Heliyon 9 (2023) e14575

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Two enigmatic ridges in the Pantelleria Vecchia Bank (NW Sicilian Channel)

Emanuele Lodolo [a,*], Paolo Nannini [b], Luca Baradello [a], Zvi Ben-Avraham [c,d]

[a] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Trieste, Italy
[b] Soprintendenza Archeologia Belle Arti e Paesaggio per le Province di Siena, Grosseto e Arezzo, Italy
[c] Department of Geophysics, Tel Aviv University, Israel
[d] Leon H. Charney School of Marine Sciences, University of Haifa, Israel

ARTICLE INFO

Keywords:
Sicilian Channel
Pantelleria Vecchia Bank
Perpendicular ridges
High-resolution bathymetry
High-resolution seismic profiles
Petrographic analysis
Direct underwater surveys
Human occupation

ABSTRACT

The Pantelleria Vecchia Bank is a submerged calcareous-arenitic shoal in the NW sector of the Sicilian Channel. Together with other morphological heights, some of which are volcanic in origin, this shoal punctuates the shallow Adventure Plateau, which was above sea level from the Last Glacial Maximum until at least 9000 years ago. The rise in sea level caused by the melting of the ice caps gradually flooded the plateau, isolating the heights and creating a broad archipelago until the area was finally submerged. High-resolution Multibeam bathymetric mapping shows that the Pantelleria Vecchia Bank has an 820 m long rectilinear ridge connecting the two main shoals of the bank, and an 82 m long ridge perpendicular to the 820 m ridge 100 m from its southern end. The top of the 820 m ridge lies in a water depth of 35 m, its base in about 42 m, and the seaward side has a fairly uniform slope of 16°–22°. The 82 m ridge has an average width of ~7 m and rises ~1 m above the surrounding seafloor. Underwater photographs document that the entire seaward side of the 820 m ridge consists of juxtaposed blocks, the largest measuring about 3 × 4 m, some of which are rectangular in shape, while the upper part consists of horizontally arranged blocks and the lower part of sub-vertical blocks embedded in the sediments. Petrographic analyses show that the blocks forming the seaward side of the 820 m ridge can be classified as late Pleistocene calcirudites, while the 82 m ridge consists of bioclastic calcarenites of Tortonian age. A series of high-resolution seismic profiles crossing both ridges and composite mosaics of the seafloor obtained from underwater videos provide a comprehensive panorama of these two peculiar and in many ways enigmatic structures. The structures described and the palaeogeographical context in which they are embedded do not exclude the possibility that they are artefacts indicating an ancient temporary or permanent human presence in the Pantelleria Vecchia Bank.

1. Introduction

The Sicilian Channel is one of the shallow shelves of the central Mediterranean where the consequences of sea-level rise after the Last Glacial Maximum (LGM), estimated at 125 ± 5 m [1–4], were particularly intense, as they were for the platforms of Tunisia and Malta, the other two shallow sectors of the area. The north-western part of the Sicilian Channel is occupied by the Adventure Plateau

* Corresponding author.
E-mail address: elodolo@ogs.it (E. Lodolo).

https://doi.org/10.1016/j.heliyon.2023.e14575
Received 9 September 2022; Received in revised form 28 February 2023; Accepted 10 March 2023
Available online 15 March 2023

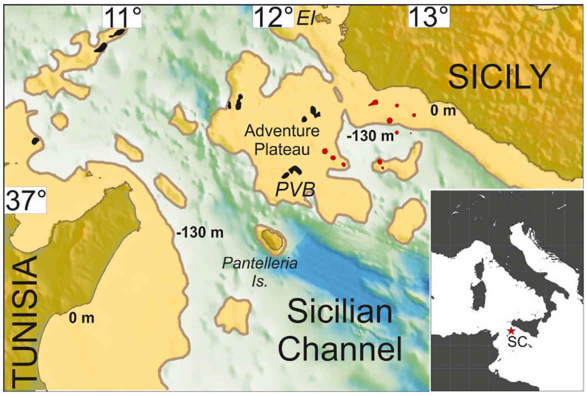


Fig. 1. Reconstruction of the ancient coastlines of SW Sicily and eastern Tunisia when sea level was ~130 m lower than today (brown contour), corresponding to the end of the Last Glacial Maximum. During part of this period, the Adventure Plateau was connected to Sicily and formed a broad peninsula. The former islands (shown on the map as small black areas for the sedimentary banks, and small red areas for the volcanic edifices) formed a broad archipelago between Sicily and the island of Pantelleria. PVB: Pantelleria Vecchia Bank; EI: Egadi Islands. The background bathymetry is from the EMODnet portal (https://portal.emodnet-bathymetry.eu/). The box in the lower right corner shows the study area (red star). See Fig. 1 of [9] for further details on the physiographic context of the study area.

(Fig. 1) which, according to geophysical studies, is punctuated by several isolated shoals, some of which are less than 10 m below sea level [5,6]. During the LGM, the Adventure Plateau was part of the former Sicilian mainland, forming a peninsula that curved southwards into the Sicilian Channel and was separated from the North African coast by less than 50 km. Gradual sea-level rise resulted in the submergence of most of the peninsula, except for some morphological heights that, at least until the early Holocene, formed an archipelago of several islands separated by sections of extremely shallow sea, as shown by the analysis of bathymetric swath mapping and high-resolution seismic profiles [6–8]. On one of these former islands - Pantelleria Vecchia Bank - located at 36 nautical miles south of Sicily, detailed Multibeam bathymetric mapping has revealed several morphological elements that are in some ways difficult to attribute to natural phenomena, but rather allow the hypothesis that they are artefacts created by human activities, as described in a previous work [9].

In this paper, we describe two other relevant underwater features of the Pantelleria Vecchia Bank at 42 m water depth: a 820 m long, rectilinear ridge composed of juxtaposed blocks, and a perpendicular, 82 m long ridge. High-resolution Multibeam bathymetry, petrographic analyses of the rock samples taken from both these ridges, high-resolution seismic profiles (Chirp and Boomer data), seafloor photo-mosaics, two new radiocarbon dates, and previously published data (rock sample analysis, radiocarbon dating), provide documentation of these ridges and open a range of speculations about their nature and origin.

2. Materials and methods

In this study, we have analyzed and interpreted both Multibeam swath bathymetry and high-resolution seismic reflection data, performed radiocarbon measurements and analyzed rock samples. The Multibeam survey was conducted using a portable Reson® SeaBat 7125 installed on a rented boat sailing at 4 knots during the acquisition. The system operates at frequencies of 400 kHz and illuminates a swath on the seafloor that is 165° transverse and 0.5° longitudinal to the track. To ensure optimal data coverage, each individual swath was overlaid about halfway with the adjacent one. An inertial system integrated into the Multibeam head was used to capture vessel motion and heading. The data were fully corrected for vessel motion, navigation, sound speed and corrected tides in the following steps: (1) calibration of parameters to ensure soundings were recorded from the correct position on the seafloor, in the correct time; (2) application of Sound Velocity Probe (SVP) sound profiles to the Multibeam swath files for real-time correction of the incoming raw water depth data; (3) application of corrected tides for the surveyed area to all swath files; (4) manually editing navigation to delete incorrect navigation positions; (5) application of automatic filtering to remove spurious rays and improve the signal-to-noise ratio; (6) removal of residual spikes with a distance surface filter; (7) creation of a final Digital Terrain Model (DTM) with a cell size of 0.5 × 0.5 m.

Chirp data were acquired by the vessel *OGS Explora* using a hull-mounted Chirp II DataSonics®. The sweep length was 10 ms with frequencies between 2 and 7 kHz. The ping rate was 2 pings per second, the sampling rate was 0.05 ms and the acquisition time window was 300 ms. During data acquisition, the ship speed was 4.5 knots, so the average trace interval is ~1 m. The data were collected in envelop mode, and then sequentially processed as follows: (1) derivative method to obtain analytical traces [10]; (2) spherical divergence and absorption compensation; (3) trace processing and de-spiking; (4) automatic gain control to homogenize the traces; (5) Stolt time migration.

The high-resolution seismic Boomer source used was an electrodynamic plate mounted on a catamaran and suspended 0.4 m below sea-level. It was fed by a group of capacitors connected to a 3.5 kW generator. The pulse generated is a broad-band spectrum pulse (400–6000 Hz with a dominant frequency of 2 kHz) and results in sub-metric resolution. The receiving system was a single-channel streamer consisting of 8 pre-amplified hydrophones distributed over an active section of 3 m. The sampling rate was 0.05 ms, the shot

Table 1
Radiocarbon dating results for the calcirudite samples of RIDGE 1.

Sample ID	Lab code	Radiocarbon age (yrs BP)	Calibrated age (probability 95.4%)
S3_A	Beta-630492	38298 ± 433$^{(*)}$	42216 - 41203 cal yrs BP
TR_2	Beta-634118	41778 ± 622$^{(*)}$	44725 - 42840 cal yrs BP

$^{(*)}$ = adjusted for local reservoir correction.

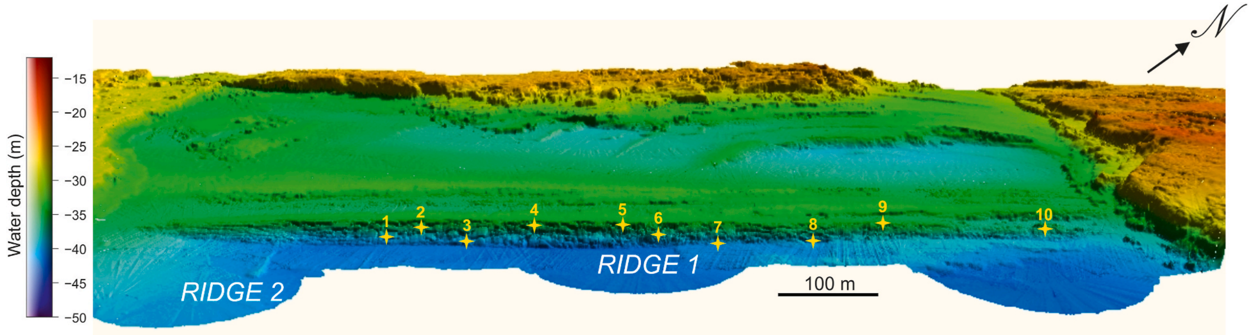


Fig. 2a. Shaded 3-D relief map of the central sector of Pantelleria Vecchia Bank (vertical exaggeration: 2×), with the locations of the underwater photographs of the RIDGE 1 (numbered yellow stars).

interval 3 shots/s and the recording length 120 ms, with data collected at an average ship speed of 4 knots. The acquired seismic data were processed using a conventional processing sequence including: (1) DC-offset removal; (2) spherical divergence and amplification; (3) time-varying band-pass filter and seafloor attenuation; (4) predictive deconvolution (focusing on the frequency range 13–35 kHz) to remove reverberation and increase vertical resolution.; (5) Stolt time migration.

Two shell fragments recovered from a rock sample taken by divers near the top of the giant ridge at 36.5 m water depth were dated by the radiocarbon method (Table 1), using the high-resolution Accelerator Mass Spectrometry (AMS). The conventional radiocarbon age was calculated using the Libby half-life (5568 years) corrected for total isotope content, and used for calendar calibration where appropriate. Ages are rounded to the nearest 10 years and are expressed as radiocarbon years before present (BP), "present" = AD 1950. The internationally accepted calibration curve for marine data (MARINE20) was used [11], with a local ΔR value of −88 ± 50 for a site near the sampling area [12].

3. Data analysis and underwater observations

Available borehole information, seismic data, and rock samples have shown that the Pantelleria Vecchia Bank is mainly underlain by Miocene rocks (patchy Tortonian reef sediments), and represents the surface expression of a broad late Miocene anticline [6,13]. Multibeam swath bathymetric surveys have mapped the entire bank and show that it consists of a large rectangular shallow shoal, with a NW-SE orientation, and two other smaller shoals to the west that terminate a submerged bay [6]. Farther west are other small isolated ridges, but these are not part of the shoal itself. The main shoal is in water depths of 16–24 m, while the surrounding areas have depths ranging from 34 to 60 m. The high-resolution bathymetric map shown in Fig. 2a focuses on the central part of the Pantelleria Vecchia Bank, where the main morphological feature is an 820 m long rectilinear ridge (for simplicity, we call it here RIDGE 1) connecting two shoals and enclosing a bay seaward. This structure was only partially described in a previous paper [9], and here we present its main features in more detail and present new underwater observations, together with high-resolution seismic profiles, thin-section rock analysis and new ^{14}C measurements. The high-resolution bathymetric map shows another ridge, here called RIDGE 2, that is perpendicular to RIDGE 1. RIDGE 2 is 82 m long, 6–8 m wide, rises 1 m above the surrounding seafloor, and lies 100 m east of the west end of RIDGE 1.

3.1. RIDGE 1

The base of this ridge lies in a water depth of 43.1–44.4 m, while its top lies between 35.1 and 36.8 m. The ridge is characterized by a flat top, about 20 m wide, and has a southwest-facing slope of 16°–22°. The steepest and thus most regular section is the middle one. A ridge parallel to RIDGE 1 is placed approximately 80 m behind it, and has an elevation approximately 2 m higher than RIDGE 1. Direct inspections were carried out on several occasions by both divers and a Remotely Operated Vehicle (ROV) along the entire length of the seaward side of the ridge to obtain photographs and video. The slopes of the ridge are free of sedimentation due to a relatively strong and constant bottom current with velocities between 2 and 3 knots. The photos show that the entire ridge is composed of blocks that are generally rectangular in shape and in close contact with each other (Fig. 2b). The blocks have in-plane dimensions of several meters, with one of the largest blocks measuring approximately 3 × 4 m. The upper part of the ridge consists of large, horizontally

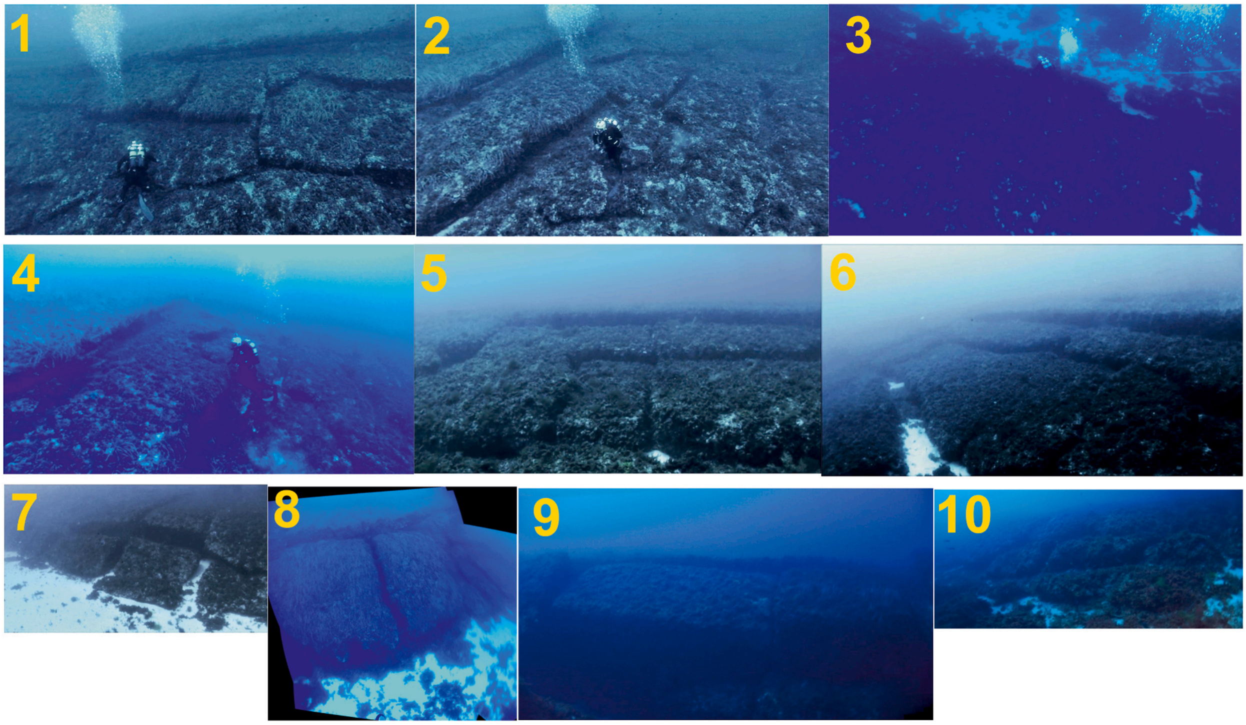


Fig. 2b. Underwater photographs taken on the RIDGE 1 (numbers indicate the corresponding locations in Fig. 2a).

arranged blocks with a thickness of about 0.5 m. The lower part is characterized by large, sub-vertically arranged blocks embedded in sediments consisting of unconsolidated, coarse organogenic sands with thicknesses ranging from a few decimeters to a few meters [5, 14].

During the bathymetric mapping, high-resolution seismic profiles (Chirp data) were also acquired, some of which cross the linear ridge (Fig. 3). The high-frequency properties of the Chirp system and the high reflectivity of the rocks that make up the ridge prevent the signal from penetrating to depth, but these seismic profiles still allow us to get a picture of the cross-sectional geometry of RIDGE 1 along its longitudinal extent. However, on three of the sections presented, reflections are visible below the seafloor, indicating the presence of thin sedimentary layers above the more compact substrate. These sedimentary bodies, located in front of the base of the ridge and visible on profiles 6, 13, and 10 in Fig. 3, are generally no more than 6 m thick (applying an interval velocity for acoustic waves of 1600 m/s). In the northern sector of the ridge, a thin sediment cover is visible on profiles 13 and 7 in Fig. 3. The three high-resolution seismic lines crossing the central part of the ridge (profiles 7, 12 and 8) are those where the tilt towards the sea is greater, as described above, so that the applied migration (Stolt time migration) is not able to collapse the diffraction hyperbolas completely.

The ridge of the Pantelleria Vecchia Bank appears to have some characteristics of a beach-rock, a common formation in the coastal areas of the Mediterranean and in many parts of the tropical zone. Beach-rock is a hard coastal geological formation consisting of beach sediments that are rapidly cemented by precipitation of carbonate cements. Lithification usually occurs in the intertidal zone and can affect all types of sediments (see Ref. [15], for a comprehensive overview of beach-rocks). However, some petrological and geometrical features of RIDGE 1 indicate that this structure is not a classic beach-rock. In terms of geometry, for example, the average dip of the seaward side of the ridge is much more pronounced (almost by an order of magnitude) than in other known beach-rocks, both in the Mediterranean and in other parts of the world. Shinn [16] has proposed a simple mechanism that can produce beach-rock geometries similar to those characteristics of the seaward side of RIDGE 1 (road-like feature). Exposure to sunlight and constant wetting and drying break the rock down into individual slabs, like to a concrete road. The size of the individual slabs is determined by the thickness of the rock. Uncemented sand under the rock also promotes cracking as the rock settles, much like ice on a frozen pond. The constant abrasion of the moving beach sand causes the corners to round and form pillow shapes.

Petrographic analysis (Fig. 4) reveals that the rocks that make up the ridge consist of grain-supported, rounded grains of diverse texture and composition that are bounded by variable amounts of interstitial carbonate cement. Grains are covered by a thin layer of aragonite with a fibrous texture, followed by a very dark micritic microcrystalline cement. This cement indicates a marine depositional environment. There is abundant debris of quartz, both disseminated and agglomerated, cemented by micrite. Red algae (rhodoliths) represent the most common type of bioclast. They have a roundish-oval morphology, in which the structure consisting of numerous, regularly arranged cells can be seen very clearly. The habitat of these organisms is usually rocky bottoms or coral reefs, and they grow and survive in the photic zone of the sea. Some clasts consist of bioclastic fragments covered with thick micritic material that has a vaguely laminated structure. Shell fragments have a distinct fibrous structure and include bryozoans, which are identified by their honeycomb-like structure. Clastic grains include numerous fragments of echinoderm spines, which have a "flower" morphology and

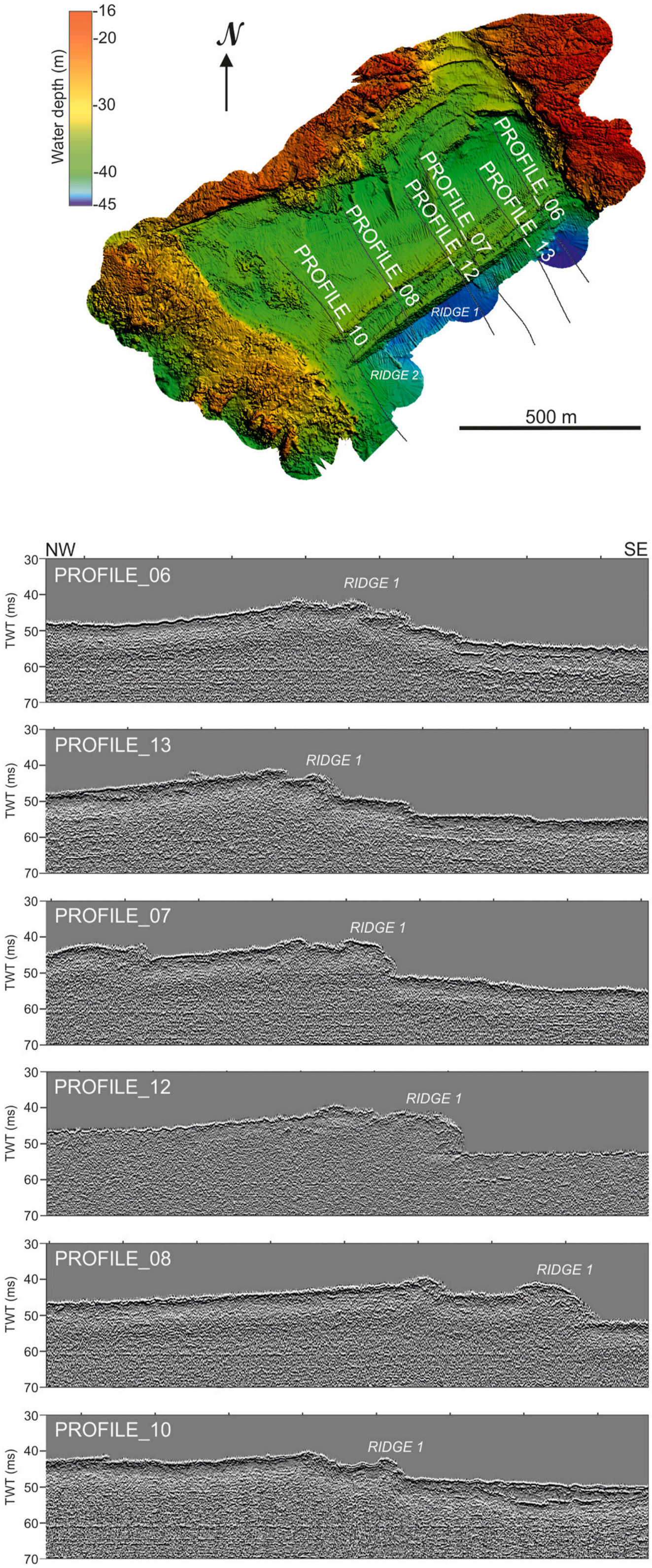
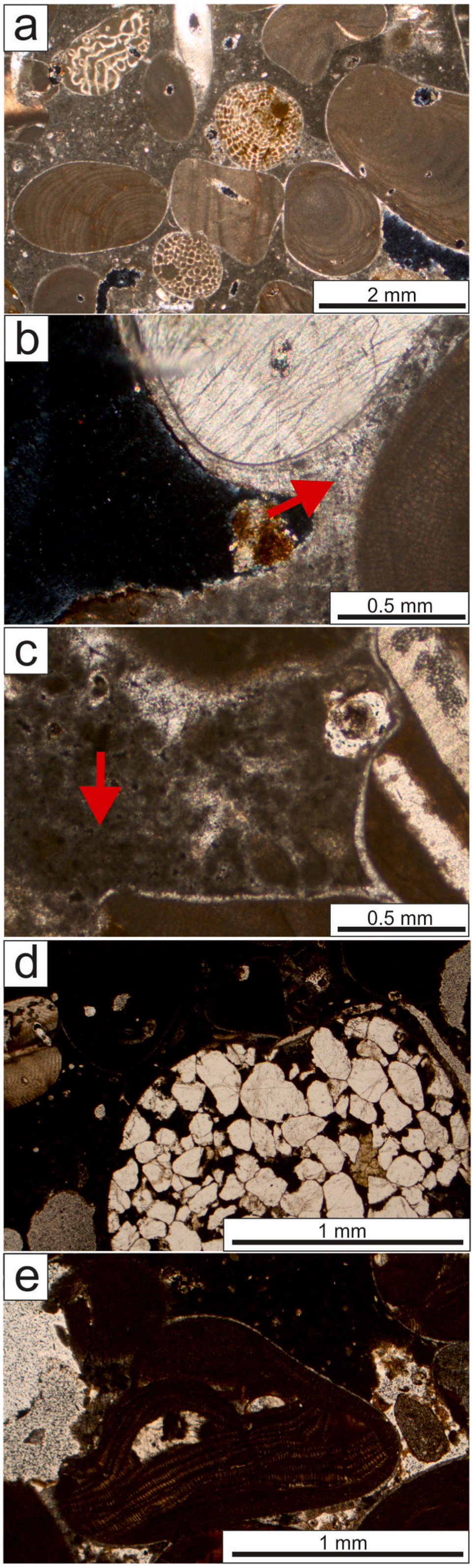


Fig. 3. (Top) Location of the migrated seismic profiles Chirp crossing perpendicularly the 820 m long ridge (RIDGE 1) in the Pantelleria Vecchia Bank, and six representative high-resolution seismic images (vertical exaggeration for all profiles: 8×).



(caption on next page)

Fig. 4. Photographs of a rock thin-section from RIDGE 1. (a) General texture of the rock, with rounded clasts in contact with each other and cemented by a very dark matrix (crossed Nicols); (b) clasts covered with a thin layer of fibrous concrete aragonite (crossed Nicols); (c) microcrystalline micritic cement between the different clasts (parallel Nicols); (d) clast composed of angular quartz fragments held together by micrite (parallel Nicols); (e) one of several fragments composed entirely of rhodolite; one can clearly see the structure given by numerous small cells arranged in a regular manner (parallel Nicols).

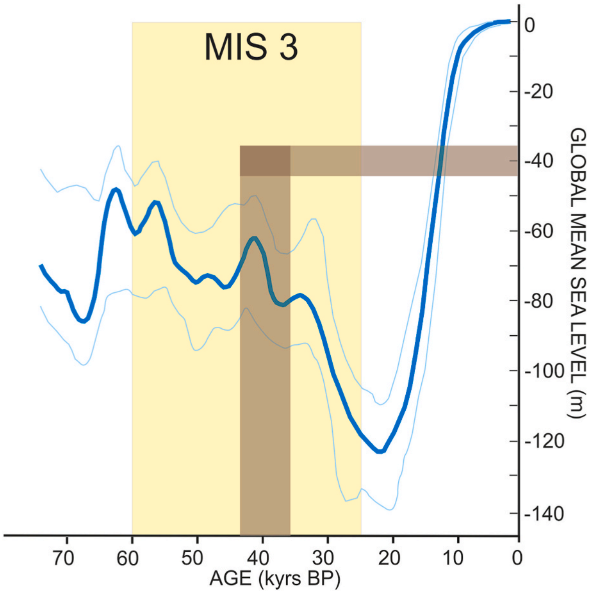


Fig. 5. Curve of global mean sea-level (bold blue curve) with uncertainty indicated by the light blue curves (from Ref. [18], modified). It covers ages up to MIS 3 (light brown rectangle). The two orthogonal bars indicate the time interval resulting from ^{14}C measurements (i.e. the ages shown in Table 1 and those reported in Ref. [9]) of the rocks that make up RIDGE 1 (brown vertical bar) and the corresponding present-day sea level at the top (minimum water depth) and base (maximum water depth) of the rectilinear RIDGE 1 (brown horizontal bar).

consist of a single calcite crystal. Grains also include foraminifera, characterized by an intensely brown microcrystalline shell. Based on the morphology of the grains, the relationships between grains and cement, and the character of the cement, the rock can be classified as a bioclastic sandstone (calcirudite). The typical habitat of the bioclasts is a rocky bottom or coral reef and we therefore infer the rocks that make up the ridge were deposited in a shallow marine environment and not in the intertidal environment where beach-rock forms (see also [9]).

Available radiocarbon measurements, carried out in two independent laboratories indicate that the ages of these rocks determined from carbonate shells extracted from the samples, range from about 36,000 to 45,000 cal yr BP (see Table 1 in Ref. [9]). The new measurements (see Table 1) show similar age results, indicating that the analyses carried out in different time periods, and by different laboratories, were consistent. All these ages fall within Marine Isotope Stage 3 (MIS 3), a period between 60 and 25 kyrs BP, characterized by several sea-level fluctuations between 60 and 90 m below present levels [3,17–19]. Projecting onto the plot of sea-level trend versus time (and its uncertainty curves) the ages obtained for the rock samples of the ridge with its current depth (from base to top), we see that these data are more than 6–8 m above the predicted positive uncertainty of the sea-level trend (Fig. 5). However, it is important to point out that the use of the carbonate component of shellfish is in several cases problematic in radiocarbon measurements, as the substance is soluble and can undergo isotopic or chemical exchange with the environment [20]. Shells may incorporate dissolved carbon dioxide or bicarbonates from “old” and deep ocean waters that are not in equilibrium with the atmosphere (reservoir effect), or from limestone areas (hard water effect). Contamination by old carbon produced by the hard water effect leads to ^{14}C ages which are too old, and contamination by young carbon, in the form of overgrowths and recrystallization, leads to ages which are too young [21]. In our case, therefore, the radiocarbon measurements do not provide a conclusive result.

On the corrections, if any, to be applied to the data to produce the curve of sea-level change over time, studies have shown that in this area of the Sicilian Channel the contribution of vertical tectonics is essentially irrelevant (the calculated vertical rate is ±0.04 mm/year [22], at least for the late Pleistocene and Holocene. This means that no corrections need to be made to the sea-level curve. The negligible contribution of vertical motion is also confirmed by independent measurements derived from semi-permanent GPS stations [23]. Moreover, comparison of high-resolution geophysical data with Glacial Isostatic Adjustment (GIA) models has shown that the locations of post-LGM seismic horizons (i.e., the wave-ravinement surfaces [24–26]) lie along the palaeo-coastline shown by the GIA model for the 21-kyr time frame BP [27,28], suggesting that there was no vertical movement during the late Pleistocene/Holocene.

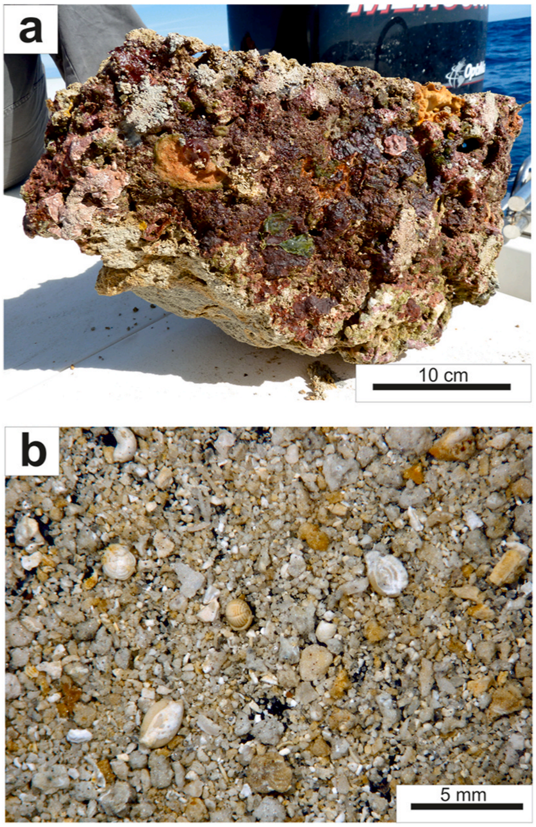


Fig. 6. (a) Sample of a Tortonian calcarenite from RIDGE 2, consisting of a lightly cemented bioclastic that also contains a siliceous fraction. In the disaggregated sediments (b) the biogenic fraction (mainly benthic foraminifera) is clearly visible.

3.2. RIDGE 2

At 100 m from the southern end of RIDGE 1, the high-resolution bathymetric data show the presence of another rectilinear ridge perpendicular to the giant RIDGE 1 and extending 82 m towards the open sea. It is between 6 and 8 m wide and generally rises 0.5–1 m above the surrounding seafloor, which is mostly covered by a relatively thin layer (generally less than 4 m) of coarse biogenic sand (see Fig. 2a). The morphology of this ridge is more pronounced and defined in the south than in the north. Analysis of a rock sample taken directly from the tip of the seaward end of the ridge (Fig. 6) shows that it is composed of relatively porous Tortonian mudstone, as indicated by the microfossil content [8]. This lithology is different from the rock samples from some blocks of RIDGE 1, which consist of a compact and hard calcirudite, as described previously.

To investigate the nature of this 82 m long ridge, a single-channel, high-resolution seismic profile was acquired with a portable Boomer system, crossing it perpendicularly (Fig. 7). The line runs parallel to the base of RIDGE 1 at a distance of 14 m. As is well known, the vertical resolution of seismic data is defined as the ability to distinguish between two features such that they can be separated and not defined as a single feature. In general, layers cannot be distinguished if their thickness is less than 1/4 of the wavelength, but some authors see the limit at 1/8 [29]. In our case, the dominant frequency (as determined from the analysis of the power spectrum from 53 to 58 ms between shot points 777 and 787) is 2900 Hz, and the speed of sound of the porous limestone that makes up the ridge is in a range between 2.5 and 3.5 km/s [30], so the vertical resolution is ~0.3 m. In our seismic profile, the two-way travel time (TWT) of the sound wave from the top to the bottom of the ridge is 1.2 ms, as shown in the migrated version of the data (Fig. 7b). A variable sound speed of 2.5–3.5 km/s gives a thickness of 1.5–2.1 m. The horizontal resolution is determined by the Fresnel zone (Fn), which depends on the speed of sound, frequency, and depth (expressed as time). The formula is as follows: $Fn = velocity^* (time/frequency)^{1/2}$. For our target, the Fresnel zone is 6.4 m. The seismic data show that another signal phase exists between the base of our target and the seafloor. This reflection is consistent with the hypothetical target size and vertical resolution. The profile definitively shows that this 82 m high ridge is not an outcrop on the seafloor, as there is no acoustic reflection associated with a deep root below it. Similarly, we can compare the seismic response of this element with the seismic reflection at shot point 750 (see Fig. 7b), where the presence of a reflection associated with tilted layers is evident. These elements strongly suggest that the blocks composing RIDGE 2 have somehow been placed on top of a sedimented seafloor.

During the geophysical surveys, divers took video and photographic images along RIDGE 2 (Fig. 8). Visual underwater observations show that it consists of decimeter-sized stone blocks that appear to have been laid one on top of the other, as can be seen from its

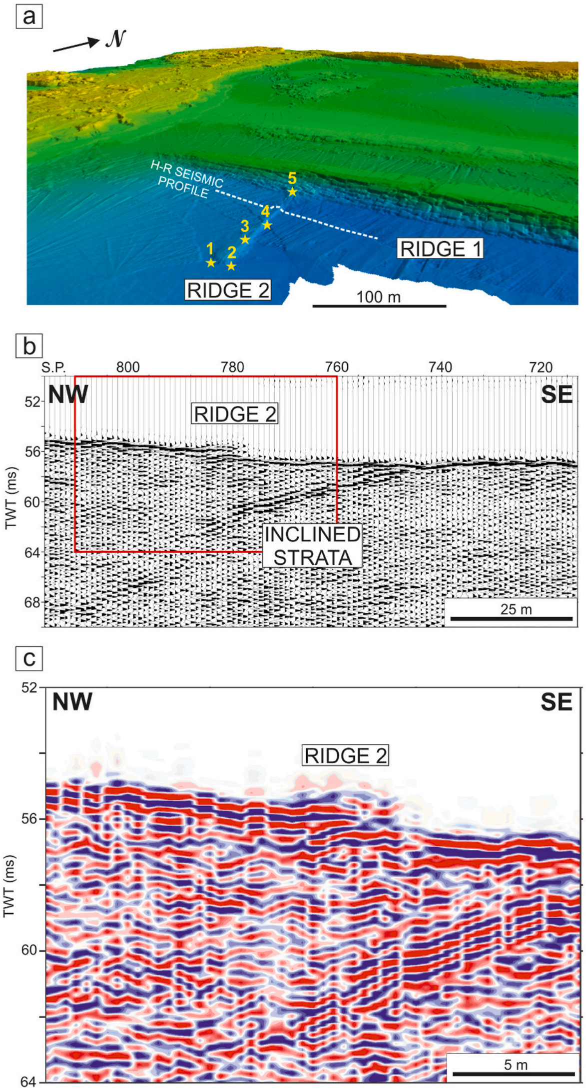


Fig. 7. (a) Shaded 3-D relief of the southwestern sector of Pantelleria Vecchia Bank (vertical exaggeration: 2x), where the rectilinear, 82 m long ridge (RIDGE 2) extending perpendicular to the outer RIDGE 1 has been identified. The white dotted line shows the high-resolution seismic profile acquired parallel to the base of RIDGE 1 and crossing RIDGE 2. The numbered yellow stars indicate the underwater photos shown in Fig. 8. (b) Processed seismic Boomer profile (vertical exaggeration: 2x), with applied Stolt migration, showing the acoustic response of the 82 m ridge and a clear reflection at shot point (S. P.) 750. It indicates the presence of inclined layers with a root at depth. A deep reflection indicating sedimentary layers at RIDGE 2 is not present. Instead, the data show a sub-horizontal reflection below the surface of the ridge, suggesting that the base of the ridge itself rests on the seafloor. The red box shows the magnification of the seismic record (c) displayed in variable area mode (vertical exaggeration: 4x).

southern end. In plan view, the top of the ridge has an almost circular shape. The central part of the ridge consists mainly of elongated blocks arranged in at least three longitudinal rows. This geometric regularity is less obvious at the intersection with the RIDGE 1, where the differences in size and shape of the blocks that make up the two ridges are visible. However, it is difficult to interpret the intersection in terms of overlapping elements, as in some places blocks of the RIDGE 1 overlap with those of the smaller ridge and vice versa. The eastern flank of RIDGE 2 rises clearly from the seafloor and forms a regular wall rising about 1 m above it, while the western flank of the ridge is less continuous, and forms reticulated walls above the seafloor only in certain sections.

4. Discussion

In this paper, we have used geophysical data, petrographic analyses, and underwater videos to describe two puzzling rectilinear, orthogonal ridges in the Pantelleria Vecchia Bank, a shoal located about 20 nautical miles north of the island of Pantelleria. Our data do not conclusively reveal either a natural or anthropogenic origin for these ridges. However, several curious features suggest an

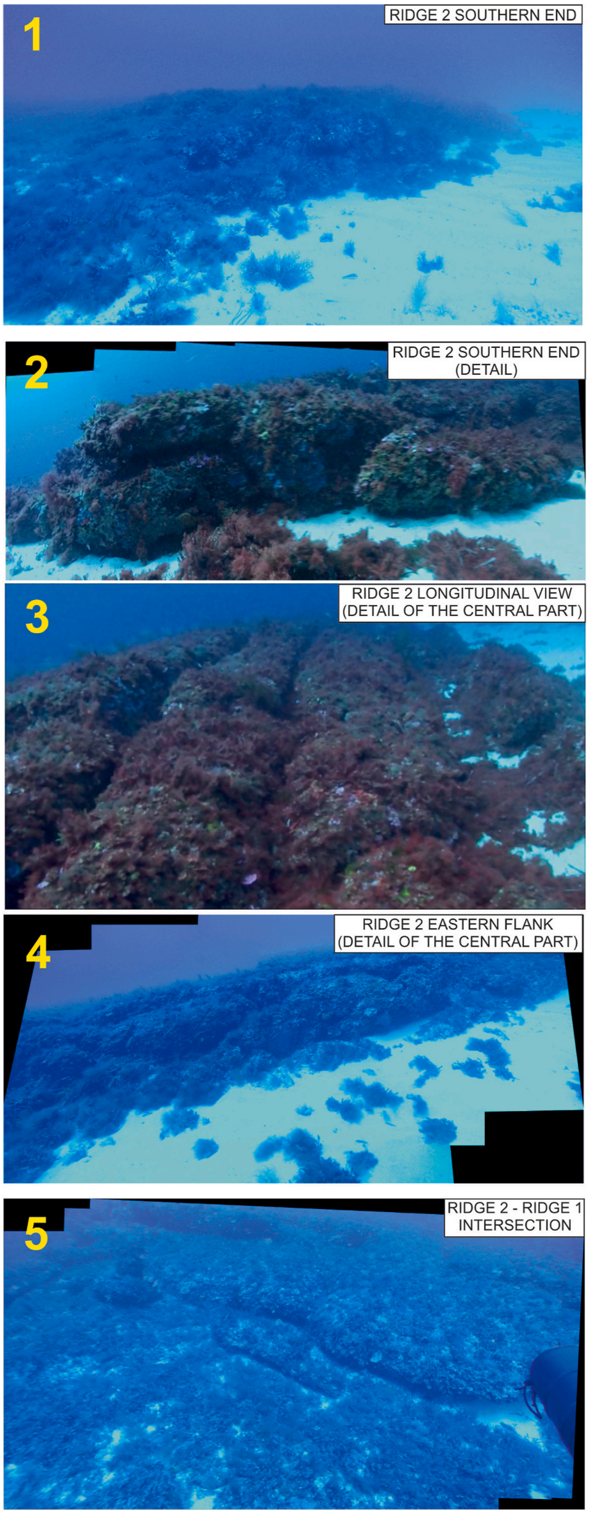


Fig. 8. Underwater photographs of Pantelleria Vecchia Bank RIDGE 2 (see locations in Fig. 7). (1) Frontal view of the seaward end of the ridge. (2) Composite photo of the seaward end of the ridge, clearly showing the stacked blocks. (3) Photo of the central part of the ridge, which in this area consists mainly of elongated blocks arranged in at least three longitudinal rows. (4) Composite photo of part of the eastern flank of the ridge (middle segment), which forms a kind of wall above the seabed. (5) Composite photo of the intersection of RIDGE 2 with RIDGE 1, showing the size and shape of the blocks that make up the two structures described in the text.

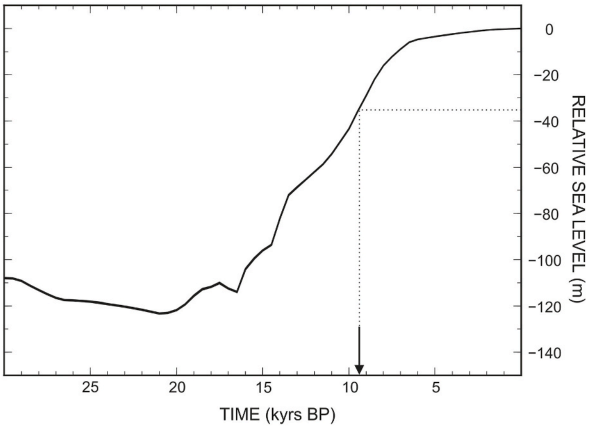


Fig. 9. Relative sea level curve vs. time calculated for the mid-latitude of the Adventure Plateau (from Ref. [27], modified). The intersection on the x-axis (black arrow) indicates the age corresponding to the water depth of the upper part of RIDGE 1.

anthropogenic influence: (i) the orthogonal geometry of the two ridges; (ii) RIDGE 1 is precisely ten times longer than RIDGE 2; (iii) the two ridges occur at the same water depths yet are composed of rocks of different ages, and do not appear to have formed as beach-rock; (iv) neither the blocky structure of RIDGE 1 or the steep slopes on its seaward margin can be easily explained by natural causes. We also note that Lodolo and Ben-Avraham [9] have already documented the presence of a huge monolith, and three concentric semicircles 60 m apart to the northeast of RIDGE 1 in the Pantelleria Vecchia Bank. It seems unlikely that this concentration of peculiar and geometrically regular structures would develop by natural processes in this small ($\sim$0.5 km^2) study area. In view of the above, it seems possible that the two ridges are associated with human occupation, also considering that this site was located in a strategic island position between Sicily and Tunisia.

Several studies have addressed the importance of small islands in human prehistory that were regularly and easily inhabited and/or accessible to terrestrial and marine resources [31], as well as the early evidence of maritime traffic and trade in this area of the Mediterranean Sea. Although many scientists believe that maritime travel probably developed after the LGM, lower sea levels would have connected many of the present-day islands and reduced the distance between other islands, making them accessible via short crossings [32]. The first (14-10 kyrs BP) reliable evidence of human settlement in Sicily derive from palaeoanthropological remains from the Grotta di San Teodoro, a site near Messina [33]. Most of the Egadi archipelago, which lies to west of the present-day Sicilian coast, was connected to Sicily until the early Holocene, and therefore represents a rather similar palaeogeographical setting with the former Adventure Plateau archipelago, which included the Pantelleria Vecchia Bank. In the Grotta d'Oriente on Favignana, one of the islands of the Egadi archipelago, radiocarbon dating, palaeogenetic and isotopic analyses of buried skeletal remains show that the island was inhabited by hunter-gatherers since 14,000 years ago [34]. Moreover, palaeogeographical reconstructions have shown that Marettimo, the outermost island of the archipelago, was separated from the other Egadi Islands by a narrow channel since the LGM, but findings of food remains in the Grotta del Tuono may indicate that seafaring in this archipelago began long before the Neolithic [35].

The water depth and inferred position of the two described ridges in the Pantelleria Vecchia Bank at or slightly above sea level suggest an early Holocene age of about 9300 yrs BP (Fig. 9). Extrapolating the data from the local sea level curve, the rates of sea level rise were about 18 mm/yr [9] at that time. Given these rather high rates, it seems unlikely that possible human occupation as a viable coastal outpost could have lasted longer than a few hundred years. In this context, it seems plausible that RIDGE 1 was built or modified to protect against sea level rise. In the Mediterranean area, the only known submerged archaeological site comparable in age to the presumed site of Pantelleria Vecchia Bank is that of Atlit Yam, off the northern coast of Israel, dated between 8900 and 8300 yrs BP [36], and which today lies between 8 and 12 m below sea level.

However, the lack of identifiable human artefacts and other underwater archaeological data poses an obvious problem for the hypothesis of anthropogenic origin. In this context, we note that less than 50% of the study area has been surveyed by video inspection. With the available data, we cannot reject the hypothesis that the steep seaward edge of RIDGE 1 may represent a submerged sea cliff, formed about 42 kyrs ago and associated with a short-lived period of lower rates of sea-level change. If we lean towards the hypothesis of a human occupation of Pantelleria Vecchia Bank, it could be that the cliff formed around 42 kyrs was modified around 9 kyrs for defensive purposes (?). It is well known that the particular characteristics of an area inspired the skills and "genius" of the ancient inhabitants, adapting the natural elements present on site to their needs. There are many archaeological sites where humans used the natural stone elements already present on site to create structures for specific purposes.

However, in order to finally unravel the fascinating mystery of the Pantelleria Vecchia Bank, further and extensive research using state-of-the-art marine technologies and data manipulation (e.g., ROV and AUV inspections, underwater photogrammetry, seafloor photo-mosaics, etc.) is needed.

Author contribution statement

E.L.: conceived and designed the experiments; analyzed and interpreted the data; wrote the paper. P.N.: analyzed and interpreted the underwater videos. L.B.: collected and processed the seismic data; contributed to the data interpretation. Z. B–H.: contributed to the design of the experiment; analyzed and interpreted the data; wrote the paper.

Funding statement

Funds for this study were partly granted within a joint Italian-Israel scientific project financed by the Italian Ministry of Foreign Affairs and International Cooperation (grant 3697715AF0).

Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

We thank the crews of the patrol boats CC-811 *"Pignatelli"* (Trapani) and CC-819 *"Maronese"* (Pantelleria) of the Italian *"Arma dei Carabinieri"* for their invaluable help in collecting data at sea. The divers of the *"Arma dei Carabinieri"* (Rome and Messina), and the professional divers Fabio Leonardi and Francesco Spaggiari from the *"Global Underwater Explorers"*, recorded underwater videos and collected rock samples. Suggestions and comments from two anonymous reviewers have helped to considerably improve this manuscript.

References

[1] K.M. Fleming, P.J. Johnston, D. Zwartz, Y. Yokoyama, K. Lambeck, et al., Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites, Earth Planet Sci. Lett. 163 (1998) 327–342, https://doi.org/10.1016/S0012-821X(98)00198-8.

[2] K. Lambeck, J. Chappell, Sea-level change through the last glacial cycle, Science 292 (2001) 679–686, https://doi.org/10.1126/science.1059549.

[3] M. Siddall, E.J. Rohling, A. Almogi-Labin, C. Hemleben, D. Meischner, et al., Sea-level fluctuations during the last glacial cycle, Nature 423 (2003) 853–858, https://doi.org/10.1038/nature01690.

[4] P.U. Clark, A.S. Dyke, J.D. Shakun, A.E. Carlson, J. Clark, et al., The last glacial maximum, Science 325 (2009) 710–714, https://doi.org/10.1126/science.1172873.

[5] P. Colantoni, G. Cremona, M. Ligi, A.M. Borsetti, F. Cati, The Adventure Bank (off south-western Sicily): a present day example of carbonate shelf sedimentation, Giorn. Geol. 3 (1985) 165–180.

[6] D. Civile, E. Lodolo, M. Zecchin, Z. Ben-Avraham, L. Baradello, et al., The lost adventure archipelago (Sicilian channel, mediterranean sea): morpho-bathymetry and late quaternary palaeogeographic evolution, Global Planet. Change 125 (2015) 36–47, https://doi.org/10.1016/j.gloplacha.2014.12.003.

[7] E. Lodolo, When the Sicily Channel was an archipelago, Rend. Onl. Soc. Geol. It. 21 (2) (2012) 1174–1175.

[8] D. Civile, E. Lodolo, M. Caffau, L. Baradello, Z. Ben-Avraham, Anatomy of a submerged archipelago in the Sicilian channel (central mediterranean sea), Geol. Mag. 153 (2016) 160–178, https://doi.org/10.1017/S0016756815000485.

[9] E. Lodolo, Z. Ben-Avraham, A submerged monolith in the Sicilian Channel (central Mediterranean Sea): evidence for Mesolithic human activity, Jour. Archaeol. Sci. Rep. 3 (2015) 398–407, https://doi.org/10.1016/j.jasrep.2015.07.003.

[10] L. Baradello, F. Battaglia, A. Vesnaver, Fast method to transform Chirp envelope data into pseudo-seismic data, Mar. Geophys. Res. 42 (2) (2021) 14, https://doi.org/10.1007/s11001-021-09436-y.

[11] T. Heaton, P. Köhler, M. Butzin, E. Bard, R. Reimer, et al., Marine20—the marine radiocarbon age calibration curve (0–55,000 cal BP), Radiocarbon 62 (4) (2020) 779–820, https://doi.org/10.1017/RDC.2020.68.

[12] G. Siani, M. Paterne, M. Arnold, E. Bard, B. Métivier, N. Tisnerat, Radiocarbon reservoir ages in the mediterranean sea and black sea, Radiocarbon 42 (2000) 271–300, https://doi.org/10.1017/S0033822200059075.

[13] D. Civile, H. Alp, Z. Ben-Avraham, et al., Seismic stratigraphy and structural setting of the Adventure Plateau (sicily channel), Mar. Geophys. Res. 35 (2014) 37–53, https://doi.org/10.1007/s11001-013-9205-5.

[14] D.J. Stanley, A. Maldonado, R. Stuckenrath, Strait of Sicily depositional rates and patterns, and possible reversal of currents during the Late Quaternary, Palaeogeogr. Palaeoclimatol. Palaeoecol. 18 (1975) 279–291, https://doi.org/10.1016/0031-0182(75)90037-1.

[15] M.I. Vousdoukas, A.F. Velegrakis, T.A. Plomaritis, Beachrock occurrence, characteristics, formation mechanisms and impacts, Earth Sci. Rev. 85 (2007) 23–46, https://doi.org/10.1016/j.earscirev.2007.07.002.

[16] E.A. Shinn, The mystique of beachrock, Int. Assoc. Sedimentol. Spec. Publ. 41 (2009) 19–28.

[17] J. Chappell, Sea level changes forced ice breakouts in the Last Glacial cycle: new results from coral terraces, Quat. Sci. Rev. 21 (10) (2002) 1229–1240, https://doi.org/10.1016/S0277-3791(01)00141-X.

[18] C. Waelbroeck, L. Labeyrie, E. Michel, J.C. Duplessy, K. Lambeck, J.F. McManus, E. Balbon, M. Labracherie, Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records, Quat. Sci. Rev. 21 (2002) 295–305, https://doi.org/10.1016/S0277-3791(01)00101-9.

[19] M. Siddall, E.J. Rohling, W.G. Thompson, C. Waelbroeck, Marine Isotope Stage 3 sea level fluctuations: data synthesis and new outlook, Rev. Geophys. 46 (2008) 1–29, https://doi.org/10.1029/2007RG000226.

[20] F.S. Busschers, F.P. Wesselingh, R.H. Kars, M. Versluijs-Helder, J. Wallinga, J.H.A. Bosch, J. Timmner, K.G.J. Nierop, T. Meijer, F.P.M. Bunnik, H. De Wolf, Radiocarbon dating of late Pleistocene marine shells from the southern north sea, Radiocarbon 56 (3) (2014) 1151–1166, https://doi.org/10.2458/56.16505.
[21] F.H. Bezerra, C. Vita-Finzi, F.P.F. Lima, The use of marine shells for radiocarbon dating of coastal deposits, Rev. Bras. Geociencias 30 (1) (2000) 211–213, https://doi.org/10.25249/0375-7536.2000301211213.
[22] L. Ferranti, F. Antonioli, B. Mauz, A. Amorosi, G. Dai Pra, et al., Markers of the last interglacial sea-level highstand along the coast of Italy: tectonic implications, Quat. Int. 145–146 (2006) 30–54, https://doi.org/10.1016/j.quaint.2005.07.009.
[23] E. Serpelloni, M. Anzidei, P. Baldi, G. Casula, A. Galvani, Crustal velocity and strain-rate fields in Italy and surrounding regions: new results from the analysis of permanent and non-permanent GPS networks, Geophys. Journ. Intl. 161 (2005) 861–880, https://doi.org/10.1111/j.1365-246X.2005.02618.x.
[24] O. Catuneanu, Principles of Sequence Stratigraphy, Elsevier, Amsterdam, 2006, p. 386.
[25] M. Zecchin, S. Ceramicola, E. Lodolo, D. Casalbore, F.L. Chiocci, Episodic, rapid sea-level rises on the central Mediterranean shelves after the last glacial maximum: a review, Mar. Geol. 369 (2015) 212–223, https://doi.org/10.1016/j.margeo.2015.09.002.
[26] M. Zecchin, O. Catuneanu, M. Caffau, Wave-ravinement surfaces: classification and key characteristics, Earth Sci. Rev. 188 (2019) 210–239, https://doi.org/10.1016/j.earscirev.2018.11.011.
[27] E. Lodolo, G. Galassi, G. Spada, M. Zecchin, D. Civile, M. Bressoux, Post-LGM coastline evolution of the NW Sicilian Channel: comparing high-resolution geophysical data with Glacial Isostatic Adjustment modeling, PLoS One 15 (2) (2020), e0228087, https://doi.org/10.1371/journal.pone.0228087.
[28] E. Lodolo, M.F. Loreto, D. Melini, G. Spada, D. Civile, Palaeo-shoreline configuration of the Adventure Plateau (Sicilian channel) at the last glacial maximum, Geosciences 12 (3) (2022) 125, https://doi.org/10.3390/geosciences12030125.
[29] M.B. Widess, How thin is a thin bed? Geophysics 38 (6) (1973) 1176–1180, https://doi.org/10.1190/1.1440403.
[30] T. Bourbié, O. Coussy, B. Zinszner, Acoustics of Porous Media, Gulf Publishing Company, Houston, TX, 1987, p. 334.
[31] S.M. Fitzpatrick, V.D. Thompson, A.S. Poteate, M.F. Napolitano, J.M. Erlandson, Marginalization of the margins: the importance of smaller islands in human prehistory, J. I. Coast Archaeol. 11 (2016) 155–170, https://doi.org/10.1080/15564894.2016.1192568.
[32] N. Phoca-Cosmetatou, R.J. Rabett, Reflections on Pleistocene island occupation, J. Mediterr. Archaeol. 27 (2) (2014) 255–278, https://doi.org/10.1558/jmea.v27.i2.255.
[33] G. D'Amore, S. Di Marco, G. Tartarelli, R. Bigazzi, L. Sineo, Late Pleistocene human evolution in Sicily: comparative morphometric analysis of Grotta di San Teodoro craniofacial remains, J. Hum. Evol. 56 (2009) 537–550, https://doi.org/10.1016/j.jhevol.2009.02.002.
[34] M.A. Mannino, G. Catalano, S. Talamo, G. Mannino, R. Di Salvo, V. Schimmenti, et al., Origin and diet of the prehistoric hunter-gatherers on the mediterranean island of Favignana (Egadi islands, sicily), PLoS One 7 (11) (2012), e49802, https://doi.org/10.1371/journal.pone.0049802.
[35] V. Lo Presti, F. Antonioli, M.R. Palombo, V. Agnesi, S. Biolchi, L. Calcagnile, C. Di Patti, S. Donati, S. Furlani, J. Merizzi, F. Pepe, G. Quarta, P. Renda, A. Sulli, S. Tusa, Palaeogeographical evolution of the Egadi Islands (western Sicily, Italy). Implications for late Pleistocene and early Holocene sea crossings by humans and other mammals in the western Mediterranean, Earth Sci. Rev. 194 (2019) 160–181, https://doi.org/10.1016/j.earscirev.2019.04.027.
[36] E. Galili, Y. Nir, The submerged Pre-Pottery Neolithic water well of Atlit-Yam, northern Israel, and its palaeoenvironmental implications, Holocene 3 (3) (1993) 265–270, https://doi.org/10.1177/095968369300300309.