ANTHROPOLOGY

Early science and colossal stone engineering in Menga, a Neolithic dolmen (Antequera, Spain)

José Antonio Lozano Rodríguez[1,2]*, Leonardo García Sanjuán[3], Francisco J. Jiménez-Espejo[4], Antonio M. Álvarez-Valero[5], Jesús M. Arrieta[1], Eugenio Fraile-Nuez[1], Antonio García-Alix[6], Raquel Montero Artus[3], Francisco Martínez-Sevilla[2]

Megaliths represent the earliest form of monumental stone architecture. The earliest megalithic chambers in Europe appeared in France in the fifth millennium BCE. Menga is the oldest of the great dolmens in Iberia (approximately 3800 to 3600 BCE). Menga's capstone #5 weighing 150 tons is the largest stone ever moved in Iberia as part of the megalithic phenomenon and one of the largest in Europe. The research presented here proposes a completely innovative interpretation of how this colossal monument was built. It comprises a geoarchaeological analysis encompassing three major components: (i) the angles of the planes of each stone, (ii) the stratigraphic polarity of each structural element, and (iii) the depth of the foundations. Our results show that Menga is a unique example of creative genius and early science among Neolithic societies. It was designed as a completely original engineering project, for which we know of no precedents in Iberia.

INTRODUCTION

Megaliths are structures made of large stones and are found in variety of regions throughout the world. In Late Prehistoric Europe, megalithic monumentality was a widespread phenomenon, spanning 3000 years, from the mid-fifth (France) to the late second millennia (Balearic Islands, Corsica, Sardinia, Greece). Megaliths, the earliest stone-made monumental constructions, framed and embodied profound social and ideological messages in a long-lasting and visible manner. The longevity of the large stones (as opposed to wood) and their visual impact on the surrounding landscapes suggest that long-term persistence was a major driver in their construction (*1*, *2*). As monuments endowed with deep social significance and cultural memory, megaliths often present extended biographies, spanning several millennia of use, frequentation, and transformation, which makes them one of the most enduring and fascinating phenomena in human history (*3*).

As Colin Renfrew noted half a century ago (*4*), large megaliths demanded the mobilization of a substantial labor force and the deployment of advanced engineering and architectural expertise in stone construction never attained before. Megalithic monuments are prominent and pervasive features raising a wide interest in contemporary society. Yet, multidisciplinary studies of early megalithic engineering supported by archaeological, petrological, stratigraphic, and geological evidence have been quite rare, although some exceptions exist (*5*–*9*). This is surprising, since technology mediates human interaction with the world, and its knowledge is essential to comprehend past societies.

Here, we examine a great Neolithic engineering feat: the Menga dolmen, Iberia's largest megalithic monument. As listed by UNESCO, the Antequera megalithic site includes two natural formations, La Peña de los Enamorados and El Torcal karstic massif, and four major megalithic monuments: Menga, Viera, El Romeral, and the one recently discovered at Piedras Blancas, at the foot of La Peña de los Enamorados (*10*) (Fig. 1A). Menga, built between approximately 3800 and 3600 BCE, is the earliest of all four megaliths and stands out on account of its enormous size and the colossal weight of its stones (Fig. 1, B to E). Its extraordinary dimensions demanded sophisticated design and planning, a large mobilization of labor, as well as perfectly executed logistics. Because of the originality of design, with three preserved pillars aligned with the central axis of the monument, and the massive size of the stones, Menga was already acknowledged as a groundbreaking discovery shortly after the first explorations were undertaken in the 1840s (*11*).

Like most early megaliths, Menga has never been analyzed from an interdisciplinary perspective combining archaeological, petrological, and stratigraphic (sedimentological and paleontological) evidence. Therefore, the challenges involving its construction have not been evaluated as an engineering problem. This paper proposes a revolutionary interpretation concerning the way this remarkable monument was built, based on a geoarchaeological analysis of the angles of the planes of each stone, the stratigraphic polarity of each structural element, and the depth of the foundations relative to the original bedrock level. Our hypothesis represents a completely original take on hitherto unresolved critical problems, such as why was the monument largely embedded in the ground, or how were the massive stones, made on soft and moderately soft rocks, placed inside the monument, or what was the purpose of the tumulus. Answers to these questions are critical to understand how a building made using supposedly "primitive" technology has successfully stood on its feet for almost 6000 years, thus becoming one of the most remarkable known examples of Neolithic architecture. Our findings run entirely counter to the idea of "primitiveness" or "rudeness" (*12*) that for a long time has underpinned both the popular and scientific understanding of Neolithic societies.

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[1]Canary Islands Oceanographic Center (COC), Spanish Institute of Oceanography (IEO), Spanish Research Council (CSIC), Santa Cruz de Tenerife, Spain. [2]Department of History and Philosophy, Prehistory Area, University of Alcalá, Alcalá de Henares, Spain. [3]Department of Prehistory and Archaeology, University of Sevilla (US), Sevilla, Spain. [4]Andalusian Institute of Earth Sciences, Spanish Research Council, University of Granada (CSIC-UGR), Armilla, Granada, Spain. [5]Department of Geology, University of Salamanca (USAL), Salamanca, Spain. [6]Department of Stratigraphy and Paleontology, University of Granada (UGR), Granada, Spain.
*Corresponding author. Email: ja.lozano@ieo.csic.es

Fig. 1. Location and interior of the Menga dolmen. (**A**) Panoramic view of the city of Antequera, with the location of the Cerro de la Cruz quarry, the Viera and Menga dolmens, the *Tholos* of El Romeral, and the Piedras Blancas at La Peña de los Enamorados. (**B**) Entrance to Menga. (**C**) Interior of the dolmen from the second pillar. (**D**) Interior of Menga, and three pillars currently preserved. (**E**) Dolmen chamber. Credits: (A) and (B) correspond to the main author; (C) and (E) were provided by the Antequera Dolmens Archaeological Site on behalf of the Andalusian Regional Government (Miguel Ángel Blanca de la Rubia); (D) (*61*).

Site location

The Menga dolmen is located on a hilltop rising some 50 m above the surrounding plain and dominating the southern edge of the neighboring Guadalhorce River valley. Recent investigations have revealed intense and sustained human activity on the Menga hill preceding its construction (*13*). Basically, the specific choice of the location for the great dolmen site is directly related to the natural conditions of the regions surrounding it, including Antequera's character as cross-roads, the presence of a fertile plain generated by the Guadalhorce River, and wealth of abiotic resources (fig. S1). The latter is of particular relevance, as Antequera boasts a range of abiotic resources that were widely sought after in Late Prehistoric Iberia (*14*). This is explained by the proximity of Antequera to the contact between the Internal Zones and the External Zones of the Betic Cordillera, where resources for multiple prehistoric products are available, including quarries for flint tools (*15*–*19*), axes of ophitic and doleritic composition (*20*), marble bracelets (*21*, *22*), axes and adzes on sillimanites (fibrolite variety) (*23*), copper carbonates for metallurgy (*24*), and important salt springs related to the "Trías de Antequera" (*25*). The availability resources near Antequera also includes rocks suitable for the construction of large megaliths (*14*) as well as iron oxides existing in materials from the Upper Triassic age, ideal for pigmentation.

Menga is a large-sized (Fig. 1, B to E) simple-gallery dolmen spanning 24.9 m in length with a maximum width of 5.7 m and a height rising from 2.50 m at the entrance to 3.45 m at the back of the chamber (on average). Access to the inner space is achieved through a small unroofed atrium (Fig. 1, B to E). Currently, it presents three preserved pillars aligned with its longitudinal axis, although probably there was a fourth, now missing (*14*) standing below the joints of the capstones (Figs. 1, C to E, and 2A). Its interior space is delimited by 10 uprights on each side, covered by five capstones and ending in a massive backstone. Two additional uncovered orthostats on the right side of the entrance and one on the left complete the monument at present, but there may have been some more orthostats in the past (*14*). The 32 stones that form Menga weight about 1140 tons (*14*, *26*). Capstone C-5, with an estimated weight of 150 tons, is the largest stone ever moved as part of the megalithic phenomenon in Iberia, and the second largest one in Europe, only surpassed by the Grand Menhir Brisé (southern Brittany, France). Needless to say, future research may establish the existence of other larger megalithic stones. The rocks used to make the uprights, capstones, and pillars mostly include calcarenites and bioclastic calcirudites and one breccia, all of them of Upper Tortonian age (*14*, *27*) and considered soft or moderately soft rocks (*27*). The orientation of the original strata can be seen in many of the stones because of the polarity of fossil bivalve shells, embedded pebbles, and ichnofacies (Fig. 2 and fig. S2).

The longitudinal axis of Menga, closest to its axis of symmetry, is oriented toward La Peña de los Enamorados northern cliff (locally known as Tajo Colorado), where prehistoric rock art dating to before ~3800 BCE was found in the Matacabras shelter (*28*). But Menga also displays an astronomical alignment, with a solar orientation that, in the summer solstice, causes the left side of the chamber (as one enters) to remain in the shadows, while much of the right side is illuminated (*14*). The nuances of this orientation add further complexity to the design of Menga.

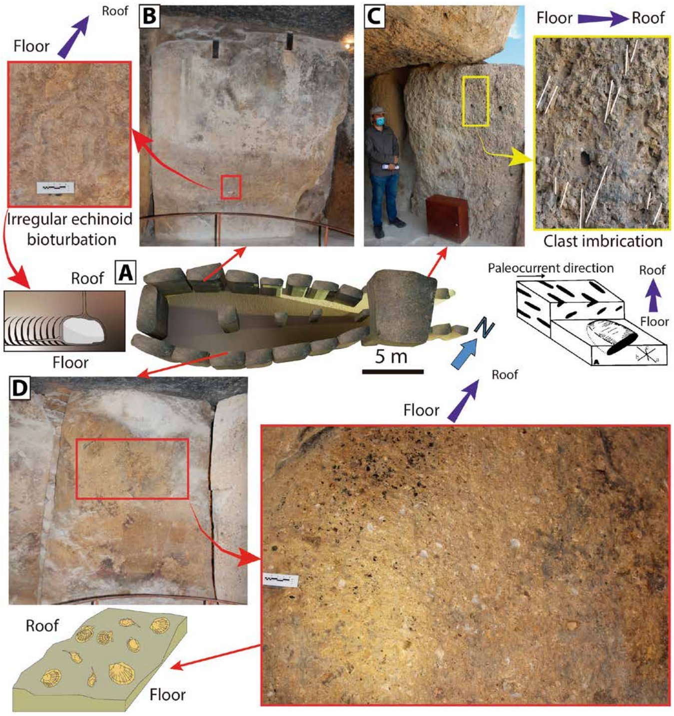

Fig. 2. Polarity criteria of roof and floor in the original geological stratification at the Cerro de la Cruz quarry. (**A**) 3D model of Menga based on laser scanning with AutoCAD (*14*). (**B**) Irregular echinoid bioturbation: surficial and meniscate locomotion trace produced by the Spatongoid (*62*, *63*), in upright O-14. (**C**) Lithofaous and ophagues and embedded pebbles in upright O-22. (**D**) Concave shells of bivalves in upright O-9 and schematic representation of their original position in the deposits. Credits: All photos are the property of the primary author.

RESULTS

Determination of polarity (roof and floor of the original stratification)

Elements of stratigraphic polarity (roof and floor of the original stratum) can be readily observed on most uprights, capstones, and pillars. They correspond to the original stratification of the rocky outcrops the stones were quarried from. The presence of bioturbation by echinoderms (Fig. 2B), with the flat base of the ichnite, shows the position of the floor in the original stratum, facing toward the inner space of the monument. The existence of imbrication pebbles is another piece of evidence that allows to reconstruct the polarity (Fig. 2C), showing the direction of the paleo-stream in which the original sedimentation of the sediments forming the rocks occurred. In this sense, various uprights show abundant disarticulated bivalve shells, the vast majority of which show their concave sides toward the inner part of the monument (i.e., facing the chamber) (Fig. 2D). As an indicator of polarity, this reveals that the visible side of the stones belonged to the floor of the original stratum, while the other side, facing the mound, would have corresponded to the roof. Since the location of the quarries that provide the material to the dolmen is known with certainty (*27*), it has been possible to verify that the geological stratification is in a horizontal position. Therefore, the quarrying and ulterior placement of the stones preserved the original horizontal position of the rocks.

Determination of the existing angles

Once inside Menga, it becomes readily apparent that the uprights do not stand perfectly vertically. They are gently tilted toward the interior with an average angle of 85.2 ± 1.6° (left side)–84.0 ± 2.0° (right side) with regard to the horizontal (i.e., the floor) (Fig. 3A and Table 1). This causes the space inside the dolmen to have a trapezoidal section. Although the angle of tilt could not be accurately measured for some areas of the orthostats because of the erosion they have suffered, especially in their lower part (mostly in recent historical times due to friction by animals—probably sheep or goats) (*29*), most of them display well-preserved and measurable areas. That is the case of uprights O-11 and O-13, which rest on the backstone (O-12) (Fig. 3B).

As well as leaning inward, the orthostats also lean sideways against each other, with angles of 80°, 86°, and 88°, both on the right and left sides of the dolmen, with an average of 87.1 ± 2.4° (left side) and 88.0 ± 1.9° (right side) (Fig. 3, C and D, and Table 2). This is a key indicator to assess the order in which the stones were placed and, therefore, to infer how the monument was built.

Determination of the depth of the geological level and of the foundation

All depths of the estimated trench line, the geological level and the estimated geological level, have been calculated using the information available in the plans, photographs, and renderings of the dolmens made since the 1840s. Yet, special attention has been paid to the most recent scientific excavations (*30*).

Two of these excavations were carried out by the universities of Malaga in 1991 and Granada in 2005–2006, partly inside the dolmen and investigating the foundation sockets of the stones. The records from these excavations have enabled precise estimations of the base level of some orthostats (O-1, O-2, O-3, O-4, part of O-5, part of O-12, O-13, O-16, part of O-19, O-20, O-21, O-22, O-23, O-24) and all three pillars (P-1, P-2, and P-3), as well as the trench line

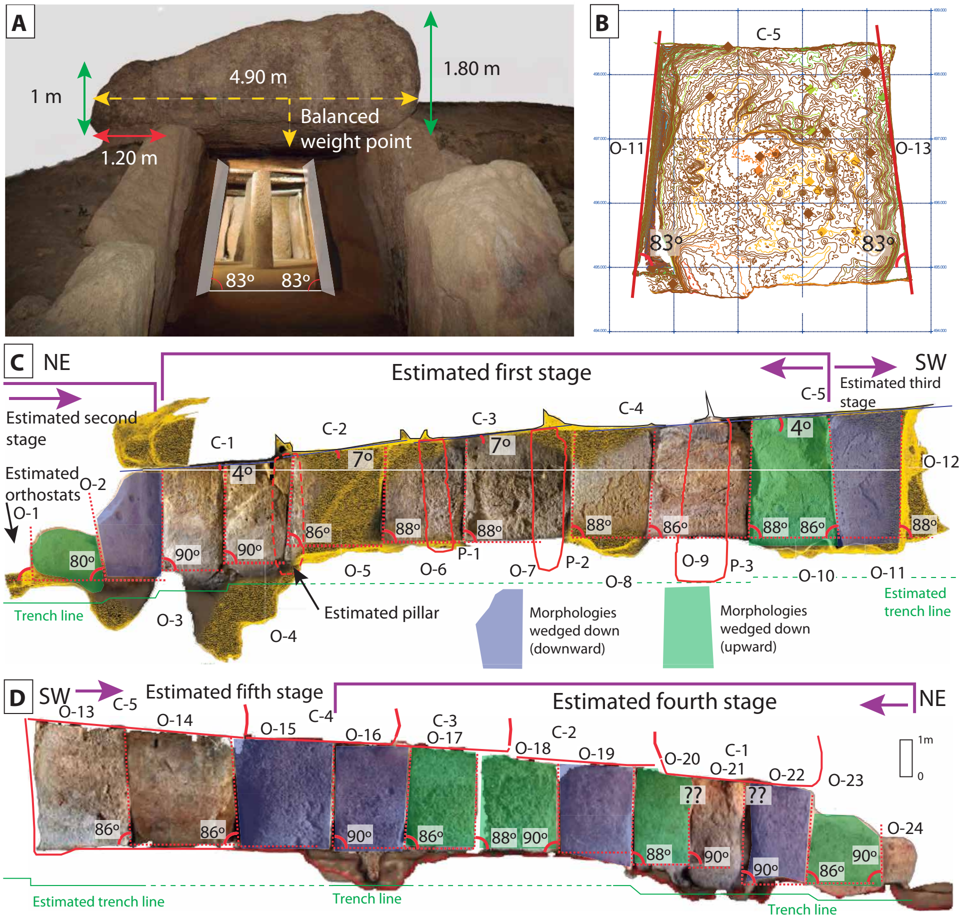

Fig. 3. Architecture of the Menga dolmen. (**A**) Frontal view of Menga showing dipping angles on some of the uprights and asymmetric placement of capstone C-1 with regard to the uprights. The latter shows a clear distribution of weights (yellow lines and dotted arrows) with regard to the difference in thickness of capstone C-1 (vertical green arrows), which sticks out of the uprights (red horizontal arrow) where it is less thick. (**B**) Microtopography of the backstone (O-12) in contact with uprights O-11 (left) and O-13 (right), which form an angle of 83° (topographic data from TDTEC S.L. 2005) (*55*). At the base of the rock, you can see the beginning in a curved shape, partially hidden under the foundation. (**C** and **D**) Lateral view of the left and right sides of the dolmen (as one walks in) (topographic data from TDTEC S.L. 2005) (*55*), showing the dipping angles of the uprights and capstones. Purple arrows and brackets indicate the hypothetical sequence of placement of the uprights, while red arrows show the pillars. The trench line (green line) and the estimated trench line (green dashed line) are calculated from the excavations carried out by the University of Málaga at the end of the last century and the University of Granada at the beginning of this century and with the help of the laser-scan plans (*55*, *60*). Credits: (A) (*61*).

(Fig. 3, C and D, and fig. S3). The foundation ditches form a stepped terrace descending toward the entrance. The estimated trench line and estimated geological level were calculated using laser-scan plans (*26*, *27*) (Fig. 3, C and D) as well as the information in other plans, renderings, and photographs of the dolmen (*28*).

DISCUSSION

To build a monument of such extraordinary dimensions and complexity, the Neolithic architects and engineers must have relied on expert craftspeople well versed in the working of timber, wood, basketry (*8*, *31*), and stone, as well as a substantial workforce capable of quarrying, dressing, and transporting the stones from the quarries to the building site. The quarries are at a maximum distance of 850 m on Cerro de la Cruz (Fig. 1A), at a location 50 m higher than the place chosen for the construction of Menga, and therefore with a favorable, descending slope (*27*).

After selecting and cutting the rocks, the first challenge had to be the transport of such massive stones. This would have been only workable on a previously made and carefully designed road (or "track-way") that would minimize friction. Using wooden beams forming a track from the quarries to the Menga hill would have helped, as well as the use of huge sledges (fig. S4). The transportation of such massive stones on a downhill path required precise control of their acceleration and center of mass or balance point, most likely with the use of large ropes (*32*). Such operations must have been heavily conditioned by the soft–to–moderately soft nature of the rocks, as any unexpected jolt would have damaged them. This important information, combined with (i) their stratigraphic polarity; (ii) the favorable slope from back to front in the design of the monument, following its longitudinal axis; and (iii) the elevated location of the quarry and the topography of the terrain, implies that the capstones were taken to their final position following the longitudinal axis of the dolmen, placing C-1 first and C-5 last.

Table 1. Inclination angle of the different orthostates to the left to the right as you enter the Menga dolmen. BS, backstone; nd, not determined.

Orthostate	1		2		3		4		5		6		7		8		9		10		11		12 (BS)	
	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L
Upper side	nd	87	83	nd	87	87	nd	82	85	85	84	83	84	84	88	83	nd	nd	85	85	85	85	nd	87
Center	nd	nd	nd	nd	nd	nd	84	84	86	85	85	83	88	86	88	88	85	86	86	85	85	85	nd	nd
Lower side	nd	nd	nd	nd	nd	nd	nd	85	86	85	86	nd	86	87	85	88	85	85	83	nd	83	85	nd	nd
Average in situ measurements	87.0 ± 0.0		83.0 ± 0.0		87.0 ± 0.0		83.8 ± 1.3		85.3 ± 0.5		84.2 ± 1.3		85.8 ± 1.6		86.7 ± 2.2		85.3 ± 0.5		84.8 ± 1.1		84.7 ± 0.8		87.0 ± 0.0	
Software measurements	nd		85		85		83		83		84		88		87		88		85		83		nd	
Average all measurements	87.0 ± 0.0		84.0 ± 1.4		86.3 ± 1.2		83.6 ± 1.1		85.0 ± 1.0		84.2 ± 1.2		86.1 ± 1.7		86.7 ± 2.0		85.8 ± 1.3		84.8 ± 1.0		84.4 ± 1.0		87.0 ± 0.0	
Average left orthostates	85.2 ± 1.6																							
Orthostate	13		14		15		16		17		18		19		20		21		22		23		24	
	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L
Upper side	87	84	83	83	83	82	83	83	83	83	88	85	86	85	80	80	86	nd	87	87	nd	nd	nd	nd
Center	84	83	86	83	83	83	88	84	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Lower side	83	83	83	83	79	83	83	86	nd	nd	83	87	88	86	83	84	83	nd	nd	nd	83	88	86	84
Average in situ measurements	84.0 ± 1.5		83.5 ± 1.2		82.2 ± 1.6		84.5 ± 2.1		83.0 ± 0.0		85.8 ± 2.2		86.3 ± 1.3		81.8 ± 2.1		84.5 ± 2.1		87.0 ± 0.0		85.5 ± 3.5		85.0 ± 1.4	
Software measurements	83		83		83		83		83		83		83		84		83		84		nd		nd	
Average all measurements	83.9 ± 1.5		83.4 ± 1.1		82.3 ± 1.5		84.3 ± 2.0		83.0 ± 0.0		85.2 ± 2.3		85.6 ± 1.8		82.2 ± 2.0		84.0 ± 1.7		86.0 ± 1.7		85.5 ± 3.5		85.0 ± 1.4	
Average left orthostates	84.0 ± 2.0																							

Table 2. Angles of the sides of the different orthostates leaning on each other on the left or on the right side as you enter the Menga dolmen. The measurements correspond to the angles indicated on Fig. 3.

Orthostate	1	2	3	4	5	6	7	8	9	10	11	12 (backstone)	
												R	L
Upper side	nd	nd	90	90	86	88	88	88	87	88	86	83	88
Center	nd	81	nd	nd	85	nd	87	88	86	88	87	84	84
Lower side	88	80	90	90	86	88	88	88	86	88	86	83	83
Average in situ measurements	88.0 ± 0.0	80.5 ± 0.7	90.0 ± 0.0	90.0 ± 0.0	85.7 ± 0.6	88.0 ± 0.0	87.7 ± 0.6	88.0 ± 0.0	86.3 ± 0.6	88.0 ± 0.0	86.3 ± 0.6	84.2 ± 1.9	
Software measurements	88	80	90	90	86	88	88	88	86	88	86	83	
Average all measurements	88.0 ± 0.0	80.3 ± 0.6	90.0 ± 0.0	90.0 ± 0.0	85.8 ± 0.5	88.0 ± 0.0	87.8 ± 0.5	88.0 ± 0.0	86.3 ± 0.5	88.0 ± 0.0	86.3 ± 0.5	84.0 ± 1.8	
Average left orthostates	87.1 ± 2.4												
Orthostate	13	14	15	16	17	18	19	20	21	22	23		
Upper side	86	86	90	86	88	nd	88	nd	nd	87	nd		
Center	86	nd	90	85	87	90	88	90	nd	86	90		
Lower side	85	nd	nd	nd	88	90	nd	90	90	86	90		
Average in situ measurements	85.7 ± 0.6	86.0 ± 0.0	90.0 ± 0.0	85.5 ± 0.7	87.7 ± 0.6	90.0 ± 0.0	88.0 ± 0.0	90.0 ± 0.0	90.0 ± 0.0	86.3 ± 0.6	90.0 ± 0.0		
Software measurements	86	86	90	86	88	90	88	90	90	86	90		
Average all measurements	85.8 ± 0.5	86.0 ± 0.0	90.0 ± 0.0	85.7 ± 0.6	87.8 ± 0.5	90.0 ± 0.0	88.0 ± 0.0	90.0 ± 0.0	90.0 ± 0.0	86.3 ± 0.5	90.0 ± 0.0		
Average left orthostates	88.0 ± 1.9												

We hypothesize that these huge stones were transported using sledges, as alternative transportation techniques, such as rollers, would have been found to be unpractical (*33*). Ethnographic (*34*) as well as archaeological evidence (*35*–*38*) suggest that sledges were the most likely method (see the Supplementary Materials). Transporting the capstones would have required sleds that were not wider than the distance between uprights on both sides so that they could be retrieved after placing the capstones. However, having a limited sled width required distributing the load using the balanced weight point of the capstones, a fact that is observable, for example, in capstone C-1. This 4.90-m stone rests on orthostats O-2, O-3, and O-4 on the left side and protrudes 1.20 m coinciding with the thinnest part of the capstone (1 m), while the right side (1.80 m) supported by orthostats O-22, O-21, and O-20 does not protrude at all (Fig. 3A).

The way the stones were placed provides numerous clues concerning the creative genius and early scientific engineering resourcefulness of the architects and engineers who designed and built Menga. The fact that they designed deep foundation sockets, in order that, when placed, one third of the uprights and pillars would stand underground (Fig. 4, G and H), makes very plausible the use of counterweights to place them. This technique, aimed at achieving a smooth and gradual tilting of the stones into the sockets, was crucial for two reasons: First, this allowed the placement of the stones with millimetric precision, both inside the sockets as with regard to the stones standing next (*5*) (Fig. 4), and second, it avoided the use of external descending ramps, which would have had catastrophic effects not only on account of the soft–to–moderately soft character of the stones used to make the stones (*27*) but also because they would have demanded rectifications in the position of the stones once they were inside their sockets. This, in turn, would have been impossible given their gigantic size and friction.

The lateral angles of the orthostats yield important clues regarding the hypothesized construction sequence of the dolmen (*39*). On the left side of the dolmen (as one walks in), the first upright to be placed was O-10, near the back of the chamber. Uprights O-9, O-8, O-7, O-6, O-5, O-4, and O-3 were then placed from there outward, leaning against each other. Still on the left side of the megalith, a second stage would have followed, in which upright O-0, no longer existing, would have been placed, and against which uprights O-1 (narrow side of the wedged morphology pointing downward) and O-2 (narrow side of the wedge pointing upward) were made for a precise leaning. It was followed by a third stage with the placement of O-11 (Fig. 3C).

For the right-hand side of the monument (as one walks in), however, the builders of Menga started from the entrance of the monument and moved inward. According to our interpretation, this would have been the fourth stage of the construction process. First, upright O-24 was placed, followed by O-23 (wedged down morphologies—upward), O-22 (downward), O-21, O-20 (upward), O-19 (downward), O-18 and O-17 (upward), and O-16 (downward). A subsequent fifth stage started with placing O-13, O-14, and O-15 (the latter downward) all leaning against each other (Fig. 3D). Then, the backstone (O-12) was placed probably by using fitting wedges under uprights O-11 and O-13, or even struts, to achieve enough spacing to position O-12, the last stone placed. The elimination of the wedges or struts would cause these uprights to lean on the backstone (O-12) (Fig. 3B).

The embedding of a large part of the monument into the bedrock (orthostats and pillars) required a deep foundation box and the preparation of the different orthostats with angles around 80° toward the interior of the dolmen (77.5 ± 2.7° on the left side and 78.0 ± 2.6° on the right side) (Fig. 4I, fig. S3C, and Table 3) and a slope of about 30° toward the east (outside the entrance) (Fig. 4, H

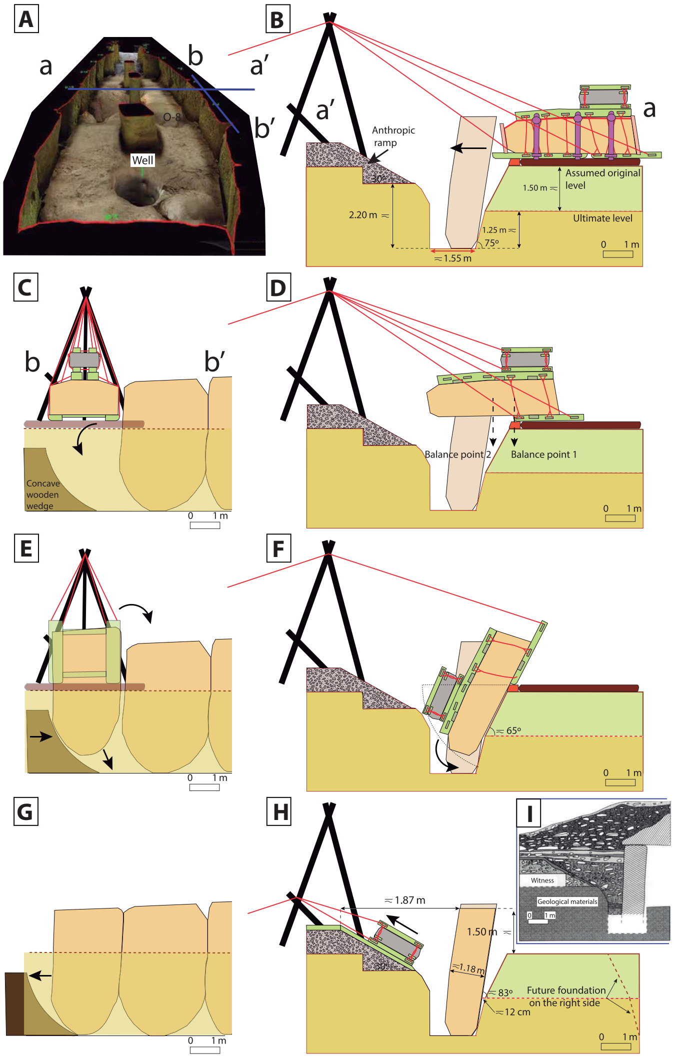

Fig. 4. Upright placement proposal. (**A**) 3D typographic rendering of the Menga's inner space from the back of the chamber (topographic data from TDTEC S.L. 2005) (*55*). Blue lines a-a′ and b-b′ correspond to the section shown. (**B**) Approaching an upright from "the interior" of Menga with counterweight. (**C** and **D**) Displacement of the balance point of the upright as a result of the counterweight and representation of the wooden wedge used as support to move the upright. (**E** and **F**) Displacement of the counterweight and tilting of the upright as a result of the change in the balance point, while at the same time the wooden wedge exerts horizontal pressure to easily adjust it laterally to the upright already placed on its side. (**G** and **H**) Removal of wooden wedge and counterweight over the external lateral ramp. (**I**) Section of this part of the dolmen (*48*). Sledge inspired in Hieroglyph U15 (*38*), the ones found in the pyramid of Senwosret III at Dahshur mortuary complex of Senwosret I at Lisht South (*35*) and the one engraved in tomb of the 12th Dynasty nomarch Djehutihotep at El-Bersheh (*64*). The efficacy of the counterweight system was experimentally proven (*5*).

and I). Similar observations as those reported here (see Fig. 4I) were made in both Danish (*29*) and French monuments (*40*, *41*), with a rupture in the composition of the tumulus at the orthostat's top side, clearly extended by a ramp used for the laying of the capstones in the case of the monument at Klekkendehoj (*42*).

According to our hypothesis, the placement of the pillars would have occurred once the orthostats were already in place, except for the backstone, following the same process involved in the erection of a menhir (S5). The penultimate construction phase of the building would have been the placement of the capstones, which would follow the same transport direction as all the previous ones (along the longitudinal axis of the dolmen, from the back to the front) and taking advantage of the downward slope that had been built into the architecture of the monument (Fig. 3, C and D). The order in which they were placed was C-1 first, followed by C-2, C-3, C-4, and finally C-5. Following the placement of each capstone from the entrance toward the back of the chamber, the interior of the monument had to be carved to retrieve the sledge and lower the capstone to its final position and eventually quarried away to the final ground level. The foundation ditches would always have a depth greater than the final ground level. The orthostats would protrude slightly above the level of the bedrock surface (Fig. 4). Only after the capstones were positioned was the bedrock cut away within the monument. Finally, the mound was built, which additionally would provide further stability to the whole structure and protection against flooding.

Another example of the remarkable resourcefulness deployed in the construction of Menga is the preparation of the uprights with angles around 85°-84°, with the aim of making the building narrower in the roof than on the floor, through a trapezoidal section (Fig. 3A and Table 1). This clever idea allowed the builders to reduce the width of the capstones, given that the stones were made of soft or moderately soft rocks and not very resistant to traction efforts. To achieve all this, it was necessary to lower the lateral of the interior of the base in the uprights with an angle of approximately 7°-6° (Fig. 5A) so that they would lean inward as required. The trimming was presumably made before the orthostats were placed in their

Table 3. Angles of the interior side of the foundation socket on the left or on the right side as you enter the Menga dolmen.

Orthostate	1	2	3	4	5	6	7	8	9	10	11
Upperside	nd	nd	nd	nd	80	nd	75	75	nd	nd	nd
Center	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Lower side	nd	80	80	nd	nd	nd	nd	75	nd	nd	nd
Average in situ measurements	nd	80 ± 0	80 ± 0	nd	80 ± 0	nd	75 ± 0	75 ± 0	nd	nd	nd
Average left orthostates						77.5 ± 2.7					
Orthostate	13	14	15	16	17	18	19	20	21	22	23
Upperside	nd	nd	75	80	80	80	80	nd	nd	nd	nd
Center	nd	nd	nd	80	nd	nd	75	nd	nd	nd	nd
Lower side	nd	nd	nd	80	nd	nd	nd	75	nd	75	nd
Average in situ measurements	nd	nd	75 ± 0	80 ± 0	80 ± 0	80 ± 0	77.5 ± 3.5	75 ± 0	nd	75 ± 0	nd
Average right orthostates						78.0 ± 2.6					

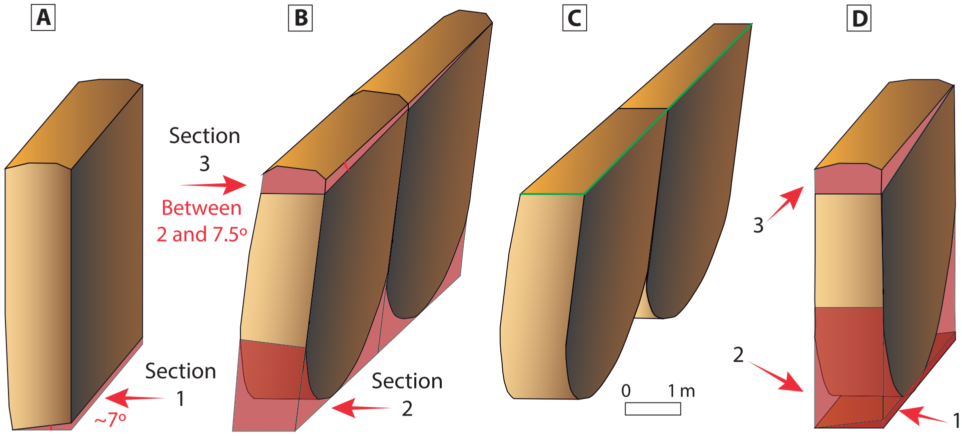

Fig. 5. Upright preparation. (**A** to **C**) Sequence of cuts made in the uprights. (**D**) Summary of all the sections removed from each upright. The final morphology of the uprights is based on the laser-scan data by TDTEC S.L. 2005 (*55*) and the photographs taken during the excavations carried out by the University of Malaga in 1991 (*65*).

final position. Such feature is not unique to Menga and can be observed in many other megalithic monuments in Europe, for example, in southern France (*43*, *44*). The side walls of the Arles hypogea, dug into the rock, also have such an inclination, providing a trapezoidal section (*45*), which is certainly part of the architecture (*46*, *47*), as designed by Neolithic builders. For all these reasons, it could also be an architectural style. Another outstanding feature of Menga's design, as mentioned above, is the uprights leaning on each other. This is achieved by generating groups of angles around 83°-84° and 86°-87° (Fig. 3, C and D; fig. S6; and Table 1), by roughing the lateral edges of the base of the uprights, to generate an ellipse-shaped surface (Fig. 5B and fig. S4, B and C). Finally, a third indentation was made in the roof of the uprights (Fig. 5, B and C), creating a descending pattern from the back of the chamber to the entrance (Fig. 3, C and D), with angles between 2° and 7.5°, which at the time of construction would have helped to place them in their final position. Altogether, three different cuttings were made in the uprights (Fig. 5D). The presence of angle groups suggests that some angle-measuring device may have been used, such as a plumb level and a square angle frame combined as a single instrument (tangent of an angle or slope).

Several clues suggest that the uprights in Menga were carried and placed from the inside of the chamber and not from the outsides, as previously thought (*48*). One of these clues is the stratigraphic polarity of roof and wall (Fig. 2 and fig. S2). The analysis of the original position of the pebbles embedded in the breccia used to make some of the uprights and capstones and the original stratigraphic position of the fossils and ichnites present in many of the orthostats reveal the position of the stones in the bedrock while they were being quarried and how they were placed in the building. This suggests that, in the case of the Menga dolmen, the orthostats were placed into their final position from the inside of the monument and not from the outside. Archaeological experimentation has conclusively shown that the placement of large stones is more efficient when the gravity point shifts gradually with the help of a moving counterweight (*5*), a procedure that achieves a smoother tilting of the stone into its socket (Figs. 4 and 6). Later, the counterweight would have been retrieved by the only available area, i.e., the 30° ramp made on the other side (outer side) of the foundation socket (Figs. 4 and 6).

With this construction procedure, it was possible to achieve a near-perfect adjustment of the orthostats to each other. This explains the precise and regular angle at which they are positioned (Fig. 3, C and D). The uprights created two strong "walls" to support the massive capstones (*39*, *49*). The trapezoidal orthostats "locked" with one another downward and upward formed a solid and lasting stone assemblage. No other monument built at that time shows that type of design. Most likely, this is explained by the aggregation of knowledge that occurred in Neolithic Antequera, since it is an area with a great wealth of abiotic resources (fig. S1), acting as an economic-social attractor (*13*). A similar architectural solution can be seen in the megalithic temple of Mnajdra, in Malta (fig. S7). At this point, it is impossible to know whether a knowledge transmission occurred between these two regions of the Mediterranean. The use of large pillars to support the enormous capstones, a remarkably original engineering feature in itself, lent additional stability to the building.

Another striking element in the design on Menga is that a large proportion of the edifice was embedded into the bedrock (Figs. 3, C and D, 4, 6, and 7 and figs. S3, B and C, and S9). This feature, which is noted for the first time in the ~200-year history of research in this

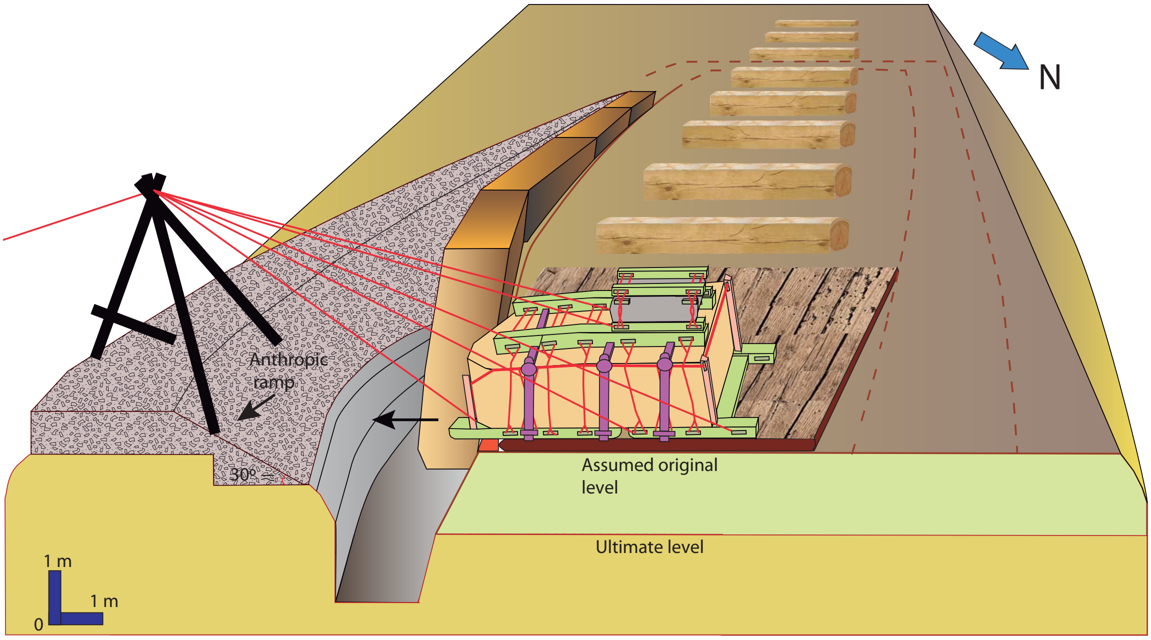

Fig. 6. Recreation of the placement of the uprights from the interior of the dolmen The figure has been based on the analysis of stratigraphic polarity of the stones and photographs taken by the University of Malaga (*65*). Sledge inspired in ancient Egyptian depictions and remains, including Hieroplyph U15 (*38*), Senwroset III pyramid in Dahshur and Senwosret I burial complex in Lisht South (*35*), and burial of 12th dynasty nomarch Djehutihotep at El-Bersheh (*64*). The efficiency of the counterweight was experimentally demonstrated by (*5*, *11*).

monument, has been recorded through a painstaking analysis of the plans and photographs (and topographic levels inferred from them) produced in the excavations of the universities of Málaga and Granada. The uprights close to the entrance of the dolmen (O-1 and O-23, under capstone C-1) are embedded to about 2.75 m in the bedrock. This means that one-third of those stones is underground. The uprights closest to the back of the chamber (O-11 and O13, underneath C-5) are embedded even more deeply, around 3.20 m (Fig. 7, B and C). This design of the foundations was intended as a "box"; hence, the base of the uprights would be fully embedded in the bedrock, and therefore completely stable. The slope of the foundations on the outside of the building is less marked than on the inside (Fig. 6I). A preparation of the geological soil under the tumulus can also be observed in stepped terraces (Fig. 7B) and a ramp that descends from the outside toward the back of the backstone (Fig. 7C).

Altogether, consciously or unconsciously, this design allowed the engineers to achieve great stability for a building located in a region with certain seismicity, where major earthquakes can occur (*50*). The monument was given additional robustness through two main design elements: (i) making the uprights "lock" with each other, thus generating a solid stone block that would hold the massive capstones; (ii) adding three (or four) pillars to provide additional support for the capstones (Figs. 3, C and D, and 7).

Finally, another important element to understand the prolonged persistence of Menga is the durability of the tumular structure. The dolmen builders created an insulating mound that keeps the interior of the dolmen perfectly dry. This insulation is especially important because the highly porous calcarenite rocks with low calcite cement that compose the main support for the dolmen would suffer major weight changes and chemical and physical weathering due to water interaction. In this sense, most of the capstones, including the

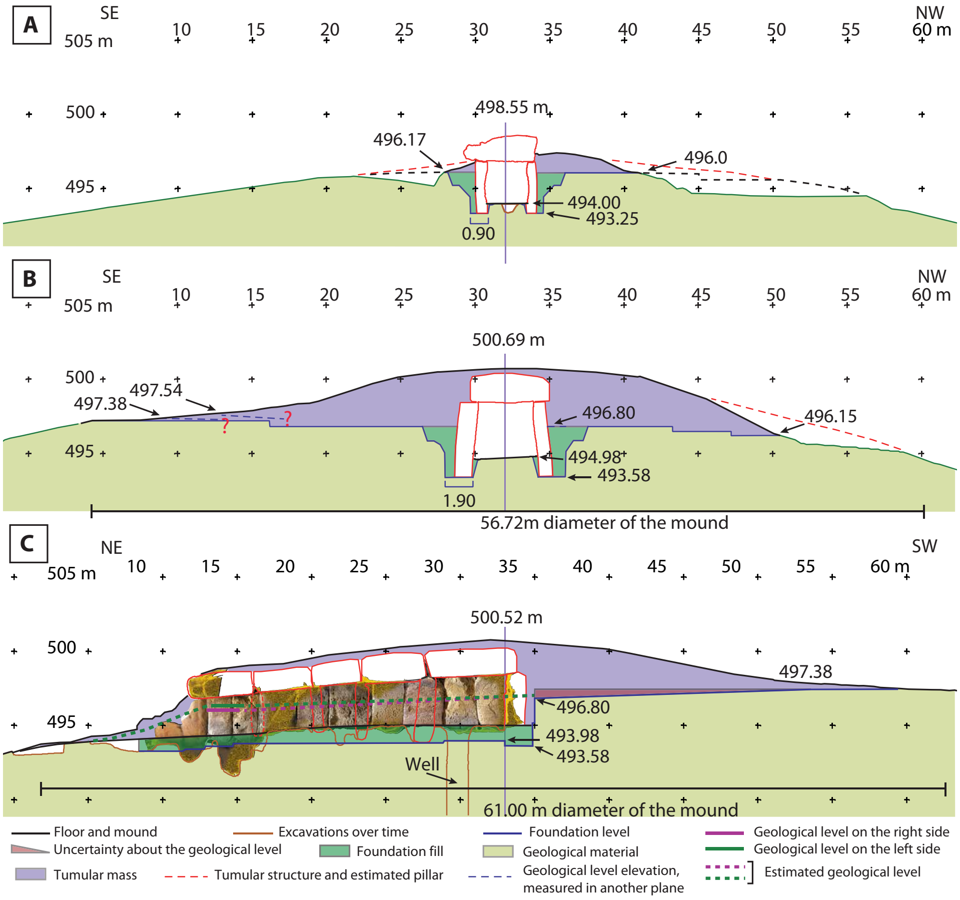

Fig. 7. Southeast-northwest (transversal) and northeast-southwest sections of Menga based on the topographic data produced by TDTEC S.L. 2005. (**A**) At the front of capstone C-1and uprights O-2 and O-22. (**B**) At the back of capstone C-5 and uprights O-11 and O13. (**C**) Right-hand side of the dolmen as one walks in. The topographic level at 493.58 m above sea level corresponds to the foundation of the backstone based in (*30*) and the photos taken by the University of Malaga in 1991 (*65*). The foundation level is based on the following criteria: altitude 493.98 on the photos taken by the University of Málaga in 1991 (*65*). The first step at the entrance is also based on the photographs of the University of Malaga 1991 excavations (*65*). Level 494.98 m above sea level is based on (*30*). The levels of the foundation sockets for the pillars are based on the photographs of the University of Málaga 1991 excavations (*65*). The thickness of the mound above capstone C-5 is also based on the photographs of the University of Málaga 1991 excavations (*65*), which do also show the thickness and shape of capstone C-5 itself. The level of the bedrock behind the backstone has been determined after the perforation of the backstone and mound made by Rafael Mitjana y Ardison in the 1840s (*57*), through ulterior illustrations by Trinidad de Rojas y Rojas,1861; Wilhelm Wattenbach, 1869; Emile Cartailhac, 1866–1867; Edouard Harlé, 1887; Marquis de Nadaillac, 1887; Luis Siret, 1891; Francisco de Paula Valladar, 1894; William Copeland Borlase; Gómez-Moreno Martínez, 1905; Obermaier, 1919; De Mergelina, 1922; Leisner and Leisner, 1943; also Juan Barrera 1896 photograph Temboury archive 1904–1905; Gómez-Moreno Martínez, 1905 archive; Fondo Duran, 1913; and Paris, 1921 (*30*), as well as 3D laser scan by TDTEC S.L. 2005 (*55*).

exposed capstone C-1 (see Figs. 1B and 3A and fig. S2B), are formed by a well-cemented conglomerate without the presence of pores, more adequate for exteriors.

The architects of the dolmen not only designed a building with pillars that could support the weight of these poorly consolidated rocks but also inferred the importance of considering the weight of the tumulus. This is deduced from the arch-shaped contour they gave to the upper side of capstone #5, which helps distribute vector forces from the center of the capstone toward the sides. This is, to the best of our knowledge, the first human-built stone structure functioning as a discharge arch (fig. S8).

The sealing of the Menga chamber, marked here by the addition of layers of clay within the tumulus, has already been noticed elsewhere. For example, it is found, again, in Danish grave passages, built around ~3300 BCE (*51*). However, it is important to keep in mind that the tumulus may have had other potentially symbolic purposes.

In Prehistoric Europe, the construction of large megaliths represents an era of great technological innovation, as it incorporates complex forms of engineering and unparalleled creative genius. It is impossible to understand how a monument as sophisticated as Menga was built between 3800 and 3600 BCE without resorting to a notion of "early science," especially considering that, to this date, no precedents have been found in Iberia suggesting a gradual, steady increase in the development of engineering expertise through trial and error. On the basis of the evidence at hand, Menga is one of the first great monumental buildings ever engineered with colossal stones. Not only no precedents existed in Iberia for such a monument when Menga was built but also no comparable monument was later made throughout all of Late Prehistory. Or at least, we have no record left. The first large megalithic constructions were made in the Near East during the Neolithic revolution (10th to 8th millennia BCE), as exemplified in Göbekli Tepe. These constructions, however, were not entirely built in stone, as the roofing was made in timber. The architectural design of Göbekli Tepe consisted of standing stones—the basic element of their structure was a T-shape stone pillar- fixed into sockets that were hewn out the bedrock, around 9600 to 8800 BCE (*52*). Other megalithic structures with astronomical alignments are found in southern Egypt, at the place known as Nabta Lake, dating from the Late and Terminal Neolithic (5500 to 3400 BCE) (*53*). In Europe, megalithic architecture occurred on the French Atlantic coast from Normandy to the Gironde. These are the corridor dolmens that are dated to the last centuries of the third millennium BCE (*54*). These are dry-rigged chambers, with a false dome roof, preceded by a narrow corridor, and covered by a circular mound. The same model can exist with small orthostats that delimit the chamber and the corridor. A variety of these monuments are found in the middle Loire basin that extends to the Cendée and inland Brittany. These are the "Angevin dolmens." Among them are the most imposing megalithic constructions in all of France: La Roche aux Fées, Ille-et-Vilaine; Bagneux, Maine-et-Loire. They are large corridor dolmens dating to between 4300 and 3500 BCE (*54*), and they could be contemporary or somewhat older than Menga. Future high-precision dating is necessary to establish the age of these megaliths. In Europe, monuments built in later periods, such as the Copper Age and Bronze Age, were far less complex (*9*).

In summary, Menga is unique for its time for several reasons. The use of pillars to support the gigantic capstones, the embedding of a large portion of the edifice in the bedrock to attain extra-stability—acquiring earthquake-resistant properties, and the inter-locking of the uprights through lateral facets dressed at similar angles are features not seen in any other megalithic construction. An in-depth knowledge of the properties (and location) of the rocks available in the region, notions of elementary physics (friction, activation energy, optimal ramp slope, mass center estimation, available rock load-bearing capacity, among others) was necessary to move and place the gigantic stones. Other forms of advanced knowledge deployed to build Menga include geometry and astronomy. This is revealed by the millimeter-scale use of obtuse and straight angles on the facets of the uprights, or the precise alignment of Menga's central symmetry axis to 45°, thus matching the natural plane of orientation of La Peña de los Enamorados northern cliff to which the dolmen faces.

The incorporation of advanced knowledge in the fields of geology, physics, geometry, and astronomy shows that Menga represents not only a feat of early engineering but also a substantial step in the advancement of human science, reflecting the accumulation of advanced knowledge. Menga demonstrates the successful attempt to make a colossal monument lasting over thousands of years. In Antequera, this early science materialized in the construction of a great engineering building made of stone.

MATERIALS AND METHODS

Our approach is multidisciplinary in nature and combines evidence from geology and archaeology in an integrated manner (i.e., geoarchaeology). The following parameters have been established.

Determination of angles

The angles formed by the dressed planes (facets) of the uprights with the floor and between adjacent uprights themselves as well as those of the capstones relative to a horizontal plane (Fig. 3) were determined using high-precision three-dimensional (3D) plans created through a laser scan of the dolmen (*55*, *56*) or directly inside the dolmen using a Xiaomi digital inclinometer mounted on a mobile device.

Stratigraphic polarity

The identification of the roof and floor in the original stratification of the sedimentary rocks used to dress the building blocks of the dolmen (Fig. 2 and fig. S2) was based on the orientation of the fossil bivalves present in the stones, clast imbrications, and bioturbations by echinoderms.

Depth of the foundations

To establish the position of the original geological level and the foundations made to build the dolmen, plans and sections published since the first exploration by Mitjana y Ardison in the 1840s (*57*) have been carefully examined. This includes illustrations by De Rojas (1861), Wattanbach (1869), Cartaihac (1886), De Nadaillac (1887), Siret (1891), De Paula Valladar (1894), Gómez-Moreno Martínez (1905), and De Mergelina (1922) (*30*), all of which show the crude opening drilled by Mitjana in the backstone in the 1840s, which also cut through the mound all the way to the surface. These renderings were useful to establish the topography of the bedrock in that area of the monument. Early photographs by Barrera (1896), Temboury (1904–1905), Gómez-Moreno Martínez (1905), De Mortillet (1921), and Paris (1921) contributed additional evidence (*30*). The plans and photographs made by the University of Málaga excavation team in the late 1980s and early 1990s (*58*, *59*), as well as those made in 2005–2006 by the University of Granada excavation team (*60*), which includes important sections, plans, and photographs, were crucial for the creation of the plans on the different figures accompanying this text. Last, but not least, the high-resolution cartography and 3D model based on a laser scan of the whole monument made by Técnicas Documentales Tecnológicas (TDTEC S.L.) in 2005 (*55*, *56*) were of great help to obtain relevant measurements in connection with the depth of the sockets of some of the uprights as well as the current height of the bedrock as compared with the floor level inside the dolmen (Fig. 3, C and D).

Supplementary Materials

This PDF file includes:
Supplementary Text
Figs. S1 to S9
References

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