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Cover photo: *Diploria strigosa*, the common brain coral, preserved in growth position at the Cockburn Town fossil coral reef site (Sangamon age) on San Salvador Island. Photo by Al Curran.

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OBSERVATIONS ON THE BIOLOGY AND GEOLOGY OF ANCHIALINE CAVES

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ABSTRACT

Significant biological and geological discoveries have resulted from the use of specialized cave diving techniques for the exploration and study of anchialine caves. Many new and higher taxa of troglobitic organisms have been found, some of which are relic "living fossils". Marine troglobites have at least three possible origins: (1) localized cave colonizations with dispersal by ocean currents, (2) Tethyan origin with dispersal by sea floor spreading and continental drift, and (3) deep sea origin, possibly in association with deep water caves. Geological phenomena of interest in anchialine limestone and volcanic caves include submerged stalactites and stalagmites, cave morphology, mineralogy, and sediments.

INTRODUCTION

Recent diving explorations of inland caves containing marine waters have revealed the presence of a unique environment containing features of special biological and geological significance. Several terms have been introduced or redefined in order to more accurately characterize these caves. The term "anchialine" was originally coined by Holthuis (1973) to describe "pools with no surface connection to the sea, containing salt or brackish water, which fluctuates with the tides". Stock and others (1986) proposed a more exact ecological definition for this term: "bodies of haline waters, usually with a restricted exposure to open air, always with more or less extensive subterranean connections to the sea, and showing noticeable marine and terrestrial influences". Submarine caves are those which are entirely filled with sea water, while littoral or sea caves are shallow erosional features opening at sea level and containing air plus sea water. The term "marine cave" is a broad one referring to all caves containing haline waters of marine origin and thus includes anchialine, submarine, and littoral caves.

METHODS: CAVE DIVING

Specialized cave diving techniques and equipment have been developed for the safe exploration and study of underwater caves (Exley, 1981; Exley and Young, 1982). Unique hazards, quite different from those encountered by divers in open waters, exist in underwater caves. When cave diving, the ceiling restricts access to the surface making a diver much more dependent upon his equipment and its proper function. Should an emergency such as an air failure occur, it is necessary to exit the cave the same way it was entered - out and then up. A basic premise of cave diving is that any piece of equipment can fail, so that redundancy is the key to safe cave diving. Typically, cave divers use double tanks connected with a dual valve manifold, two independent regulators - one for each tank valve, submersible tank pressure gauge, buoyancy compensator with automatic inflator, minimum of three underwater lights of which one must be of a minimum of 30 watts and have a burn time of at least 50 minutes, nylon guideline on reel, watch, depth gauge, decompression tables, and knife.

Special safety precautions are also required in cave diving. It is necessary to reserve at least 2/3 of the starting air supply for the swim out of the cave. A single continuous guideline must be run from the entrance of the cave throughout the route followed on the dive. Stirring up of fine bottom silt, which can reduce underwater visibility to zero, should be avoided by proper use of the buoyancy compensator and by special swimming techniques. A course in cave diving provides the opportunity for practice and development of these essential diving skills. All cave diving done under this study has met standards set by the Cave Diving Section of the U.S. National Speleological Society.

ANCHIALINE CAVES

Anchialine caves occur in both limestone and volcanic rocks. Extensive anchialine limestone caves found in Bermuda, the Bahamas, and other locations were probably formed during Pleistocene low sea stands as evidenced by their general morphology and abundant submerged speleothems (i.e. stalactites and stalagmites). The longest such anchialine cave is the 10 km long Lucayan Caverns on Grand Bahama Island. Lava tubes which extend below sea level can also be classified as anchialine. The Jameos del Agua lava cave on Lanzarote in the Canary Islands is the 2 km long, seaward-most segment of the tube that is partially or totally flooded with sea water. Other anchialine lava tubes are present in the Hawaiian Islands as well.

ANCHIALINE CAVE FAUNA

A rich and diverse endemic fauna has been found to inhabit anchialine caves. These include many relic taxa such as Remipedia, a new class of Crustacea (Yager, 1981); Mictacea, a new order of peracarid Crustacea (Bowman and Iliffe, 1985); Platycopioida, a new order of Copepoda (Fosshagen and Iliffe, 1985); Atlantasellidae, a new family of Isopoda (Sket, 1980); and Deeveyinae, a new subfamily of halocyprid Ostracoda (Kornicker and Iliffe, 1985). Over 200 species of marine macro invertebrates have been collected from Bermuda's anchialine caves, one-third of which are new (Sket and Iliffe, 1981; Iliffe and others, 1983).

The biogeography of anchialine faunas shows many striking anomalies. Remipedia, for example, is known only from limestone caves in the Bahamas and the Jameos del Agua volcanic cave in the Canary Islands (Iliffe and others, 1984). Other troglobitic taxa including the mysid *Heteromysoides*, the anthurid isopod *Curassanthura*, and the thermosbaenacean *Halosbaena* show similar amphi-Atlantic distributions. The amphipod *Pseudoniphargus* is primarily known from groundwaters and caves in the Mediterranean region and the Azores, but two troglobitic species from this genus are present in Bermuda (Fig. 1a). These distributions have been interpreted as implying a cave colonization early in the history of the Atlantic followed by dispersal by sea floor spreading and plate tectonics.

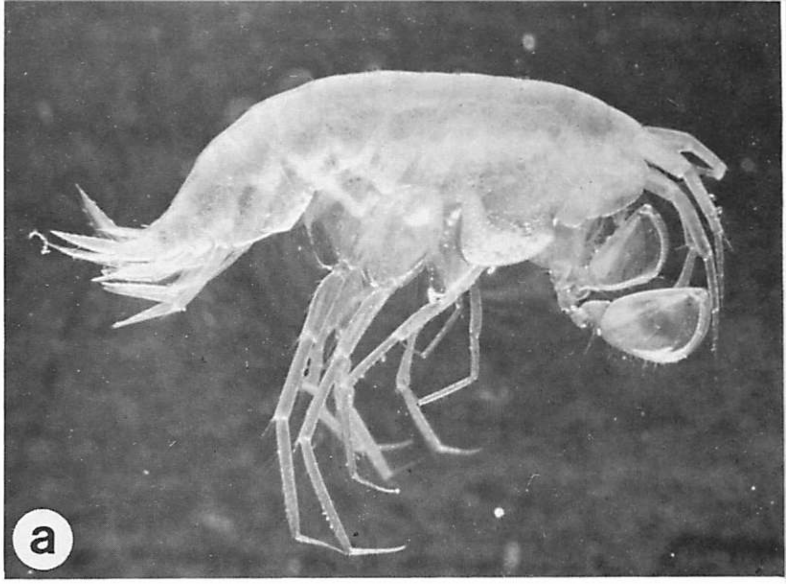
Some taxa show even more complex biogeographic relationships. The shrimp *Procaris* is known only from caves and anchialine pools on Bermuda, Ascension Island, and Hawaii. Equally puzzling is a new genus of misophrioid copepods which has new species from caves in Palau and the Canary Islands on opposite sides of the world.

Examination of the fauna from Bermuda and Lanzarote caves indicates that several derivations are likely (Iliffe and others, 1983; Iliffe and others, 1984). Those species such as Remipedia and Mictacea (Fig. 1b) which represent relic "living fossil" taxa appear to have had a Tethyan origin. Species, including the shrimp *Barbouria cubensis* which is known from Cuba, the Bahamas, and Bermuda, may have had a localized origin in caves and been subsequently dispersed by ocean currents. Still other species from anchialine caves are closely related to deep sea forms and may have originated by dispersal from this habitat. Such deep sea related cave forms include the galatheid crab *Munidopsis polymorpha* (Fig. 1c); the polynoid polychaetes *Gesiella jameensis* and *Pelagomacellicephala iliffei*; the halocyprid ostracods *Danielopolina orghidani*, *D. wilkensi*, and *Deeveya spiralis*; the amphipods *Spelaeonicippe buchi* and *S. provo*; and six species of misophrioid copepods.

In order to explain both the puzzling biogeographic distributions and the deep sea affinities of the anchialine cave fauna, Hart and others (1985) have proposed the existence of systems of caves and crevices on the steep sides of submerged sea mounts and along mid-ocean ridges in the deep sea. Such "crevicular" habitats could provide a virtual continuum linking caves on distant oceanic islands via the deep sea.

There is already substantial evidence for the existence of extensive caves in the deep sea. Keating (1985) reports on the discovery of two large, hydrologically active limestone caves containing stalactites and stalagmites at a depth of 366 m on Johnston Island. 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. Fornari and others (1985) have found a lava tube of recent origin together with numerous fissures at the

Fig. 1a. The amphipod *Pseudoniphargus grandimanus* (length about 7 mm) from Bermuda caves belongs to a genus previously known only from caves and groundwaters in the Mediterranean region, the Azores and Madeira.



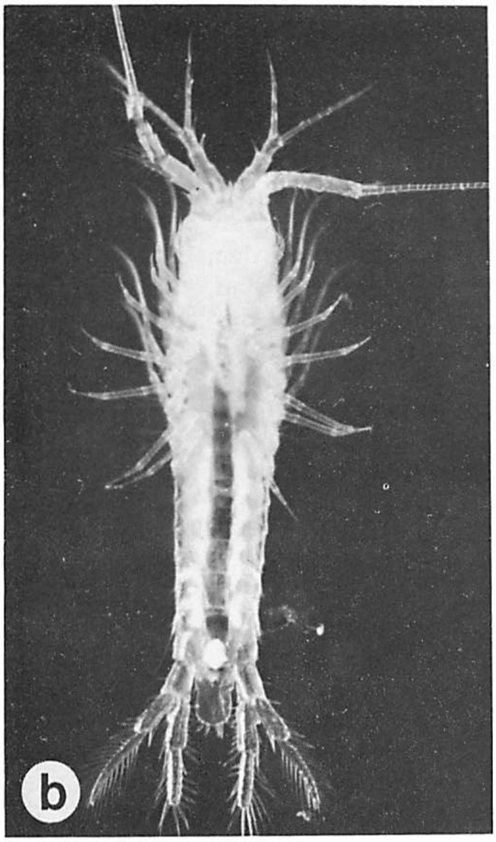


Fig. 1b. *Mictocaris halope* (length about 3 mm) from Bermuda caves is a member of the new peracarid crustacean order Mictacea whose only other representative was described from the deep sea.

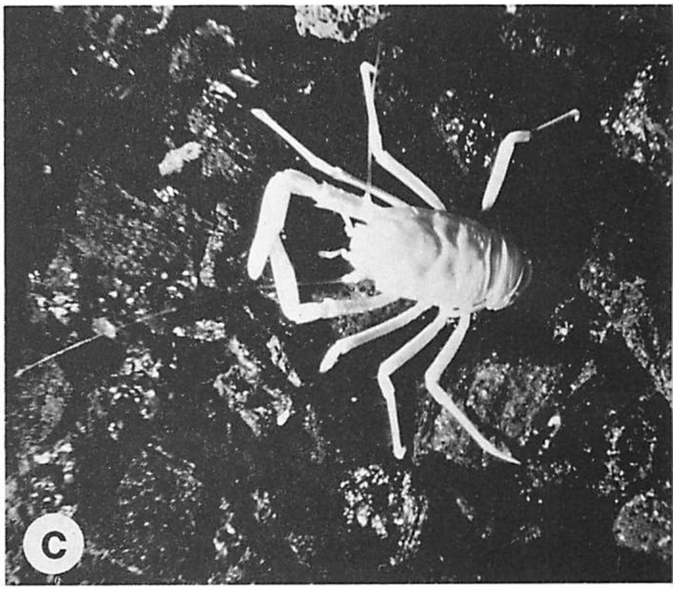


Fig. 1c. *Munidopsis polymorpha* (length up to 4 cm) from a lava tube in the Canary Islands is a member of the Galatheidae, most species of which inhabit the deep sea.

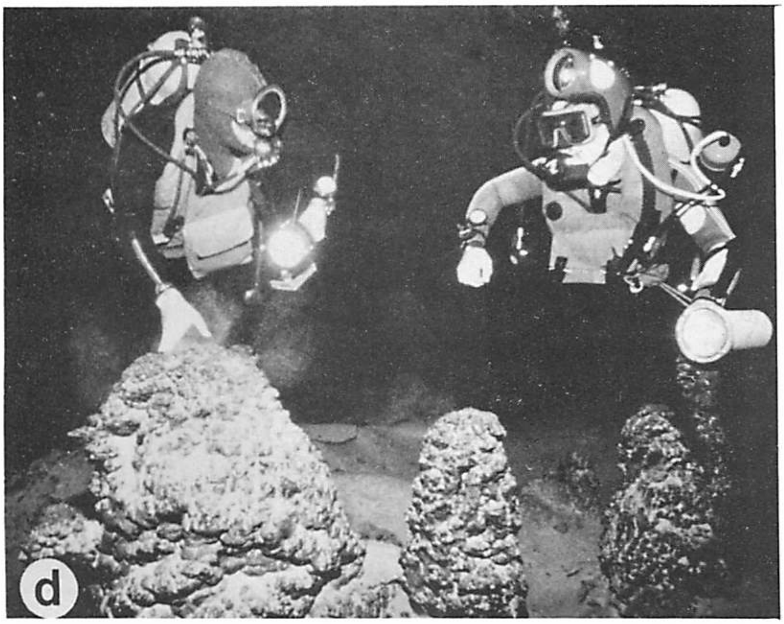


Fig. 1d. Submerged stalagmites (Deep Blue Cave, Bermuda) form only in air and were deposited during Pleistocene low sea level stands when the caves were dry.

base of a seamount in 2700 m water depths on the East Pacific Rise. Fornari (pers. comm.) believes that lava tubes are a common feature in the deep sea and are important in lava dispersal around sea floor extrusive sites. Carew and Mylroie (1984) have found solution conduits on the sides on San Salvador Island in the Bahamas at 105 to 125 m depths, near the probable low point for Pleistocene sea level.

GEOLOGICAL OBSERVATIONS

The development of specialized cave diving techniques and equipment has provided a means to gain access to extensive and geologically unique, totally submerged cave systems. During the course of current biological studies of anchialine caves, several significant geological phenomena have been noted.

Submerged stalactites and stalagmites, which can form only in air, are common features of anchialine limestone caves (Fig. 1d). These have been observed in all sections of Bermuda's caves to depths of 24 m. Underwater speleothems have been noted from a Blue Hole in Belize at depths to 122 m (Dill, 1977). Despite their long immersion, delicate helectites and "soda straw" stalactites in the fully marine waters of Bermuda's caves show no evidence of resolution. However, speleothems close to the fresh water lens in Bahamian caves are often pitted and crumbling.

Isotopic analyses of submerged speleothems can provide insights into sea level fluctuations and paleo climates. Thorium-uranium dating of speleothems can be used to document periods of lowered sea level and can thus be used for generating paleo sea level curves (Harmon and others, 1978, 1981). In addition, estimates of paleo temperatures can be made from stable oxygen isotope ratios of fluid inclusions in speleothems (Schwarcz and others, 1976).

Exploration and mapping of anchialine caves has revealed previously unsuspected morphological features. In contrast to the limited extent, predominant collapse chambers and fissures entrances of Bermuda's dry caves, the 2 km long and totally underwater Green Bay Cave System (Fig. 2) consists of nearly level, anastomosing passages, probably of vadose origin, reaching across a narrow peninsula of land from the almost completely enclosed Harrington Sound to the more open North Lagoon (Fig. 3a). The average depth of this cave, -18 m, corresponds to that of Bermuda's main reef terrace and to the maximum depth of the North Lagoon suggesting that all three features were formed by a long stationary stand of sea level at this position. Indeed, undercut walls at sharp bends in the passage and a continuous channel along the silt floor of the cave indicate vadose stream flow through the cave at some time in the past.

An as yet hypothetical deeper system of caves may exist in Bermuda at the interface between the island's volcanic pedestal and the overlying eolian limestone about 30 m below present sea level. Such caves could have formed during Pleistocene low sea stands by vadose groundwaters flowing along the top of the impermeable basalts toward the sea. Several lines of evidence point to the existence of such deeper caves in Bermuda. Cave divers have reached breakdown chokes at depths of 24 m indicating that deeper levels must have existed at some time in the past. During a drilling operation in Government Quarry, a large cave was encountered at a depth of 18 m which continued until volcanic flows were recovered from -33 m (Peckenham, 1981). A funnel shaped depression about 2 m in diameter in the sand floor of Tucker's Town Cave at a depth of 20 m suggests the presence of a lower level to the cave into which the sand is disappearing (Fig. 3b).

Cave sediments are generally a fine grained silt. The origin and rate of deposition of sediments in anchialine caves is still in question. Although moderate to strong tidal currents transporting exogenous particles into the cave are present along coastlines, caves farther inland lack noticeable currents and have waters devoid of suspended particulates. Sediments in a few caves contrast sharply with the norm. Tucker's Town Cave in Bermuda contains a 60 m long underwater chamber floored with sand probably derived from the nearby South Shore beaches. Despite the lack of noticeable currents in this cave, ripple marks are evident on the sand surface (Fig. 3b).

Other unusual features have been noted in underwater caves. A horizontal white "bathtub ring" is present on the walls at a depth of 14 m in only one section of the Green Bay Cave, Bermuda (Fig. 3c). This

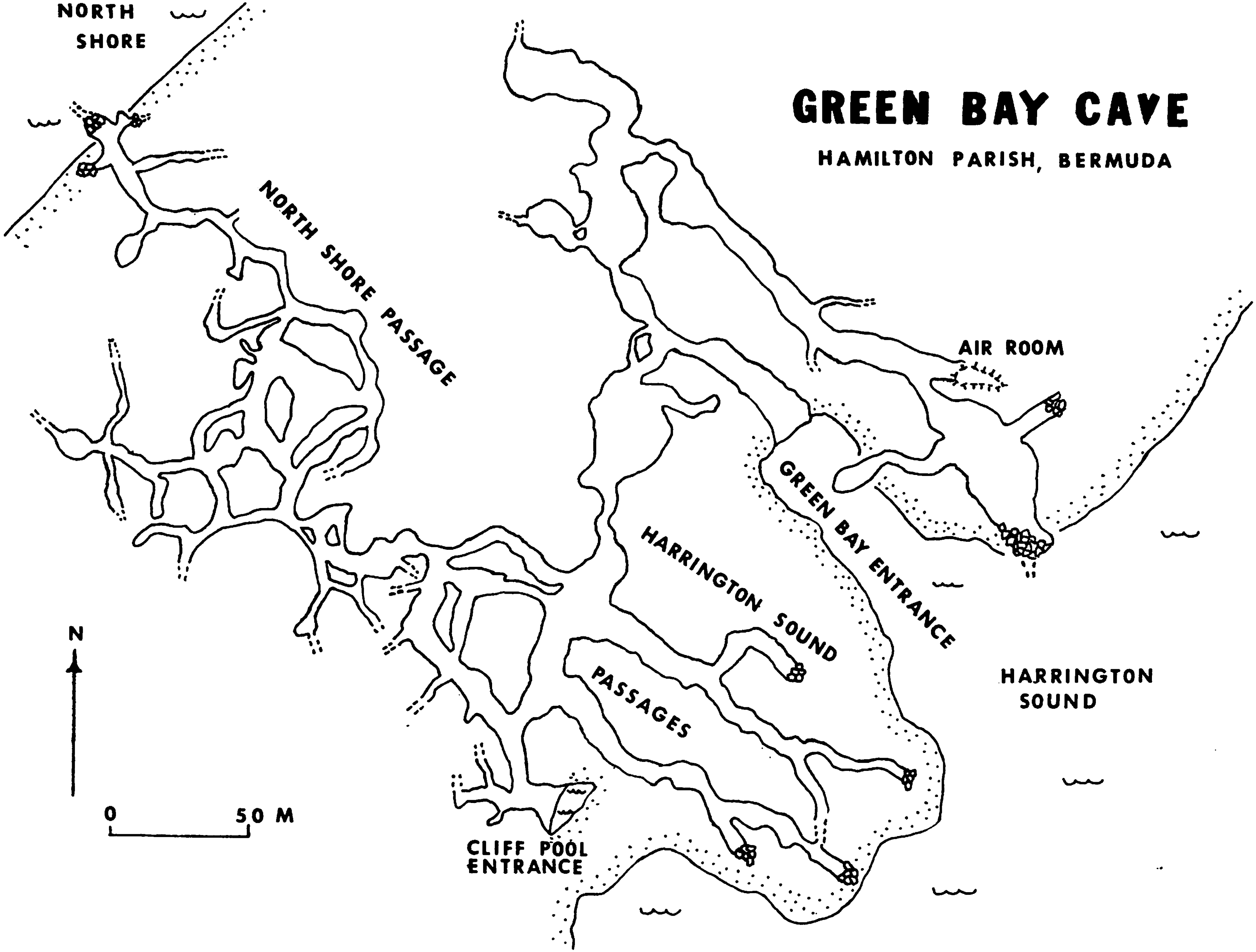


Fig. 2. Map of Green Bay Cave, Bermuda. Total explored passage length, 2287 m. Surveyed by members of the Bermuda Cave Diving Association; sketched by Robert Power, August 1986.

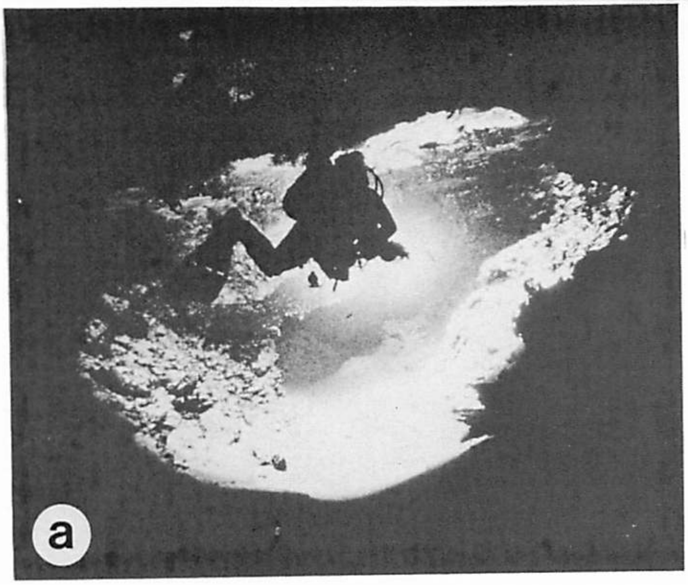


Fig. 3a. Silhouette of a diver in the North Shore Passage (Green Bay Cave, Bermuda), a long, nearly level, anastomosing passage at 18 m depth, probably of vadose origin.

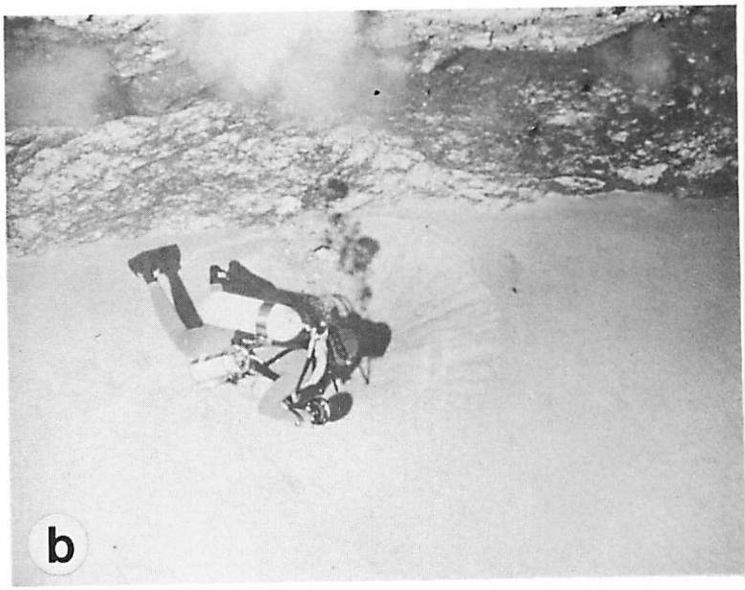


Fig. 3b. Funnel-shaped depression (below diver) at 20 m depth in Tucker's Town Cave, Bermuda was probably formed by sand dropping through a small hole into a deep cave. Note sand ripples in lower left corner.

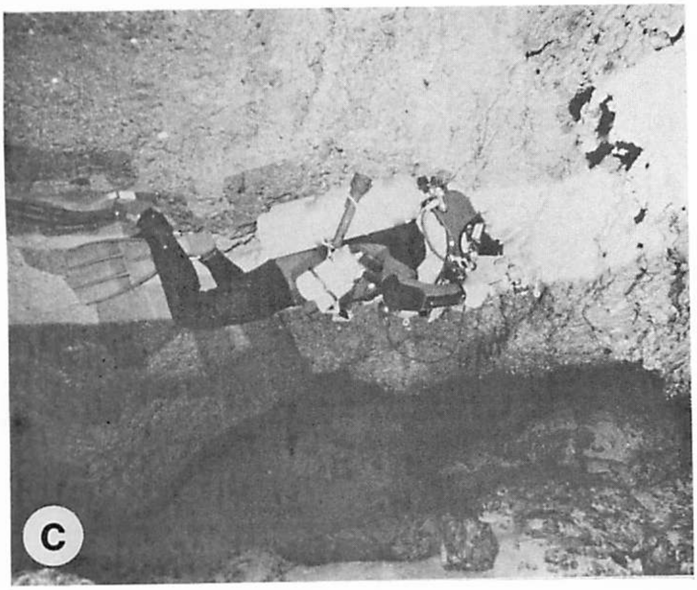


Fig. 3c. White "bathtub ring" at 13 m depth in the Harrington Sound Passage (Green Bay Cave, Bermuda) may be evidence of a paleo fresh water lens.

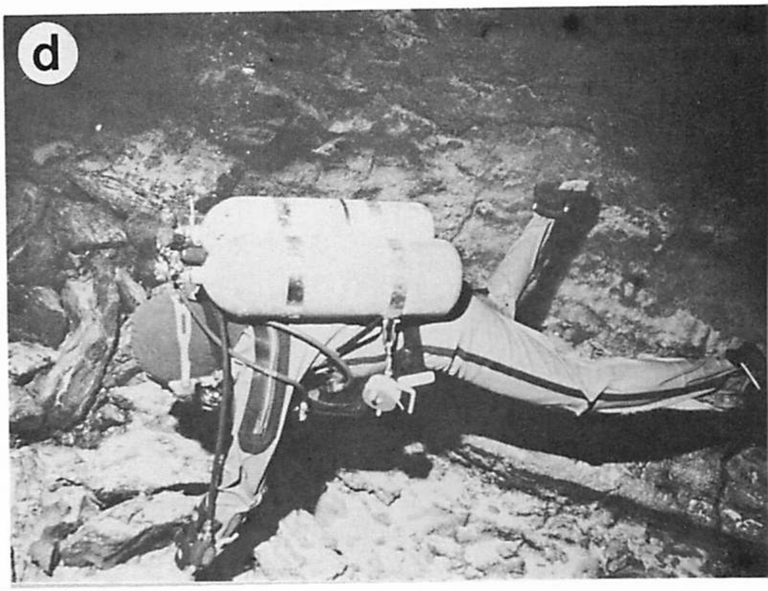


Fig. 3d. White lithified carbonate crusts on dark basalts in the Jameos del Agua lava tube (Lanzarote, Canary Islands) may be a submarine cement.

approximately half meter wide band appears to be the result of bleaching, possibly by a paleo fresh water lens, of the normally darker brown wall coating on exposed bedrock.

Anchialine lava tube caves also provide interesting subjects for study. Several of these caves are of apparently recent origin and thus were probably formed underwater. The sea water flooded sections of the caves both compare and contrast with terrestrial tubes. Both may be of comparable size and configuration and share the presence of lateral benches, lava stalactites and floors of solidified lava or breakdown. However, a lithified white carbonate crust, possibly a submarine cement, is common in underwater sections of the Jameos del Agua lava tube (Fig. 3d), but not in the terrestrial sections of the same cave.

As diving investigations of marine caves progress, further biological and geological discoveries will surely result. Caves in vast areas of the Indo-Pacific are just now beginning to be explored and studied. New equipment and techniques, such as ultra high pressure diving tanks and underwater scooters, are permitting farther and deeper penetrations into underwater caves. The use of submersibles and remotely operated vehicles (ROV) may provide a means of investigating even those caves in the deep sea.

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