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ANCHIALINE ECOSYSTEMS

Search for Bermuda's deep water caves

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Abstract The mid-Atlantic islands of Bermuda harbor one of the richest and most diverse anchialine communities known from anywhere on Earth. However, all known anchialine caves in Bermuda (maximum depth—26 m) were dry during the last glacial period extending from approximately 9,000 to 115,000 years ago when glacial sea levels were as much as 127 m lower. Since it is highly unlikely that Bermuda's endemic cave species evolved since the caves were flooded by sea level rise, alternate deeper habitats must have existed to shelter anchiane fauna for prolonged periods of lower sea level during the Pleistocene. In order to systematically search for such now deep water cave habitats, high-resolution multibeam sonar and remotely operated vehicles were used to map and explore the seafloor off Bermuda in 60–200 m depths along the outer shelf break edge of the submarine escarpment surrounding the Bermuda Platform and an adjacent seamount. Specific goals were to discover deep water cave and/or crevicular habitats and to characterize the nature, geological stratification and composition, and sea level history of the platform margin, in particular focusing on features directly relating to Pleistocene low sea stand events. During this sea floor survey, clearly defined paleo-shoreline features generated by wave and current erosion were found to encircle the Bermuda seamount and Challenger Bank at 60 and 120 m depths.

Keywords Anchialine caves · Seafloor mapping · Pleistocene · Sea level

Introduction

The islands of Bermuda occupy an isolation position in the North Atlantic with the closest major landmass being Cape Hatteras, North Carolina on the North American continent, located approximately 965 km to the northwest. Despite this mid-ocean location, remote from other shallow water marine habitats, the limestone caves of Bermuda harbor on one of the richest and most diverse anchialine communities on Earth.

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At least 83 endemic, stygobitic species, primarily crustaceans, inhabit fully marine waters in these caves with taxa showing close affinities to Caribbean, East Atlantic or even deep sea fauna (Iliffe, 2009). Furthermore, most of Bermuda's anchialine fauna show pronounced morphological adaptations to the subterranean environment, such as eye and pigment reduction suggesting a long period of adaption and residence within this lightless habitat. However, as recently as 9,000 years ago and persisting for much of the Pleistocene, the currently known extent of Bermuda's caves, which reach a maximum depth of 26 m below current sea level, would have been dry and air filled during glacial periods of lower sea level. The presence of subaerially formed stalactites and stalagmites at all depths within Bermuda's submerged caves confirms the caves must have been dry for prolonged periods of time. Accordingly, alternate but ecologically and environmentally similar habitats must have existed and are still likely present at water depths below the low point of Pleistocene sea levels at ~127 m. Thus, the geologic history, limestone and basalt stratification, numerous but relatively shallow inland caves, and endemic anchialine fauna of considerable age, all combine to make Bermuda an ideal location to search for potential now deep water caves or similar habitats. In order to systematically conduct such a search, the perimeter shelf edge of Bermuda and the adjacent Challenger Bank were mapped with high-resolution multibeam to identify possible cave entrances and voids, designed as "Points of Interest" (POI). POIs were subsequently investigated using a remotely operated vehicle or ROV.

Bermuda geology

The Bermuda islands are situated along the southeastern margin of a northeast elongated oval bank about 50 km in length from northeast to southwest and 22 km across from northwest to southeast. Beneath Bermuda is the truncated stump of a large, extinct shield volcano that began forming in the mid to late Eocene about 45–35 Mya (Vogt & Jung, 2007). Generally referred to as the Bermuda Pedestal, this seamount dominates a much larger, 1,500 km long by 500–1,000 km wide, bulge in the West Atlantic sea floor known as the Bermuda Rise. The age of the oceanic crust underlying Bermuda is about 123–124 Ma and thus considerably predates the formation of the Bermuda Pedestal, which possibly formed as a result of a worldwide reorganization of the earth's tectonic plates due to the closing of the Tethys Ocean when Arabia collided with Eurasia (Vogt & Jung, 2007). Based on the current area of the Bermuda Bank and the maximum elevation of other volcanoes, the elevation of the original Bermuda volcano would have been about 1,000 m (Vogt & Jung, 2007). Using typical shoreline erosion rates, it would have taken 3–10 million years to reduce the island to sea level. Immediately to the southwest of Bermuda lie the Argus and Challenger Banks which rise to within 50 m of the surface, while 40 km to the northeast is the Bowditch Seamount, the summit of which is submerged to 800 m depth. Referred to as the Bermuda cluster, neither these isolated seamounts nor the Bermuda Rise upon which they were formed appears to have subsided at all in the past 40 Ma (Vogt & Jung, 2007).

Volcanic rocks do not appear anywhere on the surface of Bermuda as they are covered with a 15 to 100+ m thick cap of Pleistocene marine and eolian limestone and are only seen in drill cores or with deep diving submersibles. Bermuda's limestone was formed by plants and animals in the shallow waters atop the wave eroded summit of the Bermuda Pedestal. As a result of eustatic fluctuations in sea level corresponding to glacial and interglacial periods, Bermuda's carbonate sands, composed of pellets and biogenic particles from shells and calcifying algae, were exposed to air and blown by wind into dunes. While vegetation stabilized the position of the dunes, slightly acidic rainwater percolating through them, cemented sand grains together to form Bermuda's eolianite limestone. As glacial and interglacial sea levels fluctuated, much of Bermuda was alternately submerged or exposed. During interglacial periods of higher sea level, much of the upper surface of the platform was flooded and coral reefs flourished, producing an abundance of carbonate sands, generating sand dunes and eolian limestone. However, during glacial periods when sea level was 100 m or more lower than today, few shallow water environments existed on Bermuda and sand production stopped. In these times, windblown dust from the Sahara were blown across the Atlantic and slowly accumulated to form red paleo soil layers or paleosols (Herwitz et al., 1996). Thus, Bermuda's stratigraphic column consists of a layer cake like sequence of alternating limestone beds and paleosols (Hearty, 2002).

The Bermuda islands are located along the southeastern margin of a broad and elliptically shaped, shallow water platform. An outer, elliptical, reef rim surrounds the platform and encloses a reef-filled lagoon with water depths ranging from 8 to 18 m. Bermuda at 32°N latitude has the northernmost coral reefs in the North Atlantic. Corals on the outer reefs consist primarily of massive boulder corals including the brain corals, *Diploria* spp., and star corals, *Montastrea* spp., but only form a thin veneer over what may be submerged, eolanite dune ridges. Bermuda is referred to a "pseudo-atoll" since it differs from typical oceanic atolls due to the presence of high hills on the islands, mostly submerged reefs on the rim, and a wide reef-front terrace (Verrill, 1900). A broad upper terrace extends seaward at 15–22 m water depths for distances of 800–4,800 m out from the base of the reef track to the outer platform edge (Stanley & Swift, 1968). This terrace is best developed in the southwest and northeast sectors of the platform which correspond to the prevailing directions of wind and waves. A narrower, lower terrace at 55–64 m depths is separated from the upper terrace by a possible drowned reef ridge (Stanley & Swift, 1968). The depth of the upper terrace corresponds to water depths in deeper parts of the lagoon, Harrington Sound, Castle Harbour, and Great Sound, as well as the main submerged passages in the island's anchialine caves. Likewise, the depth of the outer terrace compares well with the tops of the Challenger and Argus Banks near Bermuda. Since terraces at similar depths occur elsewhere in the world, Stanley & Swift (1968) conclude that the terraces in Bermuda are erosion relicts formed during prolonged still-stands of Pleistocene sea level.

Bermuda caves

The karst landscape of Bermuda is literally riddled with limestone caves. Rainwater runoff disappears rapidly into the ground and dissolves away limestone as it follows the path of least resistance, first vertically down to the water table, and then horizontally toward the sea (Mylroie et al., 1995). More than 150 limestone caves are known from the island, many with extensive submerged portions connected to the sea at tidal springs along the present coastline (Iliffe, 2003). Bermuda caves are characterized by fissure entrances and large breakdown chambers that formed by collapse of roof rock when formerly flooded portions were exposed to air as glacial sea levels fell. Today, the largest known caves on Bermuda are submerged caves up to 3 km long that lie beneath current landmasses and occur primarily at 18 m depth, but extend down to a maximum of 26 m. Although surface water in cave pools is brackish, the water becomes fully marine by depths of several meters. Massive stalactites and stalagmites, which form only in air by dripping water, occur in all parts of the now submerged caves. These speleothems were deposited during glacial low sea level stands and provide conclusive evidence that known caves were completely dry and air filled for glacial–interglacial periods on the order of 100,000 years. Radioisotope dating of submerged speleothems has been used as a tool to chart the chronology of Bermuda sea level history (Harmon et al., 1978, 1981).

The sea-level brackish pools in the interior and/or entrances of many Bermuda caves are classified as anchialine habitats. The term "anchialine" was coined to describe pools with no surface connection to the sea, containing salt or brackish water, which fluctuates with the tides (Holthuis, 1973; Stock et al., 1986b). Bermuda's cave pools have a thin brackish layer at the surface, overlying fully marine waters at depth. Differences in phase and amplitude between tides in the nearly enclosed Harrington Sound and those in the open sea generate reversing subterranean tidal currents with sea water entering at coastal karstic springs and moving through submerged cave passages (Iliffe, 2000). Caves farther inland typically contain slowly moving or nearly stagnant waters.

Anchialine cave fauna

An exceptionally rich and diverse endemic fauna inhabits the submarine passageways and anchialine pools of these caves (Iliffe, 2004). The stygobitic (aquatic cave-adapted) fauna of Bermuda's anchialine caves includes at least 83 species with 11 genera and one order (the peracarid crustacean Order Mictacea) restricted to the island's caves. The majority of Bermuda's stygobitic species are crustaceans, including 28 copepods, 18 ostracods, 8 amphipods, 6 shrimp, 6 cumaceans, and 5 isopods, in addition to 5 species of aquatic mites, 3 annelids, 2 ciliates, and 2 molluscs. This is among the highest density of aquatic subterranean biodiversity known on Earth. In comparison, the entire Bahamas archipelago, which occupies an area several hundreds of times larger than Bermuda, has 122 known anchialine stygobities. Included among Bermuda's anchialine fauna are several apparently ancient relict organisms. For example, the copepod *Erebonectes* is regarded as one of the most primitive of known calanoids, while *Antrisocopia* agrees in many ways with the description of a theoretical ancestral copepod (Fosshagen & Iliffe, 1985). Some of Bermuda's cave-dwelling species exhibit close affinities with European cave and groundwater fauna and probably colonized subterranean habitats on Bermuda early in the island's history when the Atlantic was much narrower. The amphipod *Pseudoniphargus*, which was originally known only from caves and groundwater around the Mediterranean, the Azores and Canary Islands, includes two species from Bermuda caves (Stock et al., 1986a). Other animals inhabiting Bermuda caves have close relatives in caves on other isolated oceanic islands from the Atlantic and Pacific. In addition to Bermuda, the misophrioid copepod genus *Speleophriopsis* also includes cave species from Palau in the South Pacific, the Canary Islands in the Eastern Atlantic, and the Balearic Islands in the Mediterranean (Boxshall & Iliffe, 1990). The isopod family Atlantasellidae includes only two species, which inhabit caves in Bermuda and the Dominican Republic (Sket, 1979). The hippolytid shrimp *Barbouria cubensis* has been reported from caves in Bermuda, the Bahamas, Cuba, Dominican Republic, and Yucatan Peninsula (Hart & Manning, 1981). Species belonging to the enigmatic shrimp genus *Procaris* are known only from caves and anchialine pools on the oceanic islands of Hawaii in the Pacific, Ascension in the South Atlantic, Cozumel in the Caribbean, and Bermuda in the North Atlantic (Hart & Manning, 1986). Thus, Bermuda's cave species are providing important clues in establishing the evolution and dispersal of present oceanic species.

Origin and age of Bermuda's cave fauna

The biogeographic affinities of Bermuda's anchialine taxa to related stygobitic species inhabiting caves on the opposite side of the Atlantic Ocean (e.g., Canary Islands, Mallorca) or even in the Pacific (e.g., Galapagos, Hawaii, Palau) are suggestive of a Tethyan origin during the Mesozoic when all continents were combined into a single land mass. However, Bermuda is a mid-ocean volcanic island that has never been part of or closer to a continent than it is today so all of the island's endemic cave fauna must have initially arrived via oceanic transport or dispersal.

Considering that the maximum water depth today in Bermuda's anchialine caves is 26 m, all known caves would have been completely dry and air filled for most of the Pleistocene according to marine oxygen isotope based reconstructions of sea level for the past one million years (Bintanja et al., 2005). The Last Glacial Maximum occurred 19–20 ka with sea level about 127 m lower (Clark et al., 2009) and sea level did not reach 26 m until about 9–10 ka. An additional consideration is that the opposite extreme of interglacial high sea level would have inundated most of Bermuda and its caves such that former inland caves would have been converted to submarine systems with quite different hydrology and water chemistry. For example, a sustained +21 m sea level high stand that occurred in Bermuda about 400 ka (Olson & Hearty, 2009) would have covered much of Bermuda and nearly all known caves.

Perhaps the most likely way that exclusively anchialine cave species could have survived on Bermuda for extended periods of glacial eustasy is that much deeper and until now, undiscovered cave or crevicular habitats may exist at points below the deepest extreme of Pleistocene sea level. This would be either at or below the depth of the limestone–basalt interface and would have provided anchialine-like refugia in terms of darkness, fully marine salinity, and restricted hydrological communication with the sea, little affected by fluctuations in sea level. The larger dissolutional passages at an average depth of −18 m in Bermuda's inland caves are believed to have formed during Pleistocene sea level lowstands by concentration of descending vadose flow that was channeled along irregularities of the basalt surface (Mylroie et al., 1995). Potential extensions of such dissolutional cave passages could have followed the basalt contact toward the platform edge and reached significantly greater depths than is known from inland caves. During periods of low sea level, the entire top of the Bermuda platform would have been exposed and with this larger catchment area, a sizeable freshwater lens should have existed. Seaward discharge of this freshwater would have accelerated dissolution both at the vadose/phreatic contact at the top of the lens and freshwater/saline contact at the bottom leading to cave formation.

Deep water caves

Evidence suggests that caves are not limited to shallow waters, but can occur at virtually any depth within the sea. Two large, hydrologically active limestone caves containing stalactites and stalagmites were discovered at a depth of 366 m on Johnston Island in the Pacific (Keating, 1985). The presence of abundant sponges on overhanging ledges in these caves, but not observed elsewhere, indicates that even in deep waters, caves offer a preferred biological niche for some animals. A lava tube of recent origin together with numerous fissures has been found at the base of a sea mount in 2,700 m water depths on the East Pacific Rise (Fornari et al., 1985). Lava tubes may be a common feature in the deep sea and function in distributing lava around seafloor extrusive sites. Lava tubes are likely to be common at mid-ocean ridges as well (Smith & Cann, 1998).

The presence of deep water caves in Bermuda is strongly suggested by geological evidence. During submersible dives, Carew & Mylroie (1987) observed solution conduits on the sides of San Salvador Island in the Bahamas at 105–125 m depths, at or near the probable low point for Pleistocene sea level. Mylroie et al. (1995) concluded that the presence of impermeable basalts, which underlie the limestone in Bermuda and were above sea level during Pleistocene low sea stands, would have channeled runoff resulting in considerably more massive conduits than those they found in the Bahamas.

Materials and methods

In order to search for now deep water caves around the edges of the Bermuda Platform and adjacent Challenger Bank, a multiphase research program was initiated consisting of a multibeam sonar survey of the shelf break edge that would identify promising sites for ROV investigations. These first two phases were carried out in September 2009 by the Seafloor Mapping Lab at California State University, Monterey Bay, while the third and last phase of the project, planned for summer 2011, will follow up at certain locations with visual inspections of the sea floor by divers.

A Reson Seabat 7125 multibeam echosounder was used to map seafloor bathymetry. Position and attitude control was provided by a CodaOctopus F185+ motion and navigation sensor. Sound velocity profiles were collected at intervals throughout the data acquisition with an Applied Microsystems SVP for correction of refraction artifacts and ray bending. Data were acquired with Triton Isis software and processed using CARIS HIPS multibeam processing software. Products included 3D point clouds and digital elevation models (DEMs) used to look for potential cave sites. Data was visualized and explored in IVS Fledermaus as 3D point clouds to aid in the search for and identification of caves. Geotif images of the DEMs in shaded relief colored by depth and in gray scale were created for use during the ROV surveys to assist with navigation and piloting of the ROV.

The Seafloor Mapping Lab also supplied a SeaBotix LBV200L2 ROV equipped with a 250 m umbilical and a depth rating to 200 m. The LBV200L2 has 1-lateral, 2-forward, and 1-vertical thruster, enabling maneuverability in four axes. The small diameter of the fiber optic umbilical presented less drag meaning the vehicle was controlled by the operator, not the umbilical. A fiber optic video system provided high-resolution images over a 270° field of view illuminated by an LED lighting array. The LBV 200 was used to explore sites identified in the preliminary multibeam data as potential cave area. The ROV pilot was able to view the position of both the surface vessel and ROV superimposed on the multibeam image. In addition to the video cameras and acoustic tracking, the ROV's onboard sonar system also aided in locating targeted seafloor features. The ROV flight path and georeferenced video imagery was digitally recorded in real-time for later playback. The flight path, recorded in Hypack software was converted to ArcGIS shapefiles for later display over the multibeam bathymetry imagery.

Results

A multibeam bathymetric survey was carried out in September 2009 and succeeded in mapping the entire rim of the Bermuda Platform between 60 and 200 m water depths, as well as approximately ¾ of the perimeter of the adjacent Challenger Bank (Fig. 1). This mapping project was conducted over a 6-day period during which more than 180 km of the platform

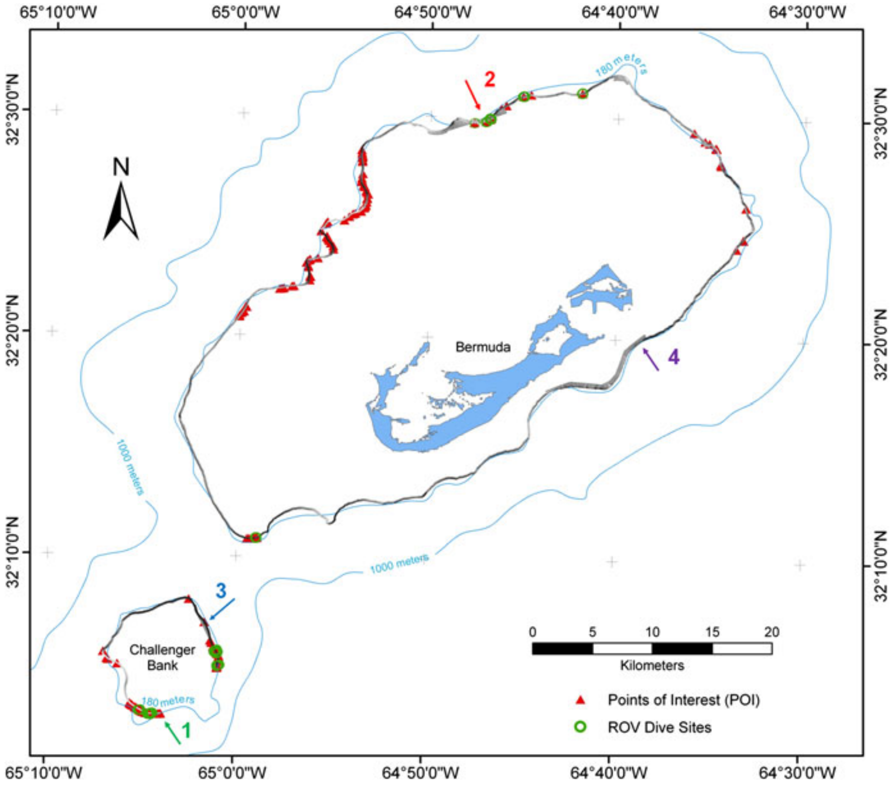

Fig. 1 Multibeam map of the shelf edge of the Bermuda Platform and Challenger Bank overlaid on top of the nautical chart of the island. POI, indicating potential cave entrances, are marked by *triangles*, while ROV dive sites are indicated by *circles*. Contour lines are from current nautical charts. *Arrow #1* denotes the location on Challenger Bank shown in greater detail in Fig. 2. *Arrow #2* shows the location of POI 67 shown in Fig. 3, as well as the sites of detailed topographic maps (Fig. 7) and cross-section profiles (Fig. 8) at North Rock indicating the mapped paleo-shorelines that encircle the Bermuda seamount and Challenger Bank. *Arrow #3* marks the location of the submarine landslide on Challenger Bank shown in Fig. 4. *Arrow #4* indicated the position of detailed topographic maps (Fig. 5) and cross-section profiles (Fig. 6) at Gurnet Rock. Note that the 180 m contour derived from nautical charts varies considerably in some locations from our more precisely mapped position

edge between 60 and 200 m isobaths around Bermuda were surveyed. By overlaying our survey on existing hydrographic charts that had been compiled from point sounds or echo soundings, we observed significant differences in the position for the shelf edge in contrast to earlier and less precise surveys.

The depth range of our survey was selected to extend from the lower terrace, as described by Stanley & Swift (1968), to depths in excess of the low point of Pleistocene sea level. Beneath the lower terrace on the main Bermuda Platform, the slope began to steepen until near-vertical rock walls were encountered at approximately 100 m depths. This vertical rock escarpment continued to depths of 130–150 m where a slope of unconsolidated sediment, lying at its apparent angle of repose began and extended down slope past the maximum depth of our survey.

One of our primary objectives was to locate possible cave entrances which were designated as POIs. A total of 161 POIs were identified, located primarily on the northwest, north, east, and southwest sides of the main platform and on the southern and eastern margins of Challenger Bank (Fig. 1). These consisted primarily of voids within the near-vertical submarine escarpment into which the sonar beam could only partially penetrate. Since the multibeam survey was conducted with our vessel navigating slightly offshore from the drop-off, cross-sectional views through voids allowed us to look part way into them and observe whether the bottom at the base of the void was sloping or level (Fig. 2). The voids followed irregular patterns possibly indicating their origin as wave cut or bioerosion notches incised into the rock face during periods of lower sea level. Water depths

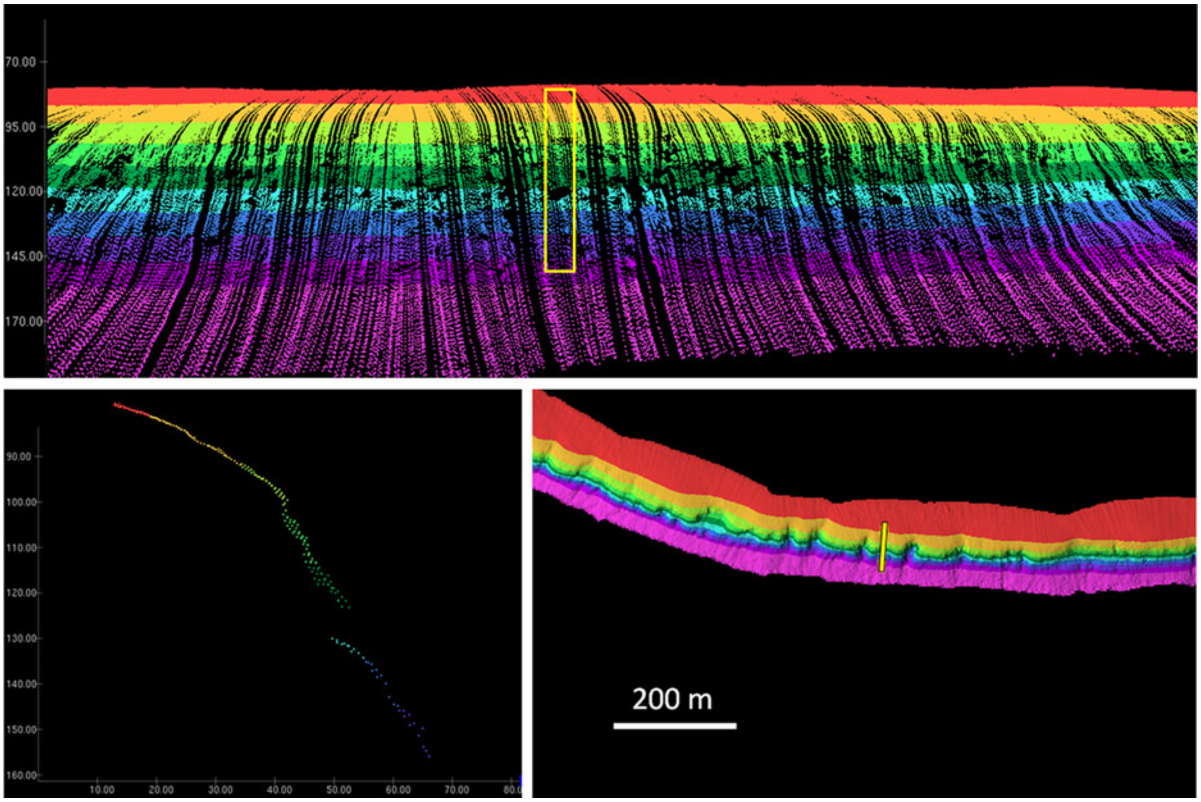

Fig. 2 Challenger Bank as seen in CARIS subset mode showing point cloud data in 3D mode (*top*), profile (*lower left*), and plan views (*lower right*). The *box* and *bar* in the 3D and plan views respectively indicate the location of the profile slice through the bank. Note deeply incised overhang with undercut floor in profile view suggestive of a cave entrance. The profile slice is 2 meters across, and the opening is 7 m tall by 8 m across. Also note numerous "voids" or dark holes without data in the 3D point cloud view of the slope in the *top frame*. Each of these features were inspected, measured, and cataloged as potential candidates for ROV dive targets

for the 161 POIs ranged from 100 to 155 m, with an average of 125.5 m.

The SeaBotix ROV was used to explore 25 POIs on the northern and southwestern sides of the main platform and on the eastern and southern edges of Challenger Bank that had the greatest apparent potential for caves (Fig. 1). The numerous undercuts into the vertical walls ranged from a few to 10 m high and as much as 30 m in length. Most had relatively flat floors covered with white sand and extending back as much as 8–10 m. Seven of the POIs investigated with the ROV including four on southwestern edge of the main platform and three on the eastern side of Challenger Bank were found to have possible caves extending back from them. The caves were relatively small, about a meter or less in diameter, tubular, and smooth walled with little encrusting marine life or other clear evidence of water currents such as sand ripples. These caves were typically found at the base of the undercuts and consisted of small tunnels extending perpendicular to the rock face. Caves on the main platform were found at 107, 112, 116, and 118 m water depths, while those on Challenger Bank were at 119, 123, and 128 m.

Just west of North Rock on the northern edge of the platform, several completely closed depressions, resembling karstic sinkholes were found near the seaward margin of the lower terrace. These were approximately 20–30 m in diameter and 3–5 m deep with steep, sometimes undercut rock walls on all sides and a relatively flat floored bottom. In this same area, a number of sediment floor channels with steeper rock walls and dendritic patterns ran perpendicular to the platform edge. In one of these channels, the multibeam showed two voids that were later investigated with the ROV (Fig. 3). This feature turned out to be a natural

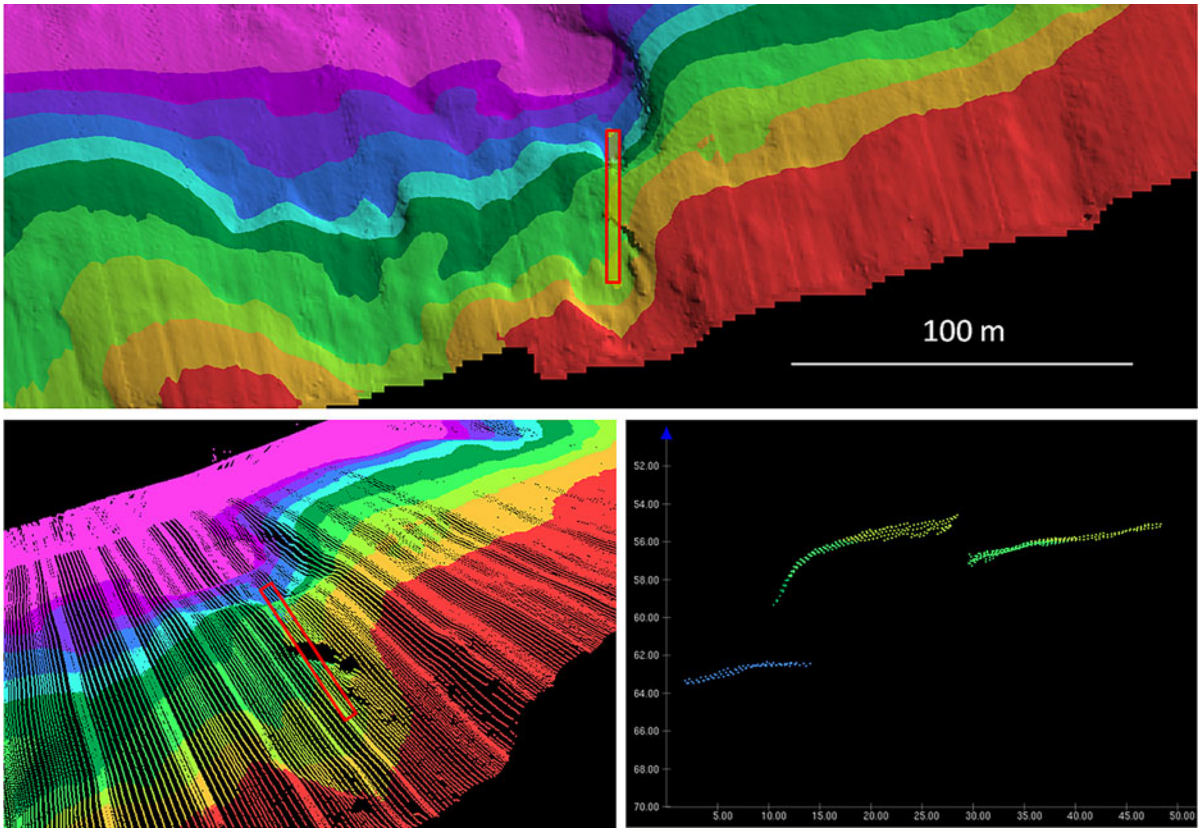

Fig. 3 Multibeam bathymetry data from the natural bridge (POI 67) located on the outer terrace at 64 m depth near North Rock displayed and *shaded* by depth at 2 m depth intervals in CARIS software subset mode. Images of tunnel clockwise from *top left*: (1) Plan view of 1 m gridded surface model in *shaded relief* shows the adjacent sand channel and sinkhole features with the position of the vertical profile referenced below indicated by the *box*, (2) vertical profile slice through the point cloud at the position of the *box* in view #1 showing both the inshore and offshore entrances of the tunnel, (3) down slope view of 3D sounding point cloud showing the upper tunnel entrance with the position of vertical profile indicated by the *box*. *Vertical* and *horizontal scales* are in meters

bridge, possibly a remnant cave structure, about 40 m long and 8 m wide, with a 6 m high tunnel extending between two entrances. Boulders and rubble of apparent collapse origin were present at the landward end of this tunnel, while the seaward entrance was unobstructed. A sand-floored channel extends in both directions from the natural bridge suggesting that this structure represents the last remaining remnant of a much larger cave system that probably carried freshwater runoff to the platform edge at the time when the lower terrace was forming.

Another feature of interest that was discovered during the mapping project were prominent gullies in the near-vertical cliff faces. Along the eastern side of Challenger Bank, a series of serrate gullies, possibly of erosional origin, appeared at regular intervals of about 40 m. These gullies began at about 100 m depths and extend down to the sediment apron at the base of the cliffs. A crescent-shaped scar in the cliff face on the main platform, with associated rubble at its base, appears to be the result of a mass wasting event where slumping of the cliff occurring a lower sea level stand (Fig. 4).

Conclusions

In order to assess evidence of sea level lowstands and geomorphic features of specific interest to this study, the multibeam swath, acquired around the circumference of the Bermuda seamount and covering the water depth range from 60 to 200 m, is being examined in

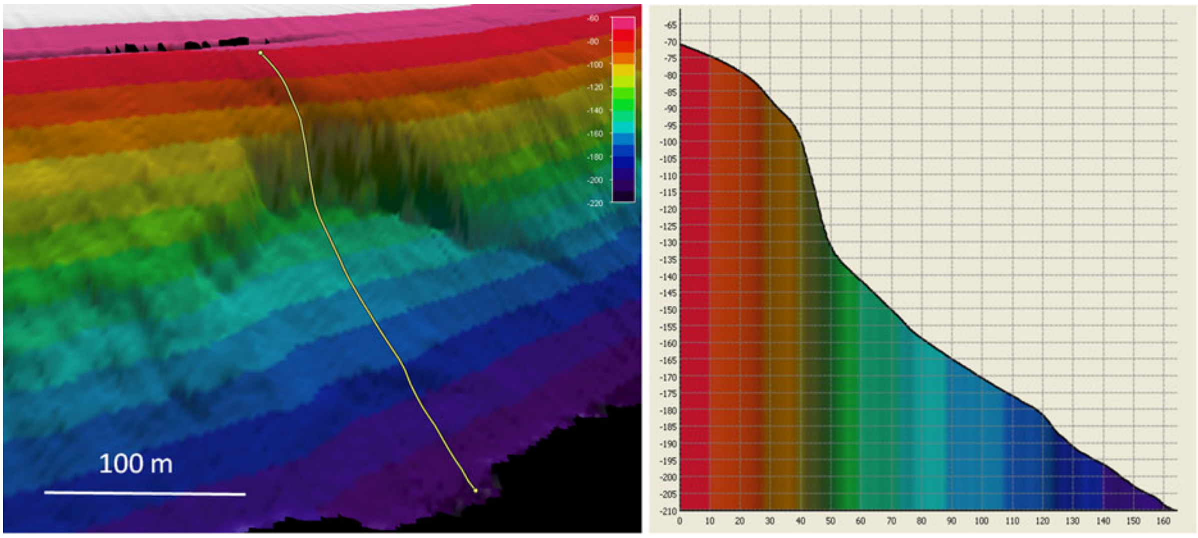

Fig. 4 Multibeam bathymetry data gridded at 2 m cell size of a submarine landslide escarpment discovered on the eastern edge of the Challenger Bank platform rendered in 3D relief, *shaded* by depth (*left*) and in profile (*right*) using IVS Fledermaus software. Position and extent of the profile across the escarpment face is indicated by the *polyline*. All dimensions are in meters

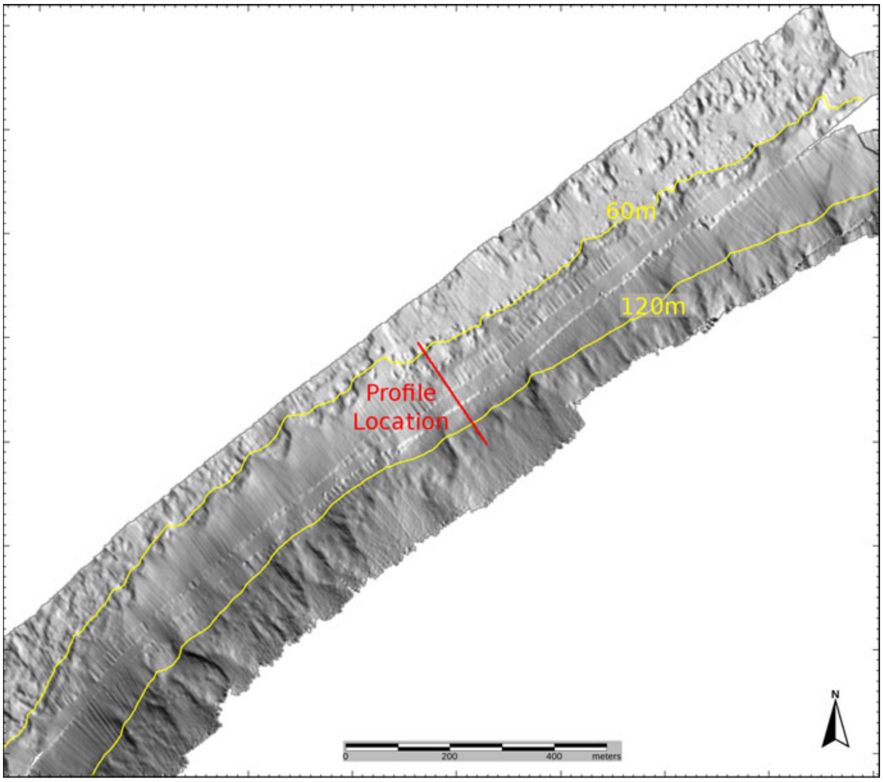

Fig. 5 Multibeam sonar map of the Bermuda shelf illustrating seabed topography on the area south of Gurnet Rock, the 60 and 120 m isobaths and location of cross section profile shown in Fig. 6. Note the distinct change in topography close to the 120 m isobath where wave and current action have not eroded the irregular seabed to more muted topography in water depths <120 m

detail. This water depth range covers the area subjected to sea level changes of 100–130 m over the last 500,000 years (Bintanja et al., 2005). Key evidence of sea level lowstands discovered under this study included two paleo-shoreline features which almost completely encircle the seamount and

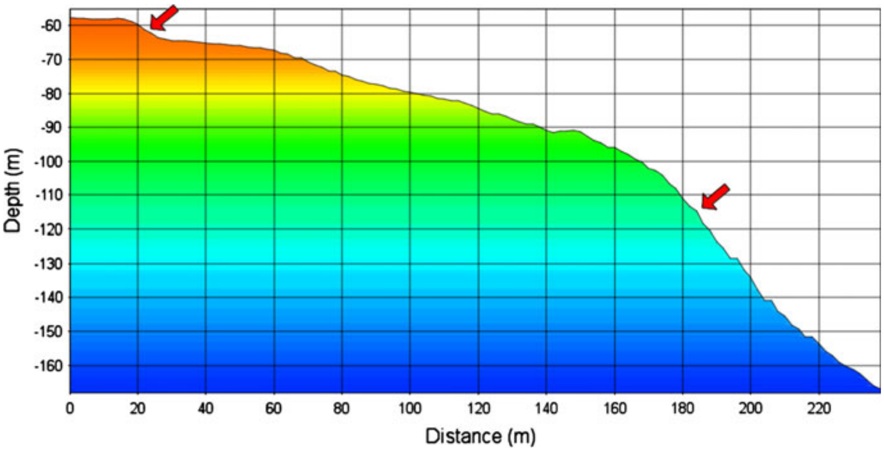

Fig. 6 Cross-section profile of the seabed south of Gurnet Rock from 55 to 170 m water depth. Paleoshoreline features are identified by *arrows* at 60 and 115 m. Other irregularities in the cross section profile may be localized topographic features or acoustic artifacts

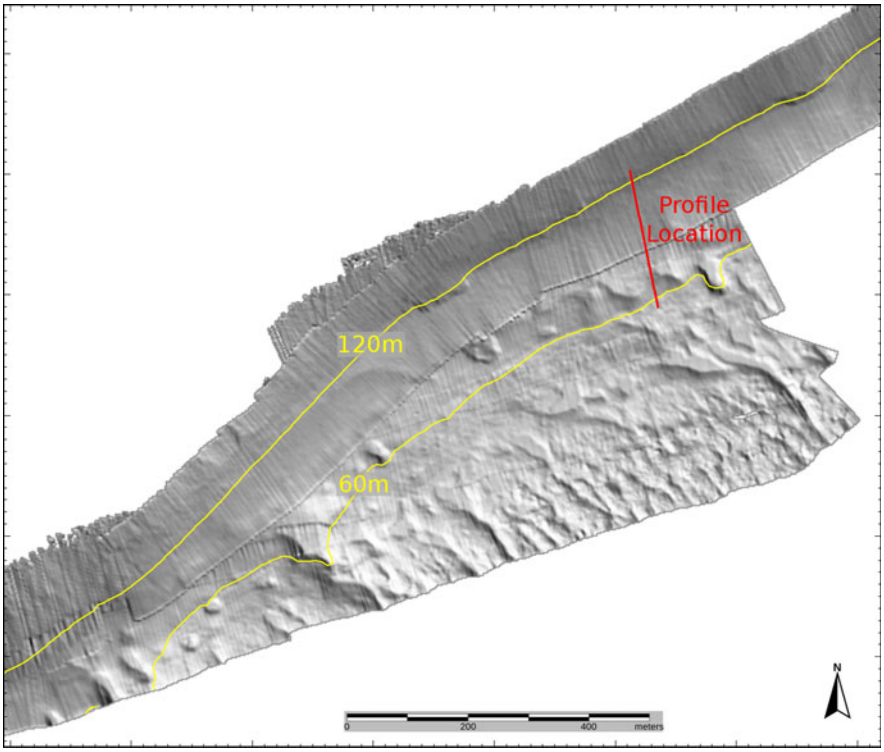

Fig. 7 Multibeam sonar map of the Bermuda shelf illustrating seabed topography on the area north of North Rock, the 60 and 120 m isobaths and location of cross section profile shown in Fig. 8. Note the distinct change in topography close to the 120 m isobath

Challenger Bank at water depths of 60 and 120 m. Seabed topography maps and associated cross section profiles derived from the multibeam sonar data have been generated south of Gurnet Rock (Figs. 5, 6) and north of North Rock (Figs. 7, 8). The paleo-shorelines are clearly defined by laterally continuous low relief ridges and incised benches eroded into relict reef complexes by wave and current action during periods of lower sea level. At the North Rock and Gurnet Rock locations, the bench feature at 60 m water depth is less than 8 m high and the bench feature at 120 m water depth is 10 m high.

Remotely operated vehicle video imagery acquired along these paleo-shoreline features revealed well-worn carbonate rocks, smoothed rock ledges, bedrock undercuts, and bedrock excavations believed to be wave cut caves. These features were most likely generated by the erosive forces of wave and current

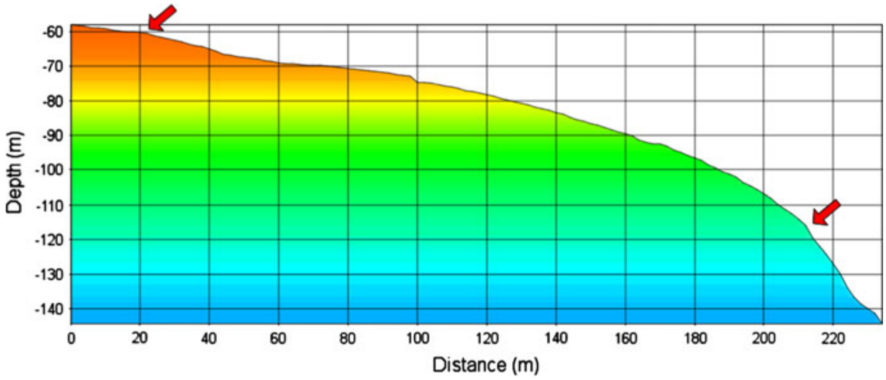

Fig. 8 Cross-section profile of the seabed north of North Rock from 58 to 143 m water depth. Paleoshoreline features are identified by *arrows* at 60 and 115 m. Note smooth seabed topography in water depths >60 m. Other irregularities in the cross section profile may be localized topographic features or acoustic artifacts

action on carbonate rocks over time in a dynamic shallow water coastal environment.

Next steps

These data justify more detailed quantitative analyses to map the topography of the two paleo-shorelines around the Bermuda seamount and Challenger Bank. ROV video imagery will be correlated with the paleo-shoreline features to map the distribution of wave cut caves and bedrock undercuts. Sites will be identified for further geological investigation by ROV and diver operations. Outcrops of reef structures associated with sea level lowstands will be identified and located for future sampling. Samples will be analyzed for composition, correlation with island stratigraphy and age dated where possible.

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