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Submerged bridge constructed at least 5600 years ago indicates early human arrival in Mallorca, Spain

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Reconstructing early human colonization of the Balearic Islands in the western Mediterranean is challenging due to limited archaeological evidence. Current understanding places human arrival ~4400 years ago. Here, U-series data from phreatic overgrowth on speleothems are combined with the discovery of a submerged bridge in Genovesa Cave that exhibits a distinctive coloration band near its top. The band is at the same depth as the phreatic overgrowth on speleothems (−1.1 meters), both of which indicate a sea-level stillstand between ~6000 and ~5400 years ago. Integrating the bridge depth with a high-resolution Holocene sea-level curve for Mallorca and the dated phreatic overgrowth on speleothems level constrains the construction of the bridge between ~6000 and ~5600 years ago. Subsequent sea-level rise flooded the archeological structure, ruling out later construction dates. This provides evidence for early human presence on the island dating at least 5600 and possibly beyond ~6000 years ago.

Mallorca, the main island of the Balearic Archipelago, is the sixth largest in the Mediterranean Sea, yet it was among the last to be colonized[1]. An in-depth discussion concerning the earliest colonization of various Mediterranean islands, including Mallorca, may be found in Cherry and Leppard[1], Dawson[2], and Simmons[3]. Despite extensive research on this topic, there has been considerable disagreement about the timing of the earliest colonization of Mallorca. Radiocarbon dating of bone material excavated from Cova (Cave) de Moleta indicate human presence on the island as early as 7000 calibrated years before present (cal B.P.)[4]. Subsequent age determinations from findings in Cova de Canet, further extended the timeline, suggesting human occupation dating back to approximately 9000 cal B.P.[5]. A series of publications[6–11] revealed inconsistencies regarding the exact stratigraphic position and context of the dated bone (sample KBN-640d[12]) in Cova de Moleta. Due to the overall poor preservation of the samples and the lack of clear and specific information on this particular radiocarbon-dated sample, Ramis and Alcover[7] suggested that the bone fragment, initially identified as human, might actually belong to *M. balearicus*, an endemic bovid. Consequently, this sample was considered not relevant for determining the timing of the island's colonization. Similarly, the radiocarbon dates from Cova de Canet were considered highly controversial because they originate from a charcoal layer that lacks clear evidence of human activity[7,8]. Furthermore, in neither of these caves do the *M. balearicus* bones show butchery marks, making it difficult to establish a clear link to contemporary human presence[2]. Due to the aforementioned issues these early results were deemed unreliable[1,8,13].

Several studies have reevaluated most of the previously dated materials and supplemented them with new radiocarbon dates obtained from charcoal, ash, and bones[6,7,9,10]. Based on these new results, there is now a consensus that the timeframe for earliest human settlement on the island is between 4600 and 4200 cal B.P.[14].

Dawson[2] presents a synthesis of the various lines of argument regarding arrival models in the Balearic islands that includes: (1) Early (~9000 cal B.P.), (2) Intermediate (~7600 cal B.P.), and (3) Late (~5000 cal B.P.) arrival phases. The last two models suggest the existence of stable settlements, yet only the third one has been deemed plausible in the local archeological literature[7,8,14].

While there has been a growing body of evidence revealing progressively earlier human settlements on many islands in the Mediterranean basin, the timeline for the initial human colonization in Mallorca has seen

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relatively minor adjustments over the past decades[8,15,16]. The latest research suggests that this colonization occurred approximately 4400 cal B.P., coinciding with the human-mediated extinction of *Myotragus balearicus*[14]. This conclusion is based on two radiocarbon ages, which provide a relatively narrow time window of 350 years ($p > 90\%$) between the last documented *Myotragus* bone (4581–4417 cal B.P.) and the first dated sheep bone (4417–4231 cal B.P.). However, it remains challenging to confirm whether the ages of these paleontological remains represent the latest or the earliest such occurrences on the island. Subsequent field work may shed light on this matter.

Our study site is a submerged archeological structure in the Genovesa Cave (also known as Cova de'n Bessó; 39°31'32" N, 3°19'2" E), situated in the eastern part of Mallorca (Fig. 1a, b). The cave hosts ceramic sherds and stone constructions. The latter includes a stone-paved path that connects the cave entrance to the first underground lake (Fig. 1d), a cyclopean stone wall running parallel to the path, and an 8.62 m long[17] and 0.5 m high stone walkway (hereafter referred as to bridge) oriented NE–SW (Fig. 1c, e, Supplementary Fig. 1, Supplementary Table 1). This last structure was built across a lake by stacking large limestone breakdown blocks on top of each other, without the use of mortar or cement. The uppermost layer comprises flat boulders of considerable size (Supplementary Fig. 1b). The largest stone measures 1.63 m in length and 0.6 m in width. Relative to the preindustrial (pre-1900 CE) sea level, the bridge is submerged by 1.05 ± 0.1 m of water at its upper part (Figs. 1e, 2). However, at the time of its construction, it served as an access path to the only other dry chamber in the cave (Sala de les Rates-pinyades, i.e., Bats Room), where pottery, tentatively attributed to the Naviform period (ca. 3550–3000 cal B.P.) was discovered[18,19]. The bridge structure was inferred to have been built around the same period[20].

Here, we integrate uranium-series (U-series) age data acquired from phreatic overgrowth on speleothems and stalactite tips in Genovesa and Drac caves, along with Late Holocene relative sea level (RSL) information available for Mallorca[21]. Additionally, we consider the presence of the bridge, the coloration mark on its upper part, and the depths at which these respective features occur. This combined evidence contributes valuable insights to the ongoing debate surrounding the timing of human colonization on Mallorca.

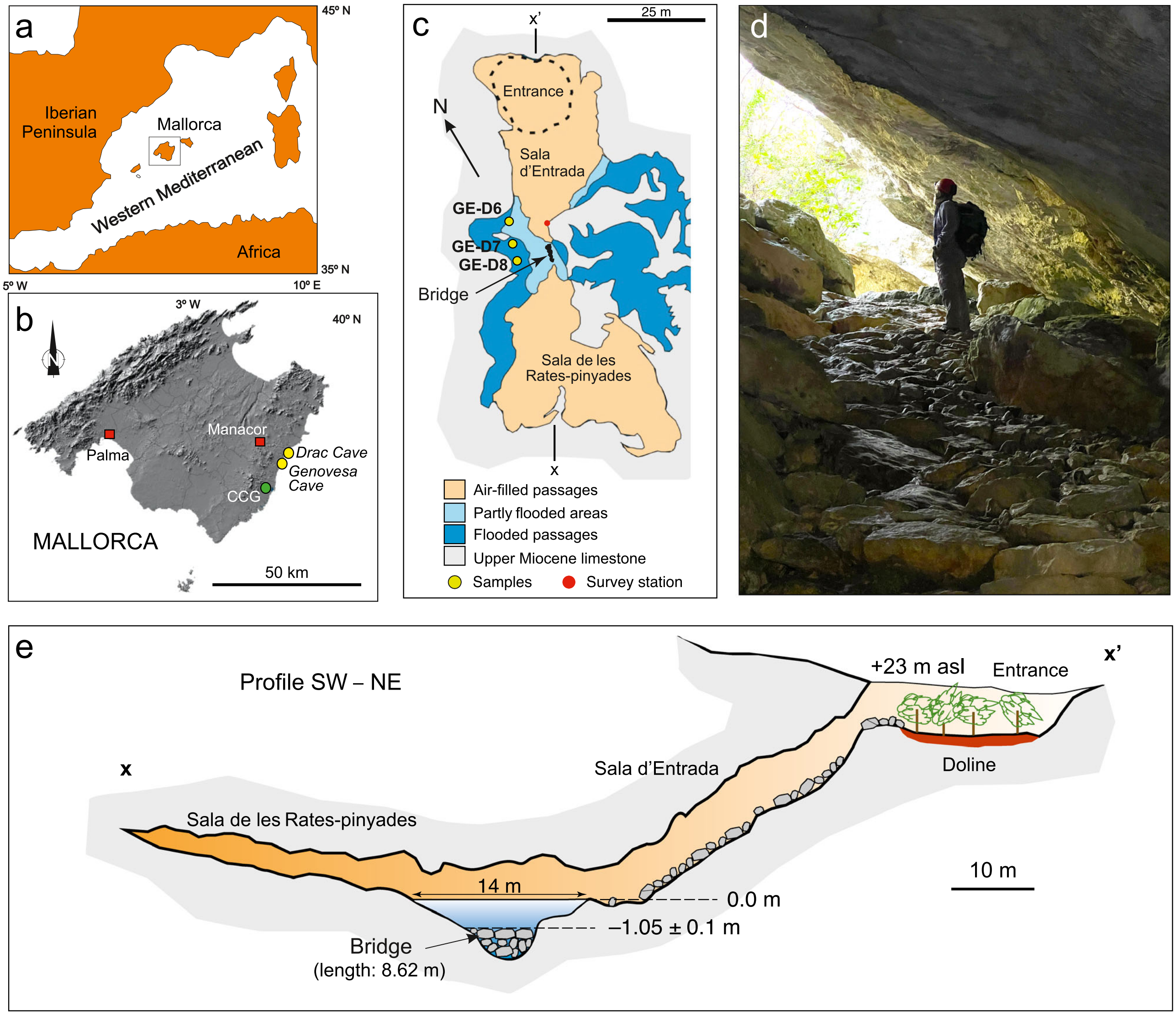

Fig. 1 | Cave and sample locations. a Map showing Mallorca in the western Mediterranean (black square). **b** Location of Genovesa and Drac caves; CCG: Closos de Can Gaià archeological site. **c** Plan of Genovesa Cave showing the location of the phreatic overgrowth on speleothems samples (yellow circles) and the survey station (red dot). **d** Photograph of the stone-paved path leading to the bridge (person height = 167 cm). **e** Cross-section (x–x') indicating the location of the submerged bridge relative to the cave entrance and the present sea level. Maps (**a**, **b**) are available under CC Public Domain License from https://pixabay.com/illustrations/map-europe-world-earth-continent-2672639/ and https://pixabay.com/illustrations/mallorca-map-land-country-europe-968363/, respectively.

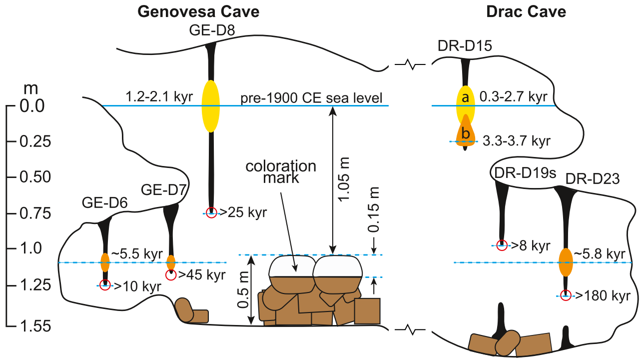

Fig. 2 | Positional relationship between the bridge, preindustrial sea level, and analyzed samples. The cross sections depict the spatial relationship between the submerged bridge and the U-series dated samples (phreatic overgrowth on speleothems: orange/yellow spindle; soda straw tips: red circle) from Genovesa and Drac caves. The vertical scale applies uniformly to all samples from both caves. All ages are reported as thousands of years (kyr) before present, where present is defined as 1950 CE.

Results and discussion

Speleothems and sea level

Proxies for cave-based sea-level reconstructions include mineralogical (sediments, speleothems)[22,23], archeological (fish tanks, saltpans, submerged structures, etc.)[24], and biological (borings, worm tubes, etc.)[24] records. In the case of Genovesa Cave, a typical coastal karst feature situated <450 m from the shoreline, both mineralogical and archeological records are present. Many of its well-decorated passages, galleries, and chambers are now flooded due to rising sea levels[20]. Because of the cave's proximity to the coast and the high permeability of the Upper Miocene host rock[25], the hydraulic gradient is negligible (9×10^{-5} m /m) for such short distances (see Methods), and thus the water table in the cave is, and was in the past, coincident with sea level[26,27]. During times of high sea level stillstands, when the cave was partly flooded, distinct encrustations of calcite and aragonite accumulated over preexisting stalactites, forming the so-called phreatic overgrowths on speleothems[28] (POS). This is a particularly useful proxy for precisely and accurately reconstructing sea-level changes across various timescales[21,29]. Furthermore, ordinary stalactites, which form in cave passages above the water table and later become submerged as sea-levels rise are also valuable in this process since they document the moment when the cave shifted from being air- to water-filled[22].

A distinct light-colored band (~15 cm wide) is visible along the entire bridge at its upper part (Fig. 2, Supplementary Fig. 1a). This coloration mark bears a resemblance to a "bathtub ring" and its presence is likely related to a relatively short-lived stable water table that allowed the precipitation of a sub-millimeter calcite crust at the water/air interface. When the water level increased, the calcite did not disappear since the water below the water table remained somewhat saturated with respect to calcium carbonate. As discussed later, this feature along with the new POS ages and their elevation play a crucial role in determining when this bridge, now submerged, was constructed.

Geochronology

The U-series ages ($n = 34$; 28 for POS and 6 from stalactites) are given in Supplementary Table 2 and are all reported as years before present (BP), where present is 1950 CE. Ten of these ages are from POS samples GE-D8 (Genovesa Cave; Supplementary Fig. 2) and DR-D15 dated as part of a prior study[21]. The latter was collected in Drac Cave (39°32'9" N, 3°19'49" E), located 1.6 km to the north-east of Genovesa Cave (Fig. 1c, Supplementary Figs. S3–S4).

Regardless of the sampling depth, all the vadose stalactites on which the POS formed in both caves, produced ages older than 8200 years B.P. (Fig. 2, Supplementary Fig. 5). The phreatic overgrowth samples GE-D6, GE-D7, and DR-D23 (Supplementary Figs. S6–S8), precipitated at ~1.10 ± 0.1 m below the preindustrial sea level (mbpsl). A ^{232}Th/^{238}U-^{234}U/^{238}U-^{230}Th/^{238}U (plotted as a Rosholt A type) isochron age of 5479 ± 120 years B.P. ($n = 3$ of 4; hereafter, ± refers to 2σ uncertainty) was measured for GE-D6 (Supplemental Table 2, Supplementary Fig. 9a). GE-D7, in the same room and at the same elevation as GE-D6, yielded a weighted average age of 5510 ± 549 years B.P. using the same correction (initial ^{230}Th/^{232}Th atomic ratio = 5.1 ± 0.4 ppm) generated by the GE-D6 isochron age. Onac et al.[21]. used a slightly higher initial for GE-D8 (8 ppm) that was located at a higher elevation than GE-D6 & -D7. For DR-D23, we obtained a ^{232}Th/^{238}U-^{234}U/^{238}U-^{230}Th/^{238}U (plotted as a Rosholt A type) isochron age of 5824 ± 140 years B.P. ($n = 6$) (Supplementary Table 2, Supplementary Fig. 9b). This isochron shows an exceptionally high initial ^{230}Th/^{232}Th atomic ratio = 527.5 ± 22.1 ppm, more than 10x higher than used for DR-D15 (44 ppm) from the same cave but at a different elevation[21]. The fluffy fibrous cotton-candy texture of the two sub-samples with high U component of DR-D23 may have something to do with the high initial ^{230}Th/^{232}Th. The isochron ages were necessary to produce accurate ages with smaller uncertainties.

Collectively, the POS data from Genovesa and the nearby Drac, reveal three distinct periods of relative sea-level stability (Fig. 2). One occurred at 0 ± 0.04 m from 2720 ± 11 to 296 ± 18 years B.P. The second period lasting from 3703 ± 14 to 3368 ± 8 years B.P., corresponds to a sea level of 0.25 mbpsl. Lastly, a third period at ~1.1 ± 0.1 mbpsl is documented between 5820 ± 140 and 5479 ± 120 years B.P. (Figs. 2, 3). By adding the uncertainty to the older age and subtracting the uncertainty from the younger age, the maximum time span of POS growth at 1.1 mbpsl ranges from 5964 – 5359 years B.P. During this interval, both the POS and the coloration mark formed. For the latter to develop, the bridge must have been submerged, at least to its upper surface, allowing calcite to precipitate during the sea-level stillstand. Therefore, this period is of particular interest because it may aid in providing the timeline of the bridge construction as detailed below.

Timing of bridge construction

The assembly date of the bridge in Genovesa Cave remains uncertain due to the absence of written records or a robust time-stratigraphic context. In order to constrain the building time of this archeological structure, we rely on a well-defined Late Holocene sea-level curve generated by Onac et al.[21]. for Mallorca (depicted by the solid blue line in Fig. 3) and the ages and depths at which POS grew and coloration mark formed. First, we assess previous assumptions regarding the timing of the submerged bridge construction using this curve. Then, we examine our new sea-level data in conjunction with the timing of the earliest human arrival model proposed by Bover et al.[14].

The prehistoric pottery discovered in Sala de les Rates-pinyades of the Genovesa Cave has been linked to the Naviform period (3550–3000 cal B.P.). This attribution is based on typological similarities between the ceramics found in Genovesa and those documented at the Closos de Can Gaià, a Bronze Age site located ~10 km south of our cave (Fig. 1b). The archeological horizon in which comparable pottery was discovered at the latter site was dated to ~3600 cal B.P[30]. However, Costa and Guerrero[31] argue that Closos de Can Gaià excavation required a reassessment of the chronological framework, due to issues with the radiocarbon dates. Despite this, adopting the previously reported radiocarbon age, Gràcia et al.[20] suggested that the construction of the bridge likely occurred toward the end of the Naviform period.

However, the RSL curve (Fig. 3) indicates that sea level was ~0.25 ± 0.1 m below the preindustrial baseline ~3500 years ago[21], implying a total water depth of ~1.3 m in the cave lake. The vertical height of the bridge is 0.5 m, and thus it was submerged by 0.8 m of water at this time (Fig. 3). The construction of the bridge around 4400 years ago, the time suggested by Bover et al.[14] to be the earliest evidence of human presence on the island, is

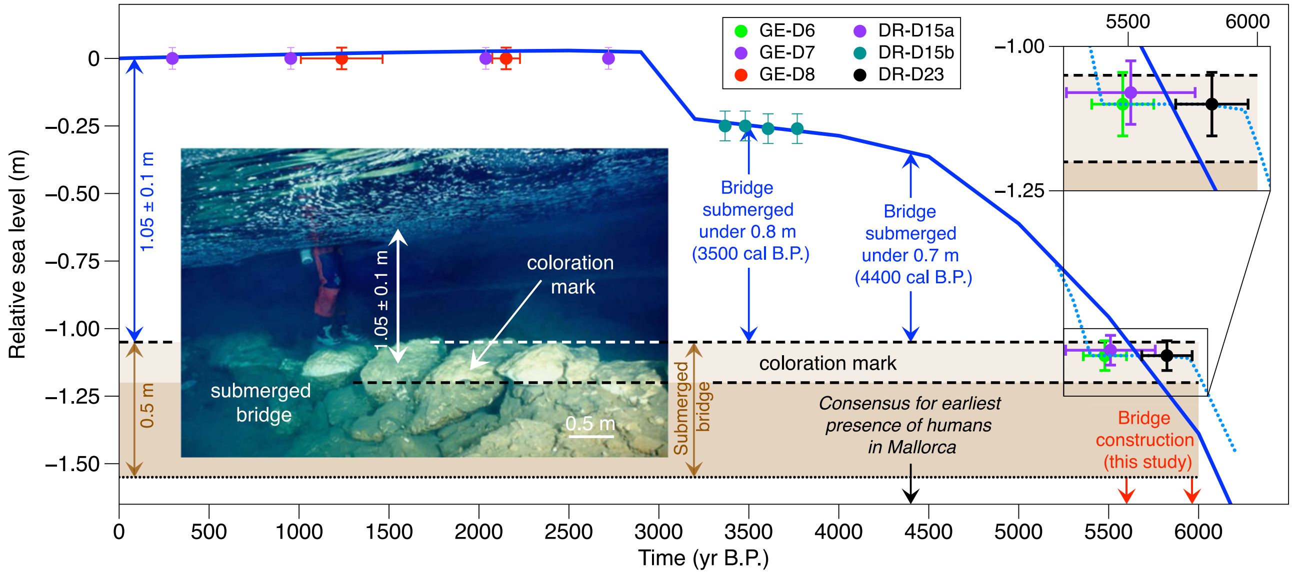

Fig. 3 | Proposed timing for bridge construction. Comparison between the position of the submerged bridge, phreatic overgrowth on speleothems (POS), coloration mark, and the RSL prediction (blue curve)[21] based on a Glacial Isostatic Adjustment model that uses the ICE-6G (VM 5) ice history with an upper mantle viscosity of 1.3 × 1020 Pa s. Solid symbols with age and depth uncertainties represent POS elevations. The brown rectangle depicts the bridge with its coloration band in the upper part. The insets show an underwater image of the bridge (Photo courtesy of R. Landreth) and a close-up view on the RSL position of samples GE-D6, GE-D7, and DR-D23 that grew at 1.1 mbpsl. The uncertainties for GE-D6, GE-D7, and DR-D23 are absolute 2 σ error bars based on three dimensional isochron ages or weighted average (GE-D7). The dotted blue line is a sea-level rise scenario that includes the brief stillstand inferred from the POS growth.

also improbable. At that time, relative sea level in Mallorca was ~0.35 ± 0.1 m below preindustrial level, and the bridge would have been submerged by 0.7 m. Building a bridge below water level is a highly unlikely scenario, and thus it was likely built at an earlier time, when sea level was lower. The predicted relative sea-level curve for Mallorca (Fig. 3) indicates that the top of the bridge would have been close to water level no earlier than 5600 years ago and this provides an approximate lower bound on the age of the feature. The distinct coloration mark on the bridge also provides strong evidence of an age greater than the ages estimated by Gràcia et al.[20] and Bover et al.[14]. As discussed earlier and according to the POS-based relative sea-level record, this mark would not have developed if the top of the bridge was well below the water level, i.e., at times more recent than ~5500 years ago. However, an age older than 6000 years for the feature can be ruled out since sea level was even lower (Fig. 3), and the construction of a bridge at its current height would have been unnecessary.

The phreatic overgrowths GE-D6, GE-D7, and DR-D23 from Genovesa and Drac caves formed at a relative sea level of 1.1 mbpsl, which is 5 cm below the upper part of the bridge. The two more precise isochron ages suggest sea-level remained relatively constant for a few hundreds of years between ~5964 and 5359 years B.P. The relative brevity of this time frame might explain why the morphology and size of the POS are somehow atypical and smaller compared to those POS that developed when the sea level was stable at 0 m for over 2000 years. Furthermore, this <600 year period of nearly constant sea level was sufficient to develop the coloration mark. Given that the occurrence of this feature correlates directly with the previously mentioned sea-level stillstand position, it suggests that the bridge was already in place. In fact, its construction could have commenced as early as ~6000 years ago when the water depth in the lake was ~0.25 m. However, it had to be completed before ~5600 years ago when the sea-level rose to the top surface of the bridge.

Conclusions

We have integrated new U-series data from POS in Genovesa Cave with the observation of a unique coloration mark found on a submerged bridge within the same cave. This mark developed during a period of sea-level stability that was responsible for the precipitation of a POS level at 1.1 mbpsl. By combining this evidence with a high-resolution Late Holocene sea-level curve for Mallorca, we offer a more accurate timeframe for the construction of this archeological structure.

The history of the bridge construction appears to be closely associated with rapid Holocene sea-level rise just prior to 6000 years ago and a brief sea-level stillstand that led to some upper sections of the cave being flooded. According to our POS chronology, the sea-level rise ceased and remained stable for several hundred years between ~5964 and 5359 years B.P. During this time, POS formed in the cave lake, and a distinctive “bathtub ring” developed on the bridge.

The building of the bridge likely began early during this period, when crossing the 0.25 m-deep lake required its construction. However, the structure must have been completed before ~5600 years when the upper part of the bridge became submerged.

Evidence indicates that humans constructed a stone-paved pathway leading to the cave’s water pool and a robust bridge, facilitating access to the only other dry section of the cave situated beyond the lake, in the Sala d’Entrada. The exact reasons behind the construction of these structures in Genovesa Cave remain elusive. Nevertheless, the chronological constraints posed by the depth of the bridge, coupled with the similar depth at which POS and the coloration mark occur, support the idea of an early human presence on the island by 5600 years B.P. and potentially dating back as far as 6000 years ago.

Methods

Location, recovery, and storage of samples

Underwater mapping to locate each sample was carried out using a Suunto SK-8 compass, a pre-knotted diving line, and a rollable measuring tape (accuracy of ±1 cm). To measure underwater sample depths, we utilized the pressure depth-meter built into the Suunto Gekko steel diving computer having an accuracy of ± 1% and resolution of 0.1 m. One of the authors (FG) employed technical scuba diving procedures to collect submerged phreatic overgrowth on speleothems and stalactites situated at depths ranging from 0.75 to 2 m below present sea level. We selected this specific depth range to precisely determine the sea level’s relationship with the bridge and its coloration mark.

All samples used in this study are housed within the University of Balearic Islands Repository of Phreatic Overgrowth on Speleothems, under the curation of the Earth Sciences Research Group.

Hydraulic gradient measurement

The calculation of the hydraulic gradient requires two variables: the change in head (elevation) and the change in distance. Measurements for both were performed using a Leica TC 405 total station, with a standard deviation of 5" (arcseconds) for horizontal and vertical angles and 2 mm + 2 ppm (parts per million of distance measured) for electronic distance measurements. In our study, we found that the head change between sea level and the cave lake surface was 0.037 m. Additionally, the distance between the survey station located on the coastline at the sea level and the one adjacent to the cave lake surface measured 412 m. Dividing the change in head (0.037 m) by the change in distance (412 m), we derived the hydraulic gradient (9×10^{-5} m /m) for Genovesa Cave. This value is even lower for Drac Cave, which is located <100 m from the coast.

Submerged bridge setting

The precise location and elevation of the submerged bridge and its coloration band were accurately established during the cave mapping process using a Suunto Tandem 360PC compass/clinometer (accuracy 0.33°/0.25°) and a Bosch GLM-50 Laser distance measurer (accuracy 1.5 mm). This location was confirmed during measurements of the hydraulic gradient with a Leica TC 405 total station, yielding discrepancies of <1.5° in azimuth and 10 mm in distance. The lake surface elevation was determined with a precision of better than 2 mm (see Hydraulic gradient measurement), enabling the direct measurement of the depth of the bridge and its coloration band from the lake surface. These depths were measured directly by our diver coauthor (FG) using a millimeter-graded measuring tape, with an error margin within 5 mm.

U-series dating

Each POS was first halved and subsamples were collected by milling 10–200 mg of powders if samples were amendable to drilling. Pieces were extracted from the tip of the stalactite and from parts of the POS. All subsamples were completely dissolved in 15 N HNO_3 in Teflon beakers and spiked with a mixed solution of ^{229}Th, ^{233}U, and ^{236}U tracers. We added a few drops of $HClO_4$, and then the sample-spike mixture was fluxed for ~1 h and dried to ensure thorough mixing and removal of organic matter from the samples. After cooling, the subsample crust was dissolved in 7 N HNO_3 for anion resin (Eichrom 1 x 8200–400 mesh, chloride form) column chemistry. Subsamples were purified in the columns using 7 N HNO_3 to remove matrix constituents. The Th fraction was eluted with 6 N HCl, and the U fraction was obtained using H_2O.

The analysis of U and Th was carried out separately using a Thermo Scientific Neptune Plus multi-collector inductively coupled plasma mass spectrometer in static mode. This mode was chosen because our instrument has enough detectors for all the required peaks. The U and Th solutions were introduced using an Aridus II desolvating nebulizer, which enhanced signal intensity by approximately a factor of 4. All isotopes, except ^{230}Th and ^{234}U, were measured on Faraday cups equipped with 10^{-10}, 10^{-11}, and 10^{-12}-ohm resistors, with the selection based on signal intensity. For ^{230}Th and ^{234}U, measurements were conducted using a secondary electron multiplier with a retardation potential that offered low abundance sensitivity (~5×10^{-7}). Gain calibration between the Faraday cups and scanning electron microscope was achieved using the U standard CRM-112 and an in-house ^{230}Th-^{229}Th standard. The obtained dates were calculated using the decay constants reported by Cheng et al.[32] (2013). The ^{232}Th/^{238}U-^{234}U/^{238}U-^{230}Th/^{238}U isochron ages were calculated using IsoplotR[33], a modified version of Isoplot[34]. We chose the Rosholt A type of isochron plots, which is the first option in IsoplotR software.

Data availability

All data generated or analyzed during this study are included in this published article and its Supplementary Materials. The full U-series dataset is available at https://doi.org/10.5281/zenodo.12609107.

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Author contributions

B.P.O., J.G., J.J.F., A.G. designed the research. F.G., B.P.O., J.G., and J.J.F. measured the depth of the bridge and its coloration band. F.G. collected and measured the elevations of underwater samples. V.J.P. and Y.A. generated the U-series ages of the phreatic overgrowth samples. J.X.M. produced the GIA models. B.P.O., V.J.P., and J.X.M. drafted the manuscript with contributions from all authors.

Competing interests

The authors declare no competing interests.

Additional information

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