber was indeed a pulley-like system, then the three wood-log-holding semi-circular indentations over which the ropes were folded must have been positioned above an open shaft (Fig. 2c, d). Inspection of photographs from the early 1900s showed that the first granite floor slab inside the Antechamber was inlaid[34] (Fig. S3), and so did the later drawings[9]. A visit to the Great Pyramid corroborated and extended this observation. The floor is very uneven with height mismatches of ~2 cm at the interfaces between the limestone of the plateau at the end of the Grand Gallery and the first granite inlay, and the last granite inlay and the King's Chamber floor. Indeed, all Antechamber floor slabs are inlays (Fig. S4). In summary, the floor shows that the Antechamber is an isolated element, not built in consistency with either of its neighboring architectural elements. The floor slabs being inlays was a condition for the model to be possible, as the area between Granite Leaf and rope grooves had to give into an open shaft until the later stages of pyramid core construction (Fig. 2c). Conversely, the fact that the Antechamber floor slabs are inlays between the walls and terribly uneven, provides further support for the Antechamber's re-assignment as a pulley-like system (Table S2).

Taken together, numerous evidence indicate that the Antechamber structure is hard to be interpreted as a portcullis system, and its execution points away from an architectural element.

Importantly, not only do the rope guidance grooves extend by ~94 cm above the wood-logs, they have been extended by ~37 cm in a today visible limestone block facing the Antechamber roof[31] (Fig. S2). This useless feature in the setting of a portcullis system should be noticed and put the assignment of the ensemble as a portcullis system into question (Figs. 2a–c and S2). A possible interpretation of the extended rope guidance grooves above the level of the wood-logs that held the ropes in the Antechamber structure is the following: At a later stage of pyramid construction, namely when the upper parts of the King's Chamber were built, the Antechamber pulley-like system of the Grand Gallery was retired, and blocks were lifted by a pulley-like system of the ScanPyramids' big void sliding-ramp directly to a higher height through the current Antechamber (see *"Construction of the pyramid core"*). Awaiting confirmation of ScanPyramids' big void, its assignment as an upper sliding-ramp remains hypothetical. This may also explain why the East-wall of the Antechamber is somewhat incomplete or damaged, i.e., the semi-circular indentations are missing, and the railings have been removed (Figs. S2, S3). The flatness of the east wall top is not a problem with regard to the Antechamber pulley-like system assignment, as it is not considered that the logs rotated. The logs may have been round on one side, placed in the West-wall semi-circular indentations, fixing them laterally and may have had a flat face on the other side, placed on top of the flat East-wall, fixing them rotationally. Alternatively, when the Antechamber pulley-like system was retired, its East-wall may have been altered for easier passage of blocks and the South-wall rope guidance grooves were extended to better guide the ropes coming from ScanPyramids' big void pulley-like system ~30 m higher up. This may explain the damage of the Antechamber South-wall with the rope guidance grooves (Fig. S5b) as the result of occasional hits by the thousands of blocks that were lifted through the Antechamber, which was then an open shaft (Table S2).

Moreover, Mariglio and Rinaldi observed that no portcullis system with slabs being lowered using logs and ropes had been built in any earlier pyramid[10] (Citation S3). Thus, if we were not to look at the system from a modern-day perspective, where we are used to see falling portcullis systems, e.g., in medieval castles, then the assignment of the structure as a portcullis system should be equally or more challenging than assigning it to a pulley-like system. It is known that the Old Kingdom Egyptians used systems combining a wooden lever and a rope to lift weights, e.g., Shadoofs[17], and pulling ropes over wood-logs was part of their daily use of boats. Importantly, excavations on the Giza plateau in the 1930s unearthed a tool, with dimensions ~12 cm × ~24 cm, made of granite that was interpreted as a pulley-like system[35] (Fig. S6). Thus, if Hemiunu experimented with small-scale pulley-like systems, he might have translated the principle to the large scale. In contrast, a falling type of portcullis system with ropes would have represented a novel invention, and should therefore, in historical perspective, attract scrutiny. As a reminder, the former portcullis system in Sneferu's pyramid featured a portcullis sliding laterally on an inclination, and later falling type portcullis systems, e.g., in the Pyramid of 5th Dynasty king Djedkare, did not comprise wood-logs and ropes[36]. As a reminder, the three plug blocks in the Ascending Passage of the Great Pyramid are, today, after ~4600 years, still unbroken. It thus appears that the assignment of the Antechamber structure as a portcullis system was based on its location in front of the King's Chamber, modern-day intuition with preconceptions about modern portcullis systems, and lacking another apt interpretation—and has been propagated since.

In summary, I propose that the Antechamber was a pulley-like system (Fig. 2c), with 4 parallel ropes that were on one end attached to a heavily loaded wood sledge that is sent sliding down the Grand Gallery, folded twice through the gaps between the three wood-logs, and secured on the other end between the two Granite Leaf slabs or elsewhere (Fig. 2d). As noted, the first log in the Antechamber is perfectly positioned to extend into a rope that stretches down into the Grand Gallery with a ~26.5° angle (Fig. 2d). I designate the system 'pulley-like' because I do not think that the logs rotated in the semi-circular granite stone indentations like wheels in modern pulley systems, instead I think that the ropes slid on well-polished and lubricated wood-logs. In such a setting, the friction coefficient of rope on well-polished and lubricated wood could have been lower than that of a wood-log rotating in a semi-circular granite stone indentation. A toy model combining a ramp with slope 1 over 2, i.e., ~26.5°, with a miniature pulley-like system mimicking the structure of the Antechamber (Fig. 2b, c) readily showed that such a pulley-like system could be used to lift weights (Movie S1).

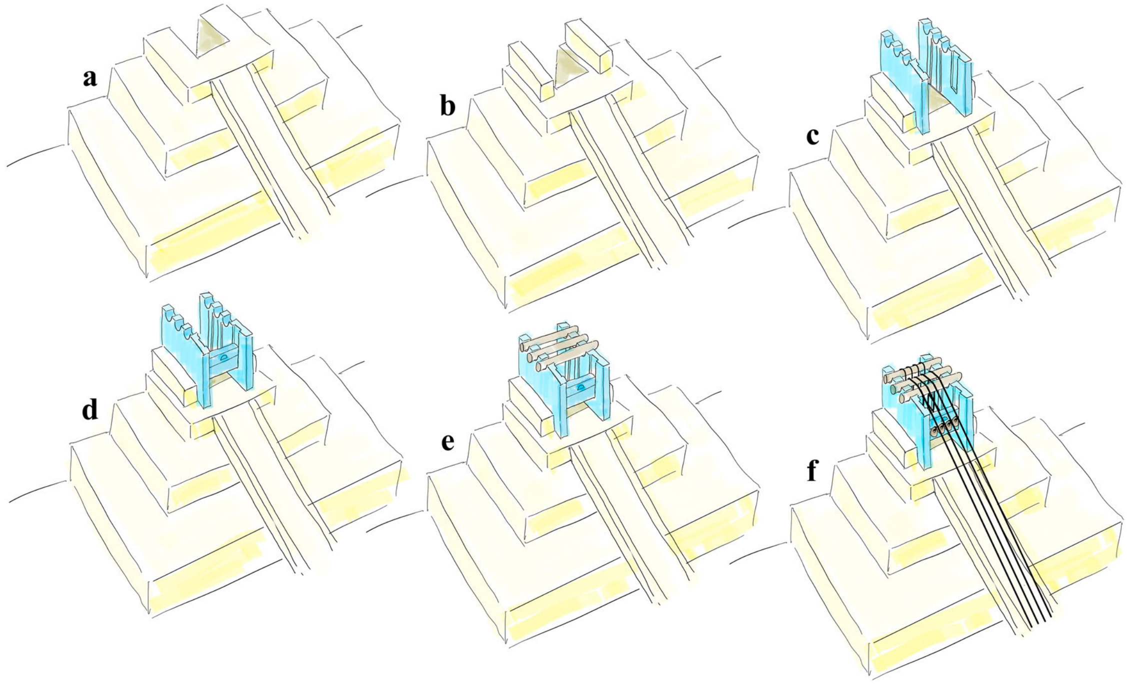


Fig. 3 | Method of assembly of the pulley-like system (schematic, simplified and not drawn to scale). a Schematic of the top of a sliding-ramp with a U-shaped shaft. The shaft structure could be created either by placing blocks in a U-shaped pattern or by corbeling the topmost blocks forward. **b** Placement of two blocks left and right outside the shaft. These blocks are shown rather small for better visibility of the latter stages. **c** Insertion of the pulley-like system side walls. The side walls are drawn symmetrically, duplicating the Antechamber West wall. **d** Insertion of the Granite Leaf fixes the side-walls and stabilizes the entire structure. **e** Addition of wood-logs (polished and lubricated) onto the semi-circular indentations. **f** The ropes are folded over the wood-logs and secured by lowering of the upper Granite Leaf slab, which could be levered up using the boss. Further details about the interface between sliding-ramp and pulley-like system, featuring vertical masonry at the upper end of the sliding-ramp to absorb lateral force, are given when discussing the Ascending Passage masonry, see *"Construction of the pyramid core"*.

The pulley-like system could be operated in various gears for force amplification

Importantly, the physics of the pulley-like system offers advantages (Fig. 2f). There are multiple ways that the ropes could be folded over the logs, allowing the system to be operated in different gears. In order to lift the heavy blocks for the construction of the King's Chamber, Hemiunu may have used a system similar to the one illustrated in (Fig. 2f, top), with two folds over the logs and thus 4 rope stretches connecting the pulley-like system to the mass to be lifted, which provides with the 4 parallel ropes a total of 16 rope stretches over which the total weight is distributed. The force needed to lift an object of weight, mg, is divided by the number, n, of rope stretches (not the parallel ropes) between the pulley-like system and the weight, which becomes mg/n (Fig. 2f, top). However, such a force amplification of the pulley-like system comes at a price: With an increasing number, n, of rope stretches between the weight to be lifted and the pulley-like system, the same number of rope stretches must be shortened during the lifting process. Thus, to lift a mass to height, Δh, the total length, l, of rope to be pulled is $l = n{\cdot}\Delta h$. In other words, when running the pulley-like system in gear 4, Hemiunu could 'reduce' the weight of a block of 60 tons, e.g., one of the granite beams, to 15 tons, but for this block to be lifted ~43 m, he had to pull ~172 m of rope. To accomplish this, the model suggests that the Granite Leaf was used, lifting and lowering the upper slab with the boss, to block the movement of the ropes (Fig. 2e) while the counter-weight sledge in the Grand Gallery was reset by the workers, the ropes reattached to the counter-weight sledge, and sequentially sent down the sliding-ramp, multiple times, until the full rope length was pulled and the granite beam lifted. The toy-model readily captures the functional mechanism of the pulley-like system and showcases that using different gears (Fig. 2f) force amplification is achieved (Movie S1).

For common use, to lift the ~2 million 'normal' blocks, I propose Hemiunu used pulley-like systems in gear 2 with 2 rope stretches between the pulley-like system and the mass (Fig. 2f, bottom, Table S1). In such a case, to lift a block of mass, m, with weight $1{\cdot}mg$, needing the pulling force to lift $0.5{\cdot}mg$, to height Δh, a counter-weight would be sent down the sliding-ramp over the distance of length $l = 2{\cdot}\Delta h$. Since, by using the pulley-like system in gear 2, the length of rope to be pulled is 2 times the height to be lifted, Hemiunu was perfectly served using sliding-ramps with slope 1 cubit over 2 cubits. I actually propose that this is the reason this slope angle was chosen for the Ascending Passage, Grand Gallery, and Descending Passage, and likely all other sliding-ramps.

Assembly and advance of the pulley-like system

As detailed below (see "Construction of the pyramid core" and "Construction of the pyramid mantle") the pyramid grew as sliding-ramps grew and the pulley-like systems were always at the open, top end of the sliding-ramps. Therefore, in order for the pulley-like system/sliding-ramp model to be efficacious, the pulley-like system must have been relatively easily (i) assembled and (ii) advanced during pyramid construction.

The assembly of the pulley-like system may have proceeded in the following way (Fig. 3): The schematic depicts the top of any intermediate of any sliding-ramp, where a U-shaped platform with two ~2 m protruding arms on the left and right of an open shaft is built (Fig. 3a). Two outside blocks are positioned on both sides of the shaft, letting some spacing between these blocks and the shaft (Fig. 3b). Next, the granite side walls of the pulley-like system are inserted on both sides of the shaft (Fig. 3c). While the two outside blocks assure that the pulley-like system side walls do not fall outwards, the insertion of the Granite Leaf assures that the pulley-like system side walls do not fall inwards (Fig. 3d). Next, well-polished wood-logs are positioned on the pulley-like system and lubricated (Fig. 3e). Finally, ropes are folded over the wood-logs, fixed on one side to the down-sliding sledge and on the other side secured between the upper and lower slab of the granite leaf (Fig. 3f). The upper part of the Granite Leaf features a semi-circular boss on its face towards the sliding-ramp (Fig. S2), likely used to position a lever to lift the upper Granite Leaf slab to insert and secure the

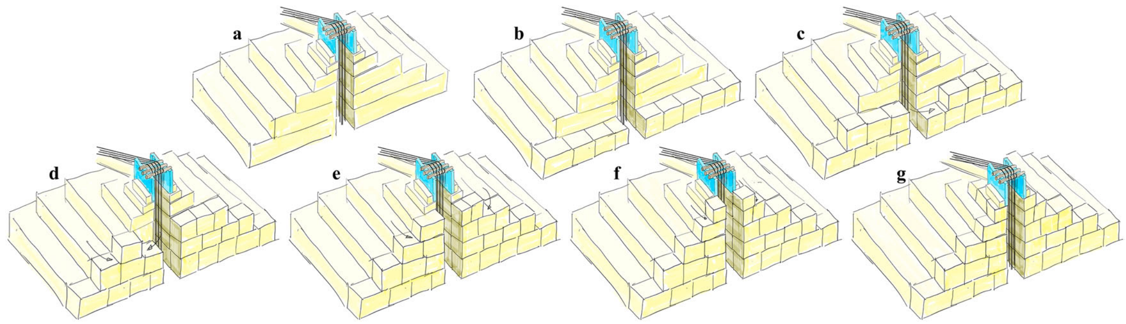


Fig. 4 | Method of advance of the pulley-like system (schematic, simplified and not drawn to scale). **a** Schematic of the pulley-like system at the top of a sliding-ramp. **b** Blocks of the base level are added. **c** Blocks of low courses are added by lifting them and extracting them laterally while the blocks are hanging on the ropes (arrow). **d** Blocks of intermediate courses are added by either lifting and laterally extracting them and/or by extracting them from the sliding ramp (arrows). In these intermediate course settings, the height-gain of a block to be lifted and the height-loss of a counter-weight block on the sliding-ramp are about equal, opening the possibility to use a construction block as counter-weight. **e** and **f** Blocks of upper courses are likely added from blocks that have been lifted entirely and then redistributed (arrows), or maybe laterally extracted from the hanging ropes. **g** As an additional course is completed, the pulley-like system is moved one step up (compare **g** to **a**).

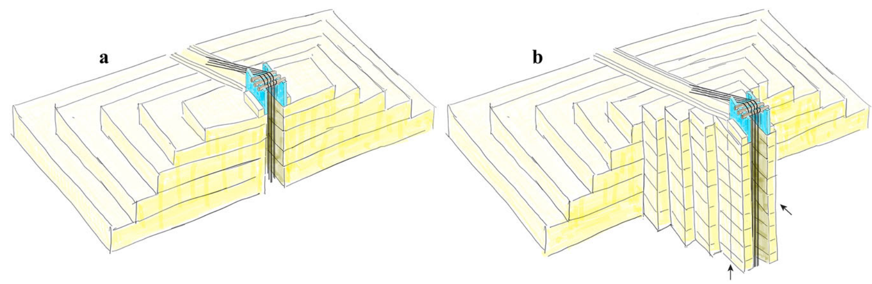


Fig. 5 | Advance of the pulley-like system explains cross-shaped joints between blocks in the Horizontal Passage (schematic, simplified and not drawn to scale). **a** Schematic of the top of a sliding-ramp with a pulley-like system. **b** The pulley-like system is advanced on a nose-like protrusion (without focus on pyramid construction), followed by an extended period of pyramid construction. The linear forward construction of the sliding-ramp can explain the cross-shaped joints in the walls underneath the ramp (arrows), as is visible today in the Horizontal Passage to the Queen's Chamber under the Grand Gallery.

ropes, maybe using small granite boulders with holes, reminiscent of small 4th dynasty anchors[37,38] (Fig. 3f).

The advance of the pulley-like system may have proceeded in the following way (Fig. 4): The schematic depicts any intermediate of any sliding-ramp, where the pulley-like system ropes reach to ground level or to the respective lower base level, in the case of any of the upper sliding-ramps (Fig. 4a). The base course blocks could be placed directly on each side of the pulley-like system shaft either on pyramid base level or by means of the pulley-like system of the sliding-ramp below the given sliding-ramp (Fig. 4b). The second course only needed lifting the blocks a couple of meters, and since in such a situation the ropes were long, it was likely easy to pull the blocks laterally out of axis and add them to the second course (Fig. 4c, arrow). I term this a 'lifting cycle' (see *"Force-generation through counter-weight sliding down the sliding-ramps"*). The third course is approximately in the middle of the sliding-ramp (in this schematic), and therefore building this course may be mediated by pulling blocks laterally out of axis and/or by adding them from blocks that went about half the way down the sliding-ramp (Fig. 4d, arrows). Indeed, using a pulley-like-system in gear 2, for any lifting height gain Δh, a counter-weight block had to slide down the sliding-ramp the length $l = 2 \cdot \Delta h$, and since its slope is 1 cubit over 2 cubits, the counter-block loses Δh in height. Also, in gear 2, the block to be lifted 'weights' 0.5 mg, while the counter-weight block sliding down the ramp generates 0.44 mg, while the friction keeps the system at rest. I term this process 'exchange cycle', meaning that two blocks, one being at the foot and one at the top of a sliding-ramp/pulley-like system, may both end up at half the height with minimal effort. In brief, these 'exchange cycles' could be interspersed with 'common cycles' using dedicated counter-weight blocks (see *"Force-generation through counter-weight sliding down sliding-ramps"*). While, for the lower courses, the lateral extraction was likely efficient, lateral extraction of blocks in the higher courses of a sliding-ramp may have been less easy because blocks hang on shorter ropes, and blocks may have been lifted in 'common cycles' all the way up and then laterally and downwards transferred to where the blocks were needed (Fig. 4e, f, arrows). Finally, ramp propagation reached the top course, and the pulley-like system was dismantled and reassembled (Fig. 3) on top of the new top course (Fig. 4g). The situation in Fig. 4g is reminiscent of the situation in Fig. 4a but one course higher.

While the process of sliding-ramp growth and pulley-like system advance should have progressed quite linearly and course-by-course (Figs. 3, 4), the pyramid construction process may not have advanced that linearly. Indeed, in light of the masonry signatures in the Horizontal and Ascending Passages[8,9], it seems likely that the sliding-ramps were advanced in spurts of ~10 m height, advancing the sliding-ramps on a nose-shaped protrusion (Fig. 5a, b), and then focus on pyramid construction from the given position of the pulley-like system. The largely linear forward progression of the nose-shaped protrusion naturally leads to an odd arrangement of the blocks under the sliding-ramp (Fig. 5b, arrows).

In the schematic representations (Figs. 3–5) the pulley-like system is shown reminiscent of the Antechamber structure for consistency and clarity. However, the Antechamber pulley-like system was/is likely an exceptional structure built in granite for the construction of the major architectural elements constituted of the heaviest blocks, ~60 tons, while in other locations where 'normal' blocks, ~2.5 tons, were lifted (see "Construction of the pyramid mantle"), likely wooden pulley-like systems were operated.

Construction of the pyramid core: Vertical shafts and vertical masonry

So far, I have detailed how the sloped passages in the pyramid may have served as sliding-ramps for force generation (Fig. 1), how the Antechamber

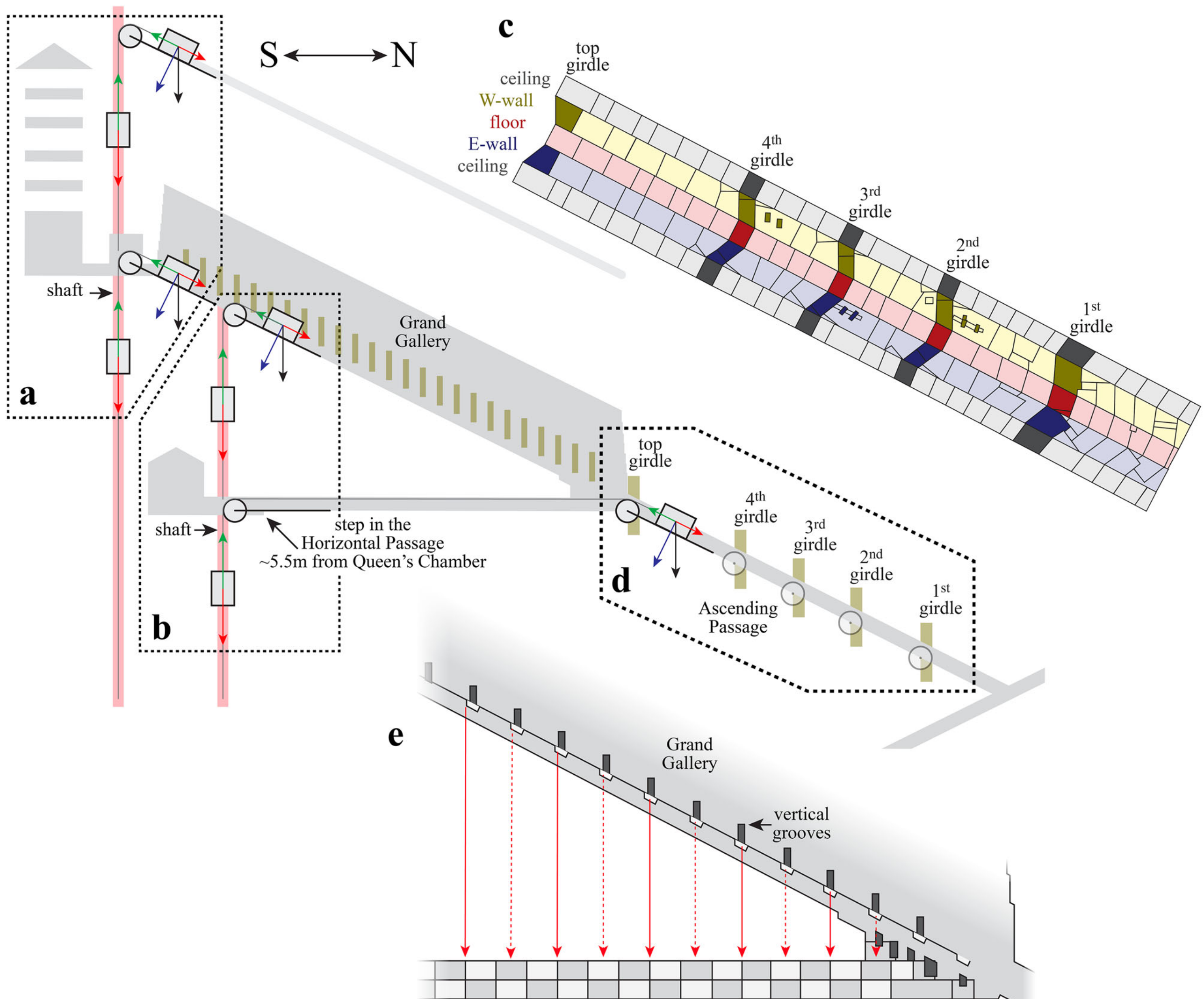


Fig. 6 | Position and evidence for vertical shafts and pulley-like systems. a The major vertical shaft (red) of the pyramid core construction should be in the vertical axis of the current Antechamber. It was established when the Grand Gallery sliding-ramp construction reached its top. The recently discovered ScanPyramids' big void[26], consistent with an upper sliding-ramp pulley-like system, is proposed to give into the same shaft. **b** At an intermediate stage of pyramid construction, a shaft (red) should have existed at the north face of the Queen's Chamber, today manifested by a low-plateau between Queen's Chamber and Horizontal Passage and a ~0.5 m step at ~5.5 m from the Queen's Chamber. In this region, between Queen's Chamber and the step, Vyse discovered sand and rubble below the floor slabs[11]. Microgravimetry reported low-density anomalies at the position of the proposed Queen's Chamber shaft[39], and in the North-East corner of the King's Chamber, thus in proximity to the proposed King's Chamber shaft[39]. **c** Masonry of the Ascending Passage (drawing based on: Tavola 5 in Vito Maragioglio, L'Architettura delle Piramidi Menfite, Part IV, Roma 1965[9]). Ceiling, East (E-) and West (W-) walls, and floor are shaded in colors and labeled, and the girdle masonry is highlighted. **d** Illustration of the girdle block positions in the Ascending Passage. The shaded wheels represent the pulley-like system intermittently positioned at each girdle position during the growth of the Ascending Passage in pyramid core construction. **e** Masonry of the Horizontal Passage to the Queen's Chamber (drawing based on: Tavola 6 in Vito Maragioglio, L'Architettura delle Piramidi Menfite, Part IV, Roma 1965[9]). Masonry blocks are shown in alternating shading to highlight the horizontal and vertical alignment of the masonry with cross-shaped joints. Red arrows: The position of the vertical grooves in the Grand Gallery matches the position of the blocks in the Horizontal Passage. The blocks in the Horizontal Passage have 2 cubits length/periodicity, while the grooves in the Grand Gallery have 3 cubits lateral periodicity, i.e., $\sqrt{1.25}\cdot 3$ cubit periodicity along the Grand Gallery axis.

structure may have served as a pulley-like system (Fig. 2), and how the pulley-like system and sliding-ramp may have been assembled (Fig. 3) and advanced (Figs. 4, 5) in the process of construction. However, is there any further data supporting the model? Are there signatures of sliding-ramps, pulley-like systems, their integration, or evidence for shafts in the pyramid architecture and masonry? In the pyramid as it can be visited today, obviously the vertical shaft underneath the Antechamber pulley-like system is not visible and/or accessible—it had to be filled when the pyramid core construction was completed, and the fact that the floor slabs of the Antechamber are inlays of uneven height represents evidence that the pulley-like system indeed gave into an open shaft that was later filled and covered by the currently visible granite slab inlays. The model would predict (Table S3) that if these slabs could be lifted, not far below, signatures of a shaft with heterogeneous filling should be found (Fig. 6a). In possible support, a microgravimetry survey in the King's Chamber showed the lowest density values in the North-East corner, thus closest to the Antechamber[39].

The position of the Antechamber shaft can be estimated based on the Antechamber floor slab structure and the position of North-South passage of the South 'airshaft' exiting from the Queen's chamber: Accordingly, the shaft should be at least ~3.4 m long (North–South) corresponding to the dimensions and position of two granite floor inlay slabs, reaching from ~0.2 m North of the Granite Leaf to ~0.8 m South of the South-wall with the rope guidance groves[9]. The shaft was entirely open to the East, from where the blocks were brought to the shaft footing (see *"Proposal for how the Great Pyramid of Giza was built"*), and extended ~2.5 m to the West, delimited by the Queen's Chamber South 'airshaft' that passes through masonry ~3 m West from its East-wall (Figs. 6a, 1b, inset). The shaft walls should have been constituted of high-quality, almost vertical masonry defined by the solid masonry that supports the King's Chamber to the South, the Grand Gallery to the North, and likely similar sturdy masonry to the West.

According to the model, the base of the King's Chamber was built using the Antechamber pulley-like system fueled by the Grand Gallery sliding-ramp, and the upper parts of the King's Chamber were built using a pulley-like system fueled by the ScanPyramids' big void sliding-ramp, where blocks were lifted through the same main shaft in a vertical axis in front of the King's Chamber and through the Antechamber pulley-like system (Fig. 6a). Note, ScanPyramids' big void[26] is not a confirmed structure, and the prediction that it is a Grand Gallery-like sliding-ramp coupled to an Antechamber-like pulley-like system is hypothetical and should be considered as such throughout the text (Table S3).

Further evidence of a vertical shaft and subsequent heterogeneous filling has been reported from another, analogous location in the pyramid: There is a quite odd step, ~0.5 m high, located ~5.5 m North of the Queen's Chamber in the Horizontal Passage[8,9,31]. The resulting low-plateau between Queen's Chamber and step is located with regard to the Queen's Chamber at the analogous position where the Antechamber pulley-like system is located with regard to the King's Chamber (Fig. 6b).

In analogy, the base of the Queen's Chamber could have been built using a pulley-like system fueled by the Ascending Passage sliding-ramp (over an extended horizontal rope), and the upper parts of the Queen's Chamber using a pulley-like system fueled by the Grand Gallery sliding-ramp (at that stage of construction ~3/4 in length) and the Ascending Passage, where blocks were lifted through a vertical shaft in an axis in front of the Queen's Chamber (Fig. 6b). Thus, the ~5.5 m long low-plateau between Queen's Chamber and step is interpreted as a structural anomaly that is the structural homolog to the Antechamber with regard to the King's Chamber—only in the case of the King's Chamber and Antechamber a granite inlay floor has later been placed[13], while this has never been done for the Queen's Chamber and the low-plateau[8]. This region in the pyramid had also attracted the attention of gunpowder archeologist Howard Vyse, who 'investigated' and described the floor in the region between the step in the Horizontal Passage and the Queen's Chamber as full of sand and rubble-work[11] (Citation S4). This qualitative assessment has been quantitatively corroborated by microgravimetry that showed strong negative values in the first ~5 meters of the Horizontal Passage next to the Queen's Chamber[39].

Thus, it seems likely that Vyse discovered in the vertical axis in front of the Queen's Chamber a shaft that was later filled with sand and rubble[11] (Fig. 6b), which the model would predict (Table S3) to be found in the vertical axis (Fig. 6a) underneath the floor inlay slabs of the Antechamber[8,9,34]. For both locations, in the case of the Queen's Chamber's Horizontal Passage at the exact position, and in the case of the Antechamber in the close-by North-East corner of the King's Chamber instead, microgravimetry anomalies with the lowest local survey values have been measured[39]. Thus, architectural analysis and physical measurements point towards the former existence of shafts related to the construction using pulley-like systems that have later been filled with crude, lower-density fill-material.

Further evidence (Table S2) for the pulley-like system/sliding-ramp model is provided by the masonry in the Ascending Passage. Indeed, the Ascending Passage features direct structural evidence for the propagation and physical integration of a pulley-like system to a sliding-ramp during pyramid construction (Fig. 4): In brief, the Ascending Passage wall masonry features blocks with joints that are perpendicular to the slope of the floor, and blocks with joints that are vertical with regard to the pyramid, termed girdles[8–10,13] (Fig. 6c, labeled '*n*th girdle'). These girdle blocks are preceded by particularly long wall blocks on either one side that feature modifications (Fig. 6c). The girdles formed vertical boundaries when they were top of the sliding-ramp construction intermediate and were therefore suited to interface with a platform on which the pulley-like system stood (Fig. 6d, see Figs. 3–5). Naturally, these vertical girdle blocks absorb the lateral force component from the counter-weight sliding down the sliding-ramp acting on the pulley-like system. The top of the ascending passage also features sides with vertical joint/ending suggestive that it also represented a sliding-ramp intermediate (Fig. 6c, labeled 'top girdle'). In this case, the shaft should be located next to where today the Well Shaft is located[9], but the sparseness of information about the Well Shaft precludes further speculations. The upper, perfectly vertical part of the Well Shaft appears, however, to feature planned masonry and could thus be related to a pulley-like system shaft at the top of the Ascending Passage[9].

In addition, Smyth described the floor of the Ascending Passage masonry as excessively hard and polished[13] (Citation S5). Smyth considered that continuous application of weight and friction hardened and smoothened the floor of the Ascending Passage, which appears more plausible in light of its use as a sliding-ramp for heavily loaded sledges than human feet. The feature is of notice as robbers would never try to circumvent the plug-stones in the Ascending Passage by digging underneath, but either over them or by the side—a reasoning that the builders were naturally considering. Thus, the fact that the floor is harder and smoother than the walls and roof indicates that the floor had either been chosen to be built of harder stone to serve as a solid support or indeed had been hardened and smoothened by use.

The Grand Gallery does not comprise vertical girdle blocks; instead, it features vertical grooves cut into the wall masonry, above holes cut into benches (Fig. 6, green). The vertical groves have an average periodicity of ~1.72 m. According to the presented model, the vertical grooves were used to insert cross-beams that secured the pulley-like system, which stood on a platform in front of them, functionally akin to the girdle blocks in the Ascending Passage. Thus, the vertical grooves report about the advance of the pulley-like system as the Grand Gallery sliding-ramp grew during construction. Thus, the lateral advance of the pulley-like system at the front of the Grand Gallery sliding-ramp, as reported by the vertical grooves, can directly explain the masonry structure in the Horizontal Passage underneath, where blocks are arranged with cross-shaped joints (Fig. 6e). The Edgars described the block arrangement in the Horizontal Passage to the Queen's Chamber, the only location in the pyramid giving direct access to study the masonry underneath a sliding-ramp, as ~20.5 m of identically 2 cubit sized blocks, 41.25 inches, i.e., ~104.8 cm, arranged with cross-shaped joints, also symmetrical with regard to the two sides of the passage[34] (Citation S6); corroborated by Mariglio and Rinaldi[9,10]. The cross-shaped joints are astonishing, as wall construction normally implies placing blocks of an upper course laterally shifted by half the block size, so as to maximize the intercalation of blocks in a wall. Astoundingly, the lateral propagation of the blocks in the Horizontal Passage, matches the locations of the vertical grooves and thus the propagation of the pulley-like system in the Grand Gallery above (Fig. 6e, arrows, Fig. 5b). Indeed, as the pulley-like system advanced with the growing Grand Gallery sliding-ramp, blocks were added in front of the sliding-ramp, leading to the lateral and vertical alignment of blocks in the Horizontal Passage underneath (Figs. 6e, 4f, masonry in the shaft, Fig. 5b). The lateral match between these structures relates every second vertical groove in the Grand Gallery with every third block in the Horizontal Passage, resulting in this rather odd groove periodicity length of ~1.72 m (~3.35 cubit) in the Grand Gallery. The further the Grand gallery grew, the less the relationship was preserved, and after ~20.5 m, the alignment was off by ~9 cm, but in this position the Grand Gallery was already ~10 m higher than the Horizontal Passage, and the non-verticality is negligible with regard to a construction process. Thus, the Grand Gallery grooves and the masonry in the Horizontal Passage establish a vertical relationship within the masonry as would be predicted by the lateral advance of a pulley-like system at the head of a sliding-ramp during the construction process (Figs. 6e, 5b).

Summarizing, the pyramid architecture and masonry, i.e., the vertical girdles in the Ascending Passage, the hardened floor in the Ascending Passage, the vertical grooves in the Grand Gallery, the cross-shaped joints in the Horizontal Passage, the relationship between the latter two structures, the inlaid floor slabs in the Antechamber, the sand- and rubble-work fillings in the low-plateau in front of the Queen's Chamber, to the local low-density features in the Horizontal passage and the King's Chamber North-East corner, offer numerous signatures in support of the pulley-like system/sliding-ramp model, and how it was laterally advanced during the construction process.

Construction of the pyramid mantle: Course height-decay bins, concavity, and central furrow on the pyramid faces

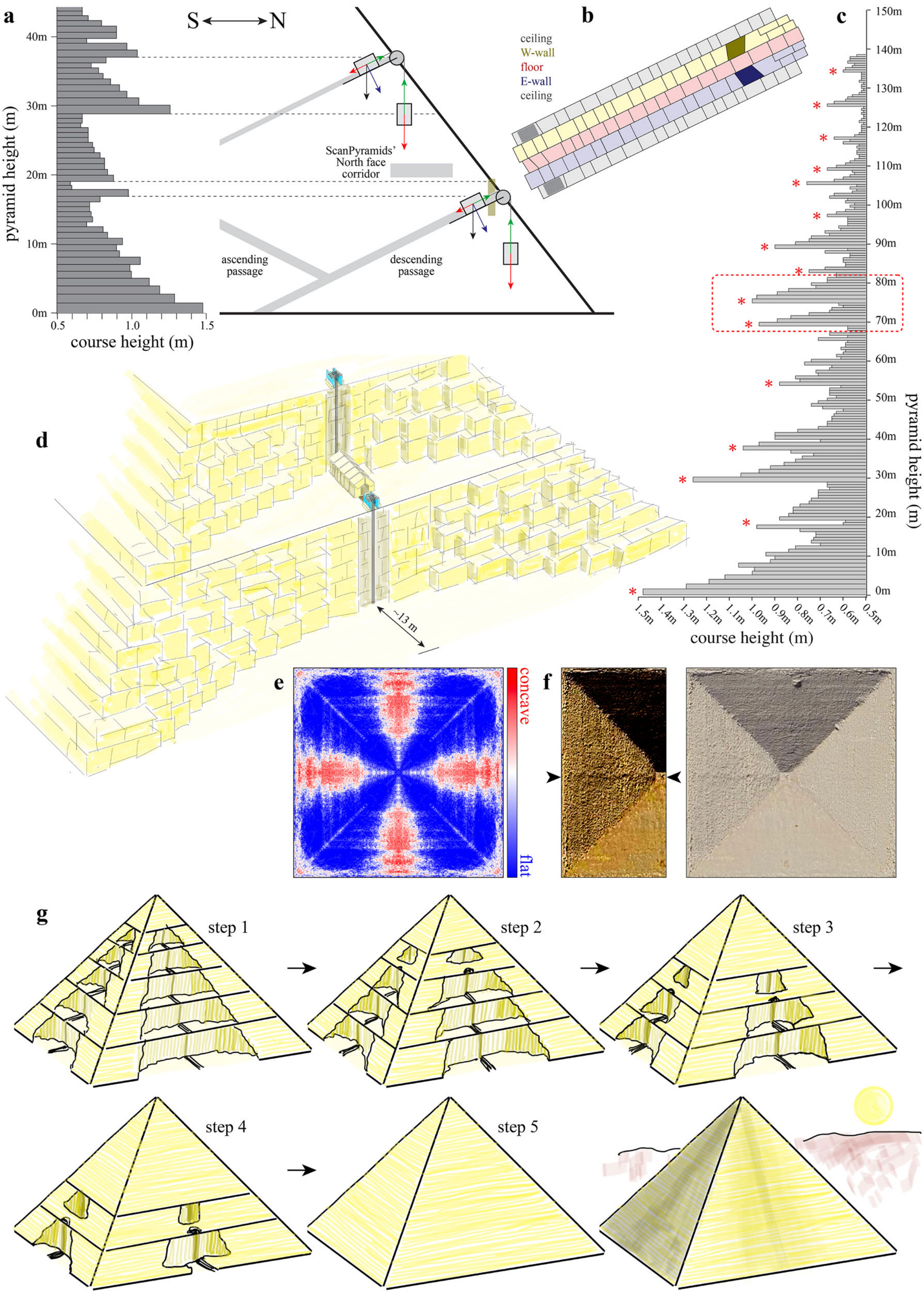
There are three further phenomena, observable today on the surface of the Great Pyramid without casing, that remained largely unexplained, namely the varying height of the pyramid courses[8], the concavity of the faces[10,29,40], and the furrow in the pyramid faces[30,40]. These phenomena can directly be explained and would be expected, within the framework of the pulley-like system/sliding-ramp pyramid construction model.

So far, only the Ascending Passage and the Grand Gallery with their slope of 1 cubit over 2 cubits have been discussed as force-generation sliding-ramps—and a hypothetical sliding-ramp higher up in the pyramid core, represented by ScanPyramids' big void—has been proposed (Figs. 1, 6). However, there is one more, today accessible, passage that shares the typical sliding-ramp characteristic: The Descending Passage (Fig. 7a, b). The Descending Passage too has a slope of 1 cubit over 2 cubits, ~26.5°[8,9,31], and 'begins', though the term 'ends' appears more appropriate—as its origin is where it pierces the Giza bedrock and splits with the Ascending Passage—at the north face entrance. Thus, I propose that a pulley-like system, fueled by the Descending Passage as sliding-ramp, operated at the north face entrance lifting blocks at the pyramid periphery to build the pyramid's mantle (Fig. 7a). Interestingly, the Descending Passage features, akin the girdles and the top in the Ascending Passage (see Fig. 6c), wall masonry towards its top with vertical borders (Fig. 7b, highlighted), potentially interfacing with a horizontally standing pulley-like system. In addition, Petrie describes the Descending Passage floor to be built of the hardest stone[8] (Citation S7). The Edgards described the floor of the Descending Passage in its lower parts, roughly below the split with the Ascending Passage, as outstandingly hard and smooth, and report that a haphazardly released block spontaneously slid down the Descending Passage, gaining speed[34] (Citation S8), consistent with it having served as a sliding-ramp.

First, as mentioned earlier, overall, the pyramid courses get thinner from bottom to top of the pyramid. However, in detail the situation is much more intriguing: The course heights vary in decaying bins from bottom to top, with several courses at intermediate heights being substantially thicker than their lower neighbors, starting new course height-decay bins[8] (Fig. 7c). Computational analysis, identifying courses with height differences to their lower neighbor course at least 3 times greater than the mean of their 4 neighboring (2 upwards, 2 downwards) course height differences, allowed to detect 14 course steps (15 including the 1st course) that start new course-height decay bins (Fig. 7c, asterisks). While the precise number of construction 'bins' on the pyramid face needs further elaboration, their occurrence and morphology are signatures of a physical process and can be explained by the presented model. The lower courses with the larger blocks within each course-height decay bin, are likely built by lifting the blocks and pulling them to the side while they hang on the ropes of the pulley-like system (see Fig. 4c), while the higher courses within each course-height decay bin may be constituted of blocks that are lifted all the way up into the pulley-like system or that have been pulled sidewise while hanging on the ropes (see Fig. 4d). In such a setting, a gradual size-decrease of the blocks should be expected with increasing height within the range of a height-decay bin, as it overall diminishes the force that the workers need to provide—and facilitates the possible lateral extraction of blocks hanging on ever shorter ropes. In agreement, the first course height-decay bin ends at 17 m height[8,9], reaching the top of the Descending Passage on the north face[9] (Fig. 7a, c). Based on this finding, the ~15 course height-decay bins on the surface of the pyramid are proposed to represent each the periphery (or a long-lasting intermediate) of a peripheral sliding-ramp, each with ~10 m average height (Fig. 7a, c). These sliding-ramp/pulley-like system ensembles would have been placed roughly in the center of the pyramid face, e.g., the Descending Passage, stacked on top of each other and towards the pyramid center (Fig. 7a, d). The fact that the course height-decay bins get shorter with increasing height (Fig. 7c, observe densification of asterisks with increasing height), matches the fact that the associated sliding-ramps also had to get shorter as the pyramid gets thinner towards the top. Importantly, while the course height-decay bins can be explained as manifestations of the pyramid construction process using pulley-like systems and sliding-ramps, they are unexplained by layer-by-layer and bottom-to-top construction models, unless one is to invoke that they were planned for having a stabilizing function[3] in which case they are unexplainably irregular; or for mystical reasons. Thus, the intriguing, binned course height-decay pattern, especially the match of the first course height-decay bin with the top of the Descending Passage, is further evidence for the pulley-like system/sliding-ramp construction model (Fig. 7a, d).

Second, another phenomenon that remains unexplained is that the pyramid faces are not perfectly flat but slightly concave. The concavity of the pyramid faces has been described since the early 1800s[8,10,30,40] (Fig. S7), corroborated by modern laser scanning and photogrammetrical analysis[29]. This high-resolution analysis showed that the overall concavity decreases from bottom to top of the pyramid; however—similar to the course height-decay bins—the detailed situation is more intriguing: The concavity displayed noticeable variations as a function of height on the pyramid faces[29]. Using the data from this survey, I calculated an average map from all sectors (Fig. 7e), and found several quality steps, i.e., abrupt changes from concave (Fig. 7d, red) to flat (Fig. 7d, blue), on the pyramid surfaces as a function of height. This data matches the construction model using the Descending Passage as sliding-ramp to fuel a pulley-like system on the pyramid surface (Fig. 7a, d): Accordingly, the Descending Passage sliding-ramp, reached its end at the pyramid main entrance with the Chevron structure, where a pulley-like system was placed (see Figs. 4, 5). Due to its working mechanism the pulley-like system lifted blocks roughly vertically up (see Fig. 4), meaning that its footing was ~13 m 'inside' the pyramid baseline (Fig. 7d). While the course on which the pulley like system was placed, likely course 18, was straight[8,9] (Fig. 7a, d), the courses below had to maintain an overall concave shape to allow blocks to be brought to the footing of the pulley-like system (Fig. 7d). Thus, the pyramid grew with concave faces, i.e., concave height sections, which was never perfectly matched and are the reason for the minor deviations from flatness that is visible today (Fig. 7e). To build the pyramid as a whole, there should have been upper pulley-like systems (Fig. 7a, d), which should each result in one or two of the course height-decay bins (Fig. 7c) and because of their vertical working mechanism also each possibly in a concavity-section (Fig. 7e). The superposition of peripheral pulley-like systems is illustrated by the second level pulley-like system in Fig. 7d. In agreement, the recently discovered ScanPyramids' north face corridor[27,28], initially likely an open-air plateau and only later covered with chevron blocks when the faces got completed, connected the first and second pulley-like system on the pyramid periphery allowing the transfer of blocks between them and thus to higher heights. ScanPyramids' north face corridor is ~9 m long and ~7 m set back from the pyramid face (today, though masonry analysis suggests that the chevrons extended further towards the periphery), which would thus indicate that the next upper pulley-like system was positioned ~20 m higher up (~(9 m + 7 m)·tan(52); where ~52° is the slant face angle of the pyramid) (Fig. 7a). In agreement, there is a course height-decay bin start at ~38 m height (Fig. 7a, left, Fig. 7c, asterisks). As the construction of the pyramid mantle approached completion, and blocks were added on the face layer-by-layer from the corners towards the center, the concavity of the face got narrower in each pulley-like system section, like a healing scar, until there was only a furrow left. Finally, the connection between the pulley-like systems was fully covered by chevrons—as ScanPyramids' north face corridor today[27,28]—and the face could be completed.

The third so-far unexplained phenomenon is the furrow in the center of the pyramid faces[30,40]. Again, like the course high-decay bins and the concavity, the furrows have been described since the early 1800s[40] (Fig. S7),



and modern photogrammetry corroborated their existence and provided further detail[30]. The furrows are visible in satellite images (Fig. 7f). It has been proposed that the central furrow was the result of damage through forceful removal and tossing of casing stones and blocks from the pyramid top down the pyramid faces[30]. According to the model presented here, the construction went through periods where the faces were concave (Fig. 7d, e), then progressively, to complete the faces in each pulley-like system section, the concavity was narrowed, until it was only a furrow, where blocks were lifted, and laterally transferred towards the pyramid center to be delivered to the next pulley-like system. A possible sequence of the completion of the pyramid mantle construction is illustrated in Fig. 7g (note, according to the height-decay bins, there should have been more, ~15, peripheral sections

Fig. 7 | Peripheral pulley-like system construction explains course height-decay bins, pyramid face concavity, and the central furrow in the pyramid faces. **a** Pyramid in side-view with Descending Passage as sliding-ramp fueling a pulley-like system at the pyramid periphery. Approximate positions of the ScanPyramids' north face corridor and a hypothetical upper pulley-like system with sliding-ramp are shown. Left: Section of course height-decay bin distribution[8], with the first bin ending in course 18 matching the top of the Descending Passage[9] (dashed lines). **b** Masonry of the Ascending Passage (drawing based on: Plate 2 in C. Piazzi Smyth, Life and work at the Great Pyramid Vol. II[13]). Ceiling, East (E-) and West (W-) walls, and floor are shaded in colors and labeled, and the masonry ending in a vertical joint is highlighted. **c** Course heights as a function of pyramid height (graph based on: Plate VIII in W.M. Flinders Petrie, The pyramids and temples of Gizeh[8]): The course heights are organized in course height-decay bins. Bin bases were computationally identified (asterisks). Dashed red outline: Two particularly short height-decay bins at ~69 and ~75 m height (see *"Proposal for how the Great Pyramid of Giza was built"*, steps 9–11). **d** Intermediate state of pyramid mantle construction (schematic, simplified, not drawn to scale) showing the first pulley-like system fueled by the Descending Passage, ScanPyramids' north face corridor covered with Chevrons, and a second, upper pulley-like system. For the footings of the pulley-like systems to be accessible (the footing of the first pulley-like system is ~13 m inside the pyramid baseline), each height section must have had a straight top course, and a concave course at the base[29,30]. During completion, the concavity sequentially narrowed, until only an open furrow remained, allowing access to the pulley-like system footing, which was eventually closed, necessitating the coverage of the connection between pulley-like systems with a chevroned roofing[27,28]. **e** Average pyramid face concavity map based on data in ref. 29: Flat-to-concave is shown in a blue-to-red false-color scale. Note that flat and concave courses are partitioned into sections. **f** Central furrow of the pyramid faces: Satellite image from Google Earth, dated April 30, 2023 (right: Raw data; left: Contrast-adjusted West face). Due to the position of the sun, the central furrow is particularly well visible in the West face, but similar furrows are present on all pyramid faces (Fig. S7)[30]. **g** Sequence of completion of the pyramid mantle construction (schematic, simplified, not drawn to scale), possibly explaining concavity and central furrow of the pyramid faces: The pyramid has a more step-pyramid-like core. Sliding ramps, e.g., the Descending Passage, may have fueled pulley-like systems that stood peripherally at the edges of each 'step'. As blocks needed to be lifted up, the uppermost sections were finished first (steps 1–5). Schematic, bottom-right, illustrates that when the sun is in specific positions, the slight concavity and central furrow of the pyramid faces can be seen by eye.

than illustrated in this schematic). Sliding-ramps, e.g., the Descending Passage, may have fueled pulley-like systems that stood peripherally at the edges of each 'step'. The pyramid would thus have had a more step-pyramid-like structure, at least in the central region of the faces. For the completion of the pyramid, blocks were lifted to the highest section, which was finished by narrowing the concave regions and closing the remaining furrow bottom-to-top. Then, this section could be retired, and the second-highest section's scar was narrowed and closed, and so on. Since the face in each section had to close from the edges, keeping the pulley-like system functional and the horizontal corridor operatable for as long as possible, this process had to result in minor imprecisions in placing the final blocks in the center, which explains the concavity and the central furrow of the pyramid faces as can be seen today. Thus, the furrows may be manifestations of imperfect closing of these clefts, where pulley-like systems lifted blocks up. Conversely, the furrow is further evidence for the proposed model. Anecdotally, the proposed model implicating narrowing the concavity from the edges and closing the central furrow from the top section to the lowest section fits Herodotus' account that the highest parts were finished first[1] (Citation S1).

As the course height-decay bins[8] (Fig. 7c), the concavity[29] (Fig. 7e), and the central furrow[30] (Fig. 7f), are found on all four faces, the suggestion comes naturally that the pyramid mantle was constructed on all four sides. As discussed in the introduction, considering a 16-h work-day over 20 years, the average pace to place blocks is estimated between 1 per minute and 1 every 3 min; and if a shorter construction period was considered[3,22], blocks had to be placed between every 30–90 s. Thus, the proposal that peripheral pulley-like systems worked on all four faces not only matches the structural appearance of the pyramid, but can also provide an explanation for the tremendous pace of the pyramid construction (see *"Proposal for how the Great Pyramid of Giza was built"*).

There is more evidence in support of this proposal: Mariglio and Rinaldi inspected Vyse's hole, the breach that Vyse dynamited into the South face, and commented that the masonry some meters beyond the well-aligned outer course was quite irregular[10] (Citation S9). In addition, microgravity measurements revealed density variations within the pyramid that could be interpreted as indicating that the Great Pyramid had a step-pyramid-like inner structure[41]. Similarly, inspection of the breach that Sultan Al-Aziz Uthman broke into Menkaure's pyramid north face, reveals a step-like pyramid core manifested by high-quality, almost-vertical masonry inside the pyramid[42]. Finally, because of their lower-quality masonry, most of the 5th Dynasty pyramids have crumbled enough to reveal that they have a step-pyramid-like core[22] (Fig. S8a).

In summary, the presented pyramid construction model provides explanations for the further three so-far unexplained phenomena, the varying course heights organized in height-decay bins[8], the concavity[29,30], and the furrow[30], on the pyramid faces. To the best of my knowledge, none of the bottom-to-top layer-by-layer construction-ramp models could or attempted to explain these phenomena, other than that they were made to stabilize construction. Alternatively, mystical reasons why Hemiunu consciously designed the course height-decay bins and deviated from pyramid face flatness can be invoked, but these suggestions are not rationally supported. Furthermore, since the entire pyramid was covered with fitted casing stones that covered/corrected these effects, the three phenomena were likely invisible in the final pyramid state and could therefore hardly serve mystical purposes. It thus appears reasonable to consider that course height-decay bins, surface concavity, and central furrow are manifestations of compromises, imprecisions, and consequences of the construction process. They cannot only be explained by a construction model using pulley-like systems fueled by peripheral sliding-ramps (like the Descending Passage), but, conversely, provide support for the proposal. In addition, masonry and microgravity analyses, where possible, support that the pyramid had internally step-pyramid-like features (Figs. 7d, g, S8a). Most generally, because the pyramid's inner structure is so different from the surface, the course height-decay bins, concavity, and central furrow on the surface are meaningful. All the detailed phenomena and evidence support that the pyramid mantle was constructed somewhat isolated from the pyramid core, and all data are compatible and support the model that the mantle was constructed using peripheral pulley-like systems arranged in a step-like fashion (Fig. 7g).

Force-generation through counter-weight sliding down the sliding-ramps

Finally, possible types of and ways how counter-weights that may have been used on the sliding-ramps to fuel the pulley-like systems are explored. Since most likely the counter-weights were sent down the sliding-ramps on wooden sledges, the pulley-like system/sliding ramp construction strategy has flexibility, and thus depending on the location and time of construction, dedicated counter-weight slabs (most commonly), blocks that themselves are integrated into the construction, or packs of boulders of size that individual workers could carry, could have been used as different types of counter-weights. In addition, as indicated above, pulley-like system/sliding ramp ensembles could be used in different ways, termed 'common cycle', 'lifting cycle', and 'exchange cycle', which also could have occurred preferentially depending on the location and time of construction. Since all sliding-ramps visible today in the pyramid, and likely all other sliding-ramps, have a slope of 1 cubit over 2 cubits, i.e., ~26.5°, and are built of smoothened stone, the physics of all sliding-ramps are identical: A weight of 1 mg creates a force, $F_{(\text{downhill})}$, of 0.44 mg, and a friction force, $F_{(\text{friction})}$, to overcome, of ~0.18 mg or less (Fig. 1c, and text), plus the friction within the pulley-like system.

Use of dedicated counter-weight slabs: According to the model, the common way to lift blocks was achieved by using dedicated counter-weight slabs mounted on a wooden sledge, generally applied on the lowest peripheral sliding-ramps. In this context, the finding of granite blocks with drill-holes in the pyramid is important to note. One of them, a damaged slab, still ~1.1 m wide, ~0.8 m high, and ~0.5 m thick with two drill-holes, can be inspected in front of the pyramid main entrance on the North face[32]. This block was, according to the Edgars, found by Petrie in the Descending Passage. The Edgards reported in the early 1900s about a total of five partly dressed granite blocks with drill-holes, found in the well, the Descending Passage, and the Recess Passage, and wondered about their original site and purpose[34] (Citation S10).

These slabs with drill-holes are generally interpreted to be the remains of the portcullis slabs from the Antechamber[32]. However, their number, size and location do not match this assignment. It could be proposed that robbers and early investigators displaced the blocks within the pyramid, but one could hold against this that these blocks were/are completely worthless, and thus were of no interest to robbers, and even for the investigators, it would represent an odd undertaking to displace them. Also, slabs like the one that is now in front of the pyramid, ~1.1 m wide, ~0.8 m high, and ~0.5 m thick, weigh ~1144 kg (using 2.6 g/cm^3 as the density of granite) and can therefore not be moved around that easily. As reported by the Edgars[34], at least some of these drill-holed granite blocks were under debris in the Descending Passage in the early 1900s, so they were likely there long before. Another interesting observation made by the Edgars is that as soon as they freed one of these blocks from debris, the slab began to slide, gathering speed[34] (Citation S10). In summary, I propose that these granite blocks were the counter-weights that were sledged down the Descending Passage thousands of times to lift blocks on the pyramid face. The Descending Passage has a cross-section of ~1.1 m width and ~1.2 m height. Thus, two such slabs stacked together could represent such a counter-weight unit, totaling ~2.3 tons. I note that the average block of the pyramid has a weight of ~2.5 tons, and the pulley-like system in gear 2 demands 0.5 times the gravitational force to lift the weight, while the sliding-ramp provides 0.44 times the gravitational force of the weight that slides down-ramp. In such a setting, the workers would essentially only have to overcome the friction force – and then work to pull, maybe also using force-amplification over pulley-like systems, the counter-weight up the sliding-ramp to reset the system (Table S1).

According to the model, dedicated counter-weight slabs were most commonly used in 'common cycles', i.e., where blocks are lifted all the way up, especially in the lower pulley-like systems / sliding ramps that needed to provide blocks for upper pulley-like systems (Fig. 7d). Alternatively, dedicated counter-weight slabs were also used in 'lifting cycles', i.e., where blocks were lifted on the face of the pulley-like system and laterally extracted, such as during the propagation of the sliding-ramps or during the completion of the pyramid faces (Figs. 4c, 5, and 7g)

Use of blocks that are integrated in construction: In specific locations and times, blocks for construction may have been lifted using previously lifted construction blocks as counter-weights, e.g., in the construction of the Grand Gallery. The large blocks of the Grand Gallery walls are integrated into the walls with the same tilt as the Grand Gallery, i.e., with joints perpendicular to the ramp slope. Hemiunu might have taken advantage of the potential energy of these blocks arriving at the top of the Grand Gallery to send them down the grand-gallery and use their down-sliding force to partially lift the next of these blocks. The Grand Gallery features a series of grooves in the benches facing the corbeled walls (see *"Construction of the pyramid core"*), which may have served to fix a wooden scaffold that would have allowed sending the wall blocks directly sliding down on the walls. This is pure speculation, but the inclination of the blocks constituting the Grand Gallery walls is suggestive of such a system. In any other setting, these blocks, tilted with regard to the pyramid structure, would have needed additional effort of lifting, tilting, and manipulating, while in a sliding-ramp force generation setting, their masonry morphology could have been exploited in an energetically favorable way.

A further possibility is that Hemiunu could, operating the pulley-like system in gear 2, lift 2 blocks with weight 2 mg having the apparent weight of 1 mg to height Δh, while sending 1 block down the sliding-ramp creating 0.44 mg over the distance of length $l = 2{\cdot}\Delta h$. The workers still had to work, to make up for the difference, 0.56 mg, and to overcome the friction of the down-sliding sledge, ~0.18 mg or less (see Fig. 1c, and text), and the friction within the pulley-like system (Table S1). At the end of one cycle, they had 2 blocks lifted for 1 block sent down the sliding-ramp. Next, one of the 2 blocks that were lifted, could be sent down on the next sledge to lift 2 further blocks in the next cycle, while the other block from the first cycle could be used to build, or being lifted further up (Fig. S9a). Such a system provides to every higher-up ramp 50% of the blocks it worked with (Fig. S9b), which does not represent a problem, as the volume distribution of the pyramid is bottom-heavy (Fig. S9c).

Cycles that use blocks that are themselves constituents of the pyramid as counter-weight are termed 'exchange cycle'. Compared to the 'common cycle' and 'lifting cycle' using dedicated counter-weight blocks, the 'exchange cycle' is much more hypothetical. However, when considering the construction of the pyramid mantle (see *"Construction of the pyramid mantle"* and *"Proposal for how the Great Pyramid of Giza was built"*), blocks were brought to and lifted at the pyramid periphery, while many blocks needed to reach the inner part of the mantle, filling the volume towards the core. There would be an interest in using these blocks also to fuel the lifting of further blocks, because in such a setting, there is no energy needed to reset the system.

Use of boulders that are integrated in the less organized masonry parts in the core: Finally, given that the pyramid inside masonry contains at locations very small blocks[10], and even sand and rubble[11], it is conceivable that instead of large blocks also crates filled with such secondary fill-material were lifted, and used in 'exchange cycles' as counterweight that thus helped lift weight on the periphery. The secondary fill-material thus reached the inner regions of the pyramid via the peripheral sliding-ramps (see *"Proposal for how the Great Pyramid of Giza was built"*), where it could be used to fill masonry gaps.

Proposal for how the Great Pyramid of Giza was built

Taking together, based on all the above-described pyramid and masonry structural analysis, evidence and hypotheses, the following novel model for the construction of the Great Pyramid is proposed. The steps outlined below refer to the illustrations in Fig. 8. Core masonry is shown in red (see Fig. 6); mantle masonry is shown in blue (see Fig. 7).

Step 0: The construction of the Great Pyramid was not started at its center, nor at its corners, but at the position where the Descending Passage emerges from the bedrock and splits with the Ascending Passage. I term this location 'origin'. This section was the part for which Hemiunu built a trial[8] (Fig. S10).

Step 1: The Descending Passage is built, ascending (see Figs. 4, 5, and 7b) from the origin in the North-sector northwards. Since the final pyramid has similar concavity and central furrows in all pyramid faces, corresponding origins from which departed homologs of the Descending Passage in the East-, South-, and West-sectors should have existed. The 4 sliding-ramps give rise to a frame-like structure. A gap is left open in the South sector for the supply of blocks to build the core. The pyramids of Khui (27°18 28"N 30°52 17"E) and Neferefre (29°53 37"N 31°12 ;05"E) could represent pyramid building attempts abandoned at this early stage, see Fig. S8b).

Step 2: The Ascending Passage is built, ascending (see Figs. 4, 5, and 6c, d) from the origin in the North-sector southwards. The masonry of the Ascending Passage features evidence of intermediate states (see Fig. 6c).

Step 3: The Ascending Passage grows into the Grand Gallery and reaches its apex, 43 m. During the growth process of the Grand Gallery sliding-ramp (open air at this stage), the Queen's Chamber is built (see Fig. 6b). I propose that the Queen's Chamber's niche and a short eastward extension from the niche served to overview the Antechamber pulley-like system shaft lifting the blocks to build the pyramid core (Text S2). The blocks lifted by the peripheral pulley-like systems complete the first 'step' of a step-pyramid-like structure by building inwards (when large amounts of masonry had to be transferred from the periphery towards the internal parts of the

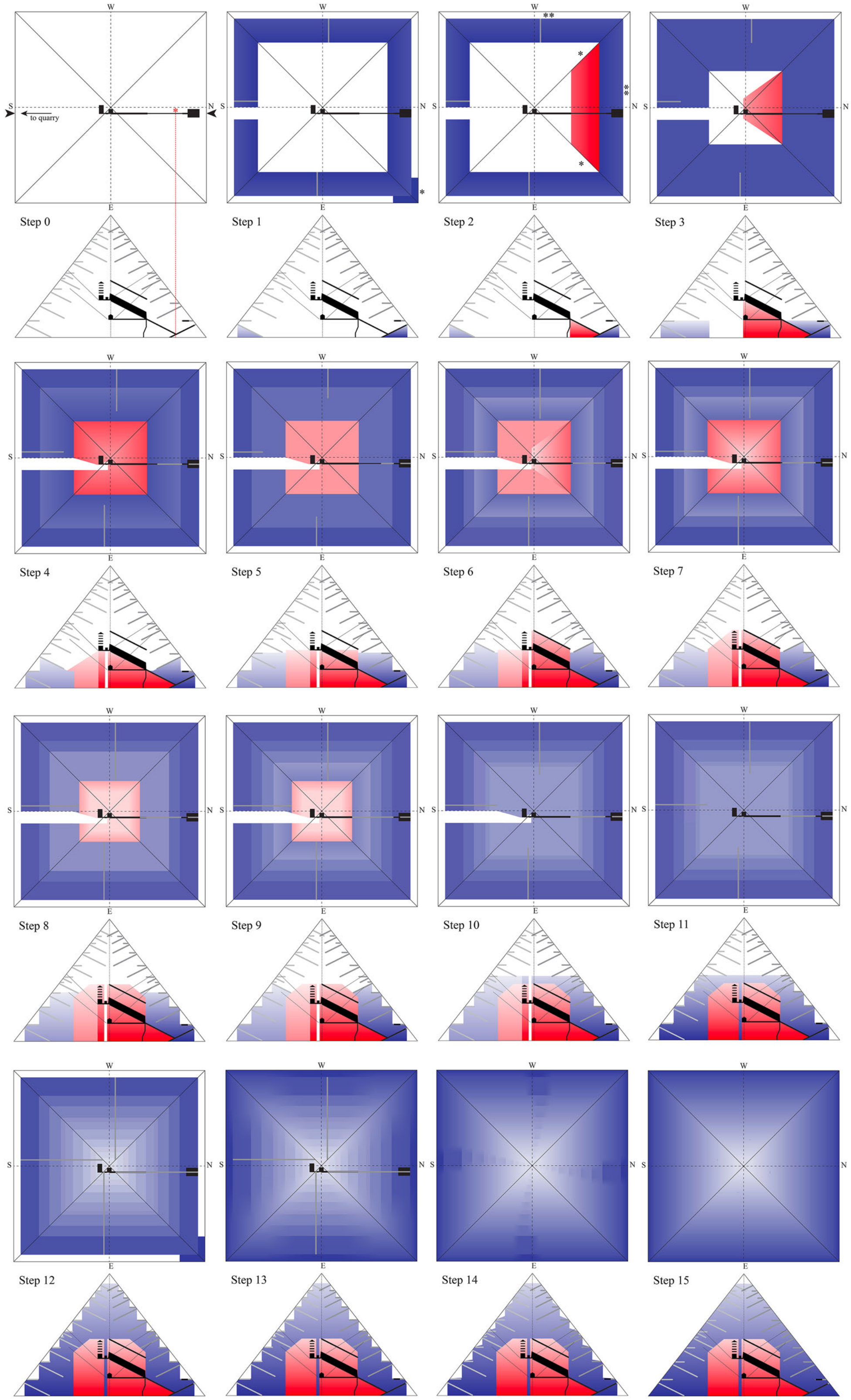


Fig. 8 | Proposal for the construction of the Great Pyramid. Sequence in 15 steps. Top: top view. Bottom: Side view. Blue: Mantle masonry, i.e., masonry lifted by peripheral pulley-like systems on the pyramid faces. Red: Core masonry, i.e., masonry lifted by pulley-like systems in the pyramid core, mainly in the vertical shaft axis of the Ante-chamber. Darker and brighter colors correspond to lower and higher height structures, respectively. Known internal volumes are shown in black, including a ramp at the approximate location of ScanPyramids' big void. The side views are shown in section along a North–South axis at ~7 m East from the center (arrowheads in step 0). For clarity, the side views (steps 1–10) show the South half of the pyramid shaded, as the masonry is ~7 m further to the West than the section (see top views). For further clarity, the background is kept white (steps 0–12) though the bedrock naturally defines the lowest level indicated by dark blue North-East corner (rock) in step 0 and step 12. Step 2: *Masonry is illustrated here with sharp borders, but was likely tapered. **Masonry in the center of the pyramid faces and/or at any intermediate position of pulley-like systems was sharp, as the pulley-like systems needed a rather vertical face to lift blocks. For a step-by-step description of the building process, see *"Proposal for how the Great Pyramid of Giza was built"*.

pyramid, 'exchange cycles', i.e., steps 3, 5, 8, etc). This process covers Descending and Ascending Passages, and corresponding sliding-ramps.

Step 4: The core grows pyramid-shaped bringing the central area to the height of the King's Chamber base. Access to the foot of the Antechamber pulley-like system is maintained, *i.e*., a vertical shaft in the Antechamber axis is established. The mantle's four peripheral pulley-like systems grow new sliding-ramps in their respective axes.

Step 5: The core flattens, growing the Grand Gallery. The mantle four peripheral pulley-like systems, now dual systems, that lift blocks to complete the second 'step' of a step-pyramid-like structure by building inwards.

Step 6: In the core, the Grand Gallery is completed (see *"Use of blocks that are integrated in construction"*) and the ScanPyramids' big void sliding-ramp grows above it, reaching its apex ~30 m above the top of the Grand Gallery. The mantle's four peripheral pulley like systems grow new sliding-ramps in their respective axes.

Step 7: Work is concentrated in the core, building the King's Chamber and its superstructures lifting blocks using a pulley-like system fueled by ScanPyramids' big void sliding-ramp. At this stage, the Antechamber pulley-like system was retired, and blocks were lifted through it, explaining the extended rope-guidance grooves in its South wall, and possibly the damage to the South wall (see Fig. S5b).

Step 8: In the core the King's Chamber construction is in their finalizing stage and ScanPyramids' big void sliding-ramp is covered. The mantle has four peripheral pulley-like systems, now triple systems, lift blocks to complete the third 'step' of a step-pyramid-like structure by building inwards.

Step 9: The core structure (red) is finished. The 'airshafts' from the Queen's Chamber were terminated as they ran into the mantle. They may have served as communication pipes between the pyramid core (Queen's Chamber) and the pyramid periphery (Text S3). The 'airshafts' from the King's Chamber exit the core masonry above the mantle as they were started later and higher up (Text S4).

Step 10: The mantle masonry (blue) grows over the core masonry (red). This is where the core masonry (red) is closest to the pyramid surface. Importantly, there is structural evidence for this: There are two sequential, very clear and very short height-decay bins, at ~69 and ~75 m height (Fig. 7c, red dashed outline). The second must thus have a sliding-ramp reaching only ~12 m (slope 1 cubit over 2 cubits) into the pyramid, suggestive that the core masonry is at this position at a similar or slightly larger distance from the surface. The height of these height-decay bins matches well the expectations: The Grand Gallery peaks at 43 m height, and ScanPyramids' big void is proposed ~30 m above the Grand Gallery, thus reaching ~73 m; the King's Chamber roof reaches ~66 m. Thus, the mantle grows using two short sliding-ramps, building inwards and over the core to complete the fourth and fifth 'step' of a step-pyramid-like structure.

Step 11: The Antechamber pulley-like system shaft and the gap in the mantle South-sector are filled and closed inside-to-outside and layer-by-layer from the south face. Likely, the upper part of the shaft is filled from above.

Step 12: The mantle step-pyramid-like structure is finalized by a series of outward sliding-ramp growths and inwards building cycles for each peripheral sliding-ramp (repeats of steps 2–3, 4–5, 7–8, etc.).

The sliding-ramps in the upper part of the pyramid must have reached almost the pyramid center. Their likely existence in all four faces might be the reason why they are off-axis, i.e., the Descending Passage in the North face is ~7 m East from the center. Thus, the sliding-ramps from all four sides are iris-like twisted (see gray lines in step 12 top view), providing better stability and avoiding sliding-ramp overlap, even if they were to exceed the pyramid center.

Step 13: The mantle becomes true-pyramid-like starting in the corners and bottom-to-top (Fig. 7d, g). The pulley-like systems and connecting paths are kept open-air as long as possible. Each sector is quite concave, with the corners true-pyramid-like and the central area step-pyramid-like.

Step 14: The pyramid faces are being closed from the corners to the center and bottom-to-top in each height-section, and top-to-bottom in general (Fig. 7g). During this step the connecting paths are covered, *e.g*., ScanPyramids' northern corridor, in the lower sections by chevron structures, likely in less sophisticated ways in the upper sections.

Step 15: The pyramid is finished.

The completion of the faces from a step-pyramid-like to a true-pyramid structure (steps 12-15) ran into imperfections and a lower-density placement of blocks in the center of the faces, which is seen today on the pyramid faces, in the absence of casing, as concavity (Fig. 7e) and the central furrow (Fig. 7f). The casing blocks are added, in the same way as all other blocks, at the very end of the construction. As other reports suggested[3,18,22], the casing blocks were likely placed in a roughly masoned state and then chiseled into a perfect fitting shape on the pyramid. This process allowed Hemiunu to correct with the casing for the minor construction imperfections, i.e., concavity and central furrow. Given that the casing stones were well fitted, the height-decay bins were still present on the pyramid face, but likely invisible in its finalized state. The pyramidion was likely lifted over the peripheral pulley-like systems as far up as possible, but the very top of the pyramid was likely built using a brute-force approach.

Discussion

The presented proposal of the construction of the Great Pyramid breaks conceptually with former proposals in major ways: First, other proposals postulate that the pyramid grew from a flat low structure layer-by-layer upwards, in contrast, according to the proposal presented here, pyramid construction started at the point where Ascending Passage and Descending Passage split, namely the section that Hemiunu built in his trial[8] (Fig. S10). The trial passages are a much smaller, e.g., the trial Ascending Passage has ~15% of its length in the pyramid, and are somewhat differently proportioned, *i.e*., the Descending Passage is comparatively longer than in the pyramid when compared to the Ascending Passage. Based on its small size, the structure most likely represented a trial rather than an abandoned pyramid construction beginning. Under the assumption that it was a trial, then it represents further evidence that the Ascending Passage and Descending Passage split is indeed a/the key structural element, and that Hemiunu might have performed experiments on it (Text S5). Construction advanced from there towards the core with the growth of the Ascending Passage and Grand Gallery, building the pyramid core with all major architectural elements, and outwards with the growth of the Descending Passage, building the pyramid mantle. Second, other proposals call for construction-ramps on which blocks were pulled up, while the proposal presented here does not call for any construction-ramps. Third, in other models, blocks are pulled upwards, suffering the energy loss to lift the blocks and work against friction, while in this proposal, the blocks are lifted free of friction, and counter-weights sliding down the sliding-ramps generate a force, multiplied over a pulley-like system, and the friction of the down-sliding counter-weight and within the pulley-like system rather serves as a natural break.

Early explorers measured the dimensions of the pyramid and its internal structures searching for divine dimensions or measures[31,34]. Still today, alternative scientists read meaning, celestial arrangements, or divine or extraterrestrial planning, into the odd arrangement of the internal structures. In contrast, modern academics appear to largely disregard that the pyramid's arrangement of internal structures and masonry could hold essential clues with regard to its construction. I found the arrangement of the internal structures odd, not esthetically pleasing, and explored pyramid structure and masonry in light of and as a result of constraints and problem-solving of the construction process. As examples: Why build the main passages, the Descending Passage, Ascending Passage and Grand Gallery perfectly North–South oriented, but ~7 m off the East-West axis center? Why build the Queen's Chamber in the North–South axis center, but its center ~4 m off the East-West axis center? Why is there a total of ~8.39 m between the top of the Grand Gallery and the King's Chamber, interspaced by two low corridors and the Antechamber? Why do the shafts extending from the Queen's Chamber not reach the pyramid surface, but the shafts from the King's Chamber do? Why are the shafts extending to the South straight, while the shafts to the North are bent? Why is the Grand Gallery's top precisely in the North-South axis center and not the King's Chamber? Is the upper end of the Grand Gallery more important than the King's Chamber? The same is true for the pyramid surface: Why are the faces slightly concave? Why the complex pattern of course heights organized in decaying bins?

Overall, the major architectural elements are close to a common vertical axis, but do not superpose[2,25], and all passages are in one North–South axis, even the newly discovered ScanPyramids' big void and north face corridor that appear otherwise disconnected from the other structures. For any layer-by-layer and bottom-to-top construction model, there is no reason for such an arrangement. Had Hemiunu used a layer-by-layer and bottom-to-top construction method, he could have placed the structural elements wherever he wanted, e.g., the King's Chamber perfectly centered. Had Hemiunu built the pyramid layer-by-layer, he could have chosen all courses to have identical thickness, or thicker and thinner layers could be organized randomly; there would be no reason for the course height-decay bins, or the faces' concavity.

The model presented here can provide explanations for all these questions and architectural features. Also, based on the understanding of the Great Pyramid's construction that the model offers, no further major architectural element is expected to be found in the pyramid core. In the mantle, further connecting corridors, like ScanPyramids' northern corridor, are expected to be found higher up, along with corresponding peripheral sliding-ramps. These should be shorter and maybe thinner than their lower counterparts, as the blocks to be lifted are overall smaller and the pyramid gets thinner at higher heights. In particular, the height-decay bin pattern suggests a concentration of sliding-ramps and connecting corridors at ~69 and ~75 m height (Fig. 7c, dashed outline). Also, based on the fact that all faces have similar concavity and central furrow, similar construction-related structures should exist on all faces. In contrast, in the core, all major elements would have to be next to the vertical axis defined by the Antechamber shaft. Since muon scanning measured a substantial angular range of the pyramid core from the Queen's Chamber upwards[26], the existence of substantial additional voids in this region can be excluded. The East from the Antechamber vertical shaft can be excluded, as that region most likely offered the path by which blocks were brought from the South quarry to the pyramid core (Fig. 8, step 4). Thus, there is a minor possibility of an architectural structure in the bottom ~20 m West of the Antechamber shaft, but since Hemiunu built everything in one North-South axis and may have had to deal with further constructional compromises, the model suggests that there is no further architectural structure to be found in the Great Pyramid.

Summarizing, a proposal for the construction of the Great Pyramid of Giza with pulley-like systems using counter-weights on sliding-ramps, is presented here. The model is radically different from construction-ramp-based models and physically favorable when compared to these (Table S1). The model allows for concerted growth of the mantle from all sides, and accounts for the construction of the core with its major architectural elements and the associated lifting of heavy blocks to the level of the roof of the King's Chamber. It is supported by a series of architectural and masonry features, and can explain structural features that remained unexplained or meaningless (Table S2). The new construction model allows to make a series of predictions (Table S3), that can potentially be tested and that will confirm or disprove the proposal. Should the model receive further support, the construction of other pyramids and other monuments should be considered in light of the technological possibilities presented by the pulley-like system/sliding-ramp model (Texts S6, S7). Overall, the model not only provides explanations for structural features that were in plain sight, e.g., the alignment of all passages and the clustering of the major architectural features around a common height-axis, but it also provides explanations for odd features, e.g., the course height-decay bins, concavity and furrow on the pyramid faces or the inlaid floor in the Antechamber. Finally, it offers the reassignment of the Antechamber to represent a highly innovative pulley-like system (Movie S1). Following these arguments, it is likely that the Great Pyramid of Giza was built in the proposed or a similar way.

Data availability

All data needed to evaluate the presented model can be found in this manuscript, the Supplementary Information file, and in the referenced literature.

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Author contributions
S.A.S. developed the model, prepared all the figures, and wrote the entire manuscript.

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