

Organic Pollution of an Inland Marine Cave from Bermuda

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ABSTRACT

Inland marine caves have served as biological refugia and, as such, frequently contain unique assemblages of taxonomically significant relict populations known only from a single cave or cave system. However, the absence of photosynthesis in this totally lightless environment and the presence of a highly stratified water column and long residence times for cave waters, characteristically result in depleted dissolved oxygen levels. Under such circumstances, organic pollution, even at low levels, can produce anoxic conditions and may consequently result in the extinction of entire species of cavernicolous fauna. We here present data on the normal environment of marine caves in Bermuda and cite as an example a cave which has become grossly polluted as a result of indiscriminate dumping.

INTRODUCTION

Marine caves have recently been recognized as a new type of habitat within the marine environment. On many islands in the Western Atlantic, extensive inland cave systems containing marine or brackish waters have

been discovered and explored. The world's longest underwater cave is the 10 km long, totally submerged, Lucayan Caverns on Grand Bahama Island (Dennis Williams, pers. comm.). Such caves have been found to contain unexpectedly rich and diverse biological communities. In Bermuda, for example, over 100 species of marine macroinvertebrates have been collected from inland caves (Sket & Iliffe, 1980). Of these, at least 35 represent new species, so far only known from this habitat. A number of the new species are relics of formerly widely distributed groups that have since become extinct, or at least considerably reduced in range (Iliffe *et al.*, 1983). Examples of such relics include Atlantasellidae, a new family of Isopoda from Bermuda's marine caves, whose nearest related families live solely in fresh waters (Sket, 1979); Remipedia, a new class of Crustacea, found only in marine caves from the Bahamas (Yager, 1981); and a new order of Peracarida which has representatives in the deep sea, as well as in Bermuda's caves (T. Bowman & H. Sanders, pers. comm.). Thus, marine caves are important biological habitats and yet are vulnerable owing to their rarity and limited geographical distribution.

Tidal currents passing through these inland marine caves serve to transport food and organic matter from outside waters to the cave interior. However, because many of the caves are extensive and subject merely to oscillating tidal flow, little net exchange of water to the farther inland caves occurs. As these cave systems are highly integrated, many seemingly geographically isolated caves are connected by submarine passageways (Iliffe, 1981). With tidal currents acting as a dispersing mechanism, material introduced into one cave can thus be transmitted over large distances through cave waters, but only very slowly be purged from the system. Several instances of serious pollution of caves in Bermuda have been discussed by Iliffe (1979). We here describe the essential marine chemistry of Bermuda's caves and cite an example of a pollution source in one Bermuda cave pool which has spread to adversely affect caves in a large area.

MATERIALS AND METHODS

Location of study site

Government Quarry Cave is situated on an isthmus between the inshore basins of Harrington Sound and Castle Harbour (Fig. 1). The cave is

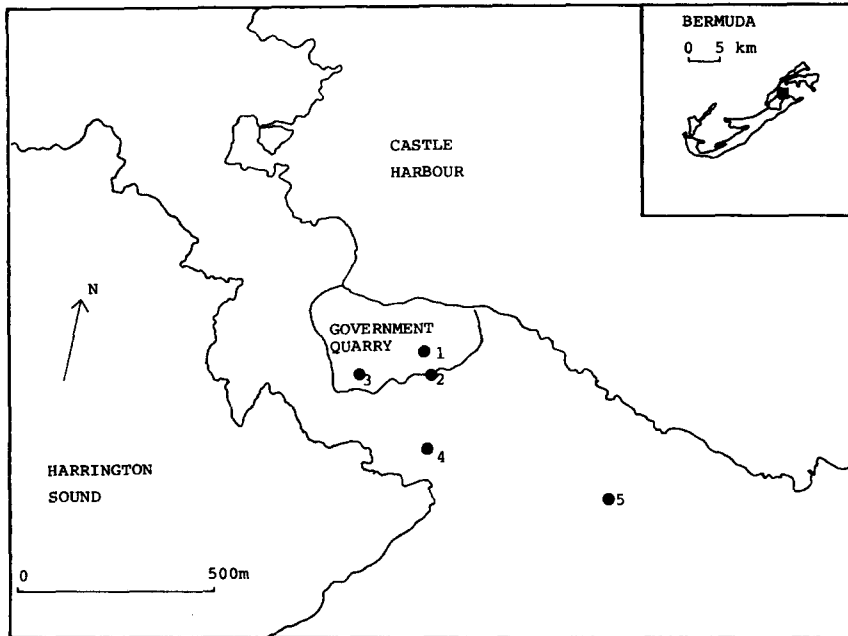


Fig. 1. Map of a section of Hamilton and St. George's Parishes, Bermuda, showing the locations of: 1, Government Quarry; 2, Horseshoe; 3, Shop; 4, Staff Quarters; and 5, Church, Caves.

developed in the Walsingham limestone, a highly altered, Pleistocene eolianite. The air-filled portion of the cave is a roughly circular chamber floored with considerable natural collapse. The cave has three entrances located along a section of cliff face in an active limestone quarry (Fig. 2). The entrances on either end open immediately over deep pools, while the centre entrance provides access to the main chamber. Divers have penetrated horizontally approximately 100 m from the easternmost pool, reaching depths of 23 m. The underwater cave consists of a complex system of only partially explored vertical fissures and collapse rooms overlain with dripstone. While drilling about 200 m away from the Government Quarry Cave, Peckenham (1981) broke into a large cavern at a depth of 18 m; the bottom of the cavern was reached at a depth of 30 m and basalt was recovered starting at a depth of 33 m. This and other evidence indicates that major caves in Bermuda may have been formed by solution at the limestone-basalt interface and extended upwards by subsequent collapse.

Other caves in the immediate quarry area include Shop and Horseshoe Caves, while Staff Quarters Cave is located about 250 m to the south in the grounds of the Castle Harbour Hotel (Fig. 1).

Church Cave, a large and relatively unspoiled cave, was chosen as a control site. It is also situated at the Castle Harbour Hotel, but located over 500 m away from the quarry. The main entrance is about 26 m above sea level and consists of an opening 25 m wide by 15 m high in a collapse



Fig. 2. Photograph of Government Quarry Cave taken in about 1979. The piles of rubbish seen in the left foreground were later bulldozed into the cave entrance pool indicated by the arrow.

sink 25 m in diameter. Inside this entrance, a steep breakdown slope descends to a sea level lake 35 m wide by 35 m across, the largest such cave lake in Bermuda. The tides in this lake have an average range of 40% that of the open sea and a lag time of about 107 min.

In 1980, quarrying was resumed in the immediate area of Government Quarry Cave after a period of inactivity lasting approximately 15 years. Several large piles of partially burned domestic wastes and scrap materials were bulldozed into the western cave pool in an effort to fill it in, prior to

quarrying the rock overlying the cave. In this manner, the pool was partially filled, but some open water still remained. Shortly after the debris was pushed into the western pool, sub-surface water samples from this and other nearby pools in Shop, Horseshoe and Staff Quarters Caves gave off a strong hydrogen sulphide odour. We therefore instituted a water sampling programme to assess the damage done to the caves in this area of Bermuda.

Sample collection

Water samples from cave pools were collected by divers using a Niskin bottle. Samples were collected from progressively greater depths so that each sample was of undisturbed water. Because of the irregular depth contours of the caves, some of the deeper samples were taken from underneath rock overhangs at short penetrations back into the underwater cave.

Chemical analyses

Samples for nutrient analyses were filtered within a few hours of collection and then frozen prior to analysis. Temperatures were measured *in situ* with mercury thermometers. Salinities were determined on a Plessey 6230 salinometer. Nitrate, nitrite, ammonia, phosphate and silicate were determined by standard colorimetric methods (Strickland & Parsons, 1972). Oxygen and hydrogen sulphide were determined by standard titrimetric procedures (Strickland & Parsons, 1972), the oxygen samples being 'fixed' on site, while those for hydrogen sulphide were sealed in airtight bottles under water for a few hours prior to analysis. Trace metal samples were analysed unfiltered after acidification to pH 2.2 so that the results represent total leachable metal at that pH. Preconcentration and analysis were by solvent extraction and graphite furnace atomic absorption spectroscopy (Jickells and Knap, in press).

The rate of microbial consumption of oxygen in the water column was measured by the BOD technique (Golterman, 1970), water samples being incubated in duplicate in the dark for 4 days at 20°C after dilution, where necessary, with water of similar salinity (± 5 ppt made by mixing deionised water with clean seawater). Final results were corrected for dilution, blanks arising from the dilution water and chemical oxidation of hydrogen sulphide.

RESULTS

A number of cave pools and submerged cave systems were sampled during this study. These caves have been divided into two classes based upon the presence or absence of the effects of gross pollution in the cave waters. Caves such as Church Cave, which are typical of the majority of Bermuda's caves, show no evidence of gross local pollution and are here referred to as the normal cave environment. Conversely, caves such as the Government Quarry Cave, which have been the site of dumping activities, are here referred to as polluted caves. A summary comparing measured physical and chemical parameters from the surface and deeper (> 1–2 m) waters of these two classes of cave, in addition to similar values for groundwater and Bermuda's inshore waters, is presented in Table 1. We also present a direct comparison of these parameters in water column profiles from Church and Government Quarry Caves (Fig. 3).

Normal cave environment: Church Cave

Salinity and temperature

Freshwater inputs occur at the surface of the cave pools either from soil percolation or lateral transport of fresh groundwater which occurs as a lens in younger, less porous, limestones (Plummer *et al.*, 1976). Greatly reduced vertical mixing, owing to the absence of wind or wave effects on the cave pools, has resulted in the development of a highly stratified water column. Most far inland cave pools contain a thin (< 1 m) brackish layer which varies in salinity from 0 to 25 ppt, depending on the size of the freshwater input and the degree of water perturbation. This perturbation is primarily due to tidal currents which generally become more diffuse with increasing distance from the sea. The surface layer is underlain by a sharp halocline, beneath which salinities increase slowly with depth to values close to those found in the surrounding Bermuda inshore waters (> 35 ppt).

Water temperatures show similar steep gradients with depth. Temperatures are lowest at the surface, increase markedly through the halocline and then more gradually with increasing depth. Iliffe *et al.* (1983) have suggested that natural geothermal heat flow may account for temperature increases below the halocline. In addition, there are seasonal temperature variations but these are minor in comparison with those in open waters.

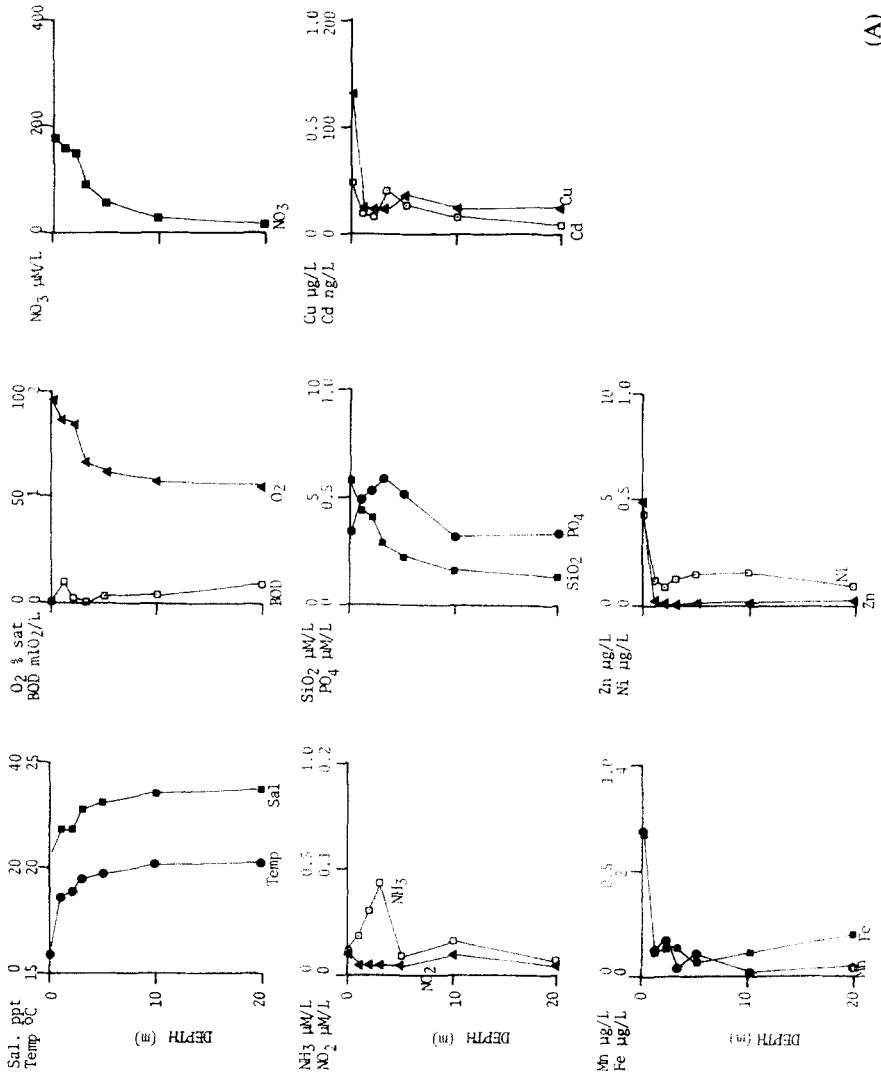
TABLE 1
 (a) The Salinities and Nutrient Concentrations in Cave Waters, Groundwaters and Associated Coastal Waters of Bermuda

Location	Salinity (ppt)	$\mu\text{M/litre}$						Number of samples	Reference
		NO_3	NO_2	NH_3	PO_4	SiO_2			
Normal caves, surface waters	4-36	5-600	0.01-0.16	0.10-0.59	0.05-1.5	2.0-31.8	10	f	
Normal caves, sub-surface waters	21.5-35.4	14-242	0.01-0.02	0.06-0.45	0.31-0.7	1.3-20.9	10	f	
Polluted caves, surface waters	5.3-7.1	82-477	0.04-0.35	0.03-0.71	0.30-4.03	19.7-45.5	6	f	
Polluted caves, sub-surface waters	12-35.7	0.3-52.5	0.01-1.97	0.24-56.5	0.41-8.68	2.5-35	12	f	
Bermuda inshore waters	36.2-36.5	0.06-1.08	0.03-0.10	0.20-0.60	0.02-0.04	0.95-2.29		a,b	
Bermuda groundwater	—	2.5-2300	0.3-4.4	0.1-9	0.1-7.4	21-216		c,d	

(b) The Concentrations of Trace Metals in Cave Waters, Groundwaters and Associated Coastal Waters of Bermuda

Location	$\mu\text{g/litre}$						Number of samples	Reference
	Cd (ng/litre)	Cu	Fe	Mn	Ni	Zn		
Normal caves, surface waters	3-139	0.39-1.23	0.9-14.5	0.02-0.68	0.13-0.45	0.2-6.5	6	f
Normal caves, sub-surface waters	8-40	0.11-0.17	0.36-0.83	0.01-0.17	0.08-0.16	0.01-0.17	6	f
Polluted caves, surface waters	20-142	0.34-2.9	1.1-240	0.4-12	0.16-0.79	1.4-20	6	f
Polluted caves, sub-surface waters	6-104	0.05-1.56	26-630	2-500	0.26-1.6	0.44-22.4	7	f
Bermuda inshore waters	4-13	0.2-1.7	1.1-6.1	0.19-1.36	0.14-0.23	0.29-2.5		b
Bermuda groundwater	18-340	0.15-6.9	1-130	0.6-28	0.01-2.4	0.05-10		d,e

References: (a) Bodungen *et al.*, 1982; (b) Jickells & Knap, in press; (c) Morris *et al.*, 1977; (d) Simmons, 1983; (e) T. D. Jickells, unpublished data; (f) this study.



(A)

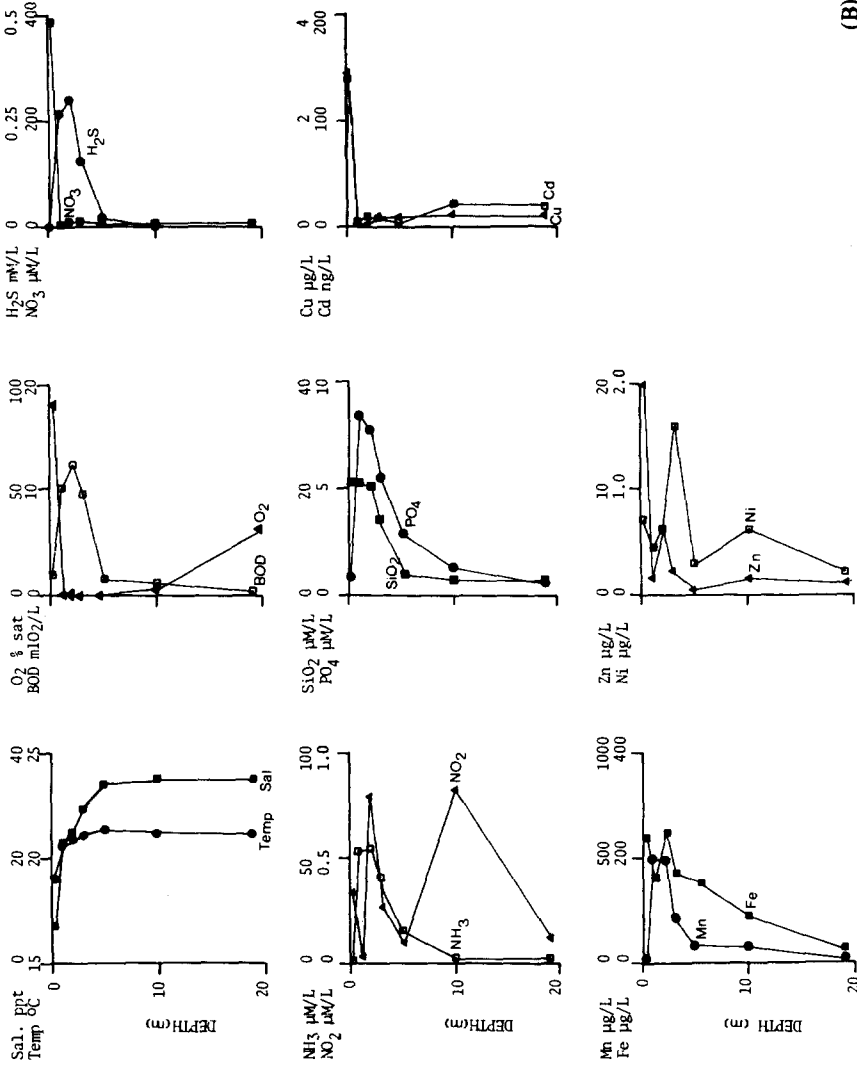


Fig. 3. Water column profiles for various physical and chemical parameters in (A) a normal cave environment (Church Cave) and (B) a polluted (Government Quarry) cave environment.

Biology

The cavernicolous fauna of most far inland cave pools live primarily below the halocline. This deeper water has characteristics of both the deep ocean (total darkness, low turbidity and little water movement) and estuaries (sharp salinity gradients). Population densities are very low as a result of the low organic input. Generally only those organisms specifically adapted for the cave environment are able to survive.

Residence times

Calculations of water residence times in caves are approximate because of uncertainties in our estimates of mixing rates and cave volumes. In Church Cave, we estimate the maximum depth to be 30 m (the depth of the underlying basalt) and have determined the average tidal height to be 40 cm. Assuming complete mixing during each tidal cycle, the residence time would be 37.5 days ($30 \text{ m} \times \text{one tidal cycle} / 0.4 \text{ m} \times 1 \text{ day/two tidal cycles}$). However, it is clearly unrealistic to assume complete mixing. Barnes & Bodungen (1978) determined that results based on this assumption underestimated residence times by a factor of 4 for Bermuda's inshore waters. For the caves, this underestimate may be at least twice that for the inshore waters since wind- and wave-induced mixing is absent in caves. Making these corrections, residence times would be of the order of about a year. Such extremely long residence times probably apply to most far inland cave systems since pronounced damping of tidal ranges has been found in all of the caves examined to date.

BOD and dissolved oxygen

BOD levels in the caves are very low ($< 0.25 \text{ ml O}_2/\text{litre}$). A small BOD maximum in the region of the halocline probably arises from the trapping of surface derived particulate material at the pycnocline.

Dissolved oxygen sags are found in the deeper waters of all the cave systems we studied, despite the very low BOD levels. Oxygen levels in the surface waters are close to saturation ($> 90\%$) since air exchange and drip waters maintain the oxygen supply. However, oxygen levels fall sharply at the halocline and remain fairly constant throughout the deeper waters. The extent of the oxygen sag varies with the amount of water exchange but has not yet been observed below 55% of saturation in any of the seven normal cave systems so far investigated.

Nutrient chemistry

The source of saline water to the caves is ultimately the Bermuda inshore

waters which have been extensively studied by Bodungen *et al.* (1982). Freshwater in the caves is derived from soil percolation. Bermuda's groundwater contains high levels of nitrate which are believed to arise from cess-pit seepage and fertiliser usage (Morris *et al.*, 1977), as nutrient concentrations in rainwater (Jickells *et al.*, 1982; Bodungen *et al.*, 1982) are too low to account for the observed levels. Low ammonia levels in groundwater indicate that the sewage from cess-pits is oxidised during percolation. Phosphate concentrations are relatively low because of removal by interaction with the limestone rock (Bodungen *et al.*, 1982; Simmons, 1983). The caves are located in areas of relatively low population density so that cess-pit seepages should be small but a golf course on the Castle Harbour Hotel property may be the source of significant amounts of fertiliser. Neither Brewer & Jickells (in press) nor Morris *et al.* (1977) could relate nitrate levels in freshwater to population density and concluded that lateral transport of sub-surface water is clearly important.

The cave waters show characteristics similar to Bermuda groundwater with high nitrate but low ammonia, nitrite and phosphate concentrations. The nitrate concentrations in surface waters of the cave pools generally increase with decreasing salinity (linear correlation coefficient, -0.773 for nineteen samples) although there is variability between and within caves. This variability is probably not surprising for samples collected at different times in different locations. This approximately linear relationship implies conservative mixing and a single freshwater source (Burton & Liss, 1975). Extrapolation of the nitrate mixing series to zero salinity using all of our data yields a freshwater endmember of about $500 \mu\text{M}$ which is an order of magnitude higher than the concentrations in cave drip water from areas overlain by the natural Bermuda forest ($18\text{--}64 \mu\text{M}$: Barnes & Bodungen, 1978; T. D. Jickells, unpublished data) although somewhat lower than the average values in the groundwater ($700 \mu\text{M}$: Morris *et al.*, 1977). Thus, as with Bermuda's groundwater, there appears to be significant contamination of the cave waters by nitrates.

Ammonia and phosphate concentrations are very low but each shows a maximum associated with the area of maximum BOD, indicating that they are released during the oxidation of the organic matter. The subsequent oxidation of the ammonia produces a very weak nitrite maximum somewhat deeper than the ammonia maximum.

Silicate concentrations in cave waters show an approximate inverse correlation with salinity (for nineteen samples from uncontaminated caves

the correlation coefficient for linear regression is -0.797) although, as with nitrate, there is some scatter. Extrapolation to zero salinity yields a freshwater endmember of $34 \mu\text{M}$ which is very similar to the concentrations found in cave drip water from the forested areas ($35\text{--}39 \mu\text{M}$; T. D. Jickells, unpublished data). This would imply that silicate is derived from soil-leaching as the concentrations of silicate in rainwater are too low (T. D. Jickells, unpublished data) for this to be the source.

The concentrations of nitrate and phosphate in the deep waters of the caves are about five times higher than in inshore waters of comparable salinity (Bodungen *et al.*, 1982) because of biological utilisation in the latter.

Trace metals

All the metals analysed show broadly similar distributions: elevated concentrations in the surface waters which fall sharply at the halocline and then remain fairly constant with depth at concentrations similar to those found in Bermuda inshore waters (Jickells & Knap, in press). The metals do not show any simple relationship with salinity, although copper, manganese, nickel and zinc are all correlated with one another while cadmium and iron behave in a more complex fashion. The concentrations of the metals are probably controlled by freshwater inputs as well as by interactions with limestone, such as adsorption and dissolution.

Polluted cave environment: Government Quarry Cave

Salinity and temperature

The physical water characteristics of the polluted caves are similar to those of the normal caves, but most measured chemical parameters are considerably outside the previously cited ranges.

Biology

Prior to the dumping in Government Quarry Cave, dip net collections from the surface waters (0–2 m) yielded unpigmented, blind amphipods which were identified as belonging to the genus *Pseudoniphargus* (Sket & Iliffe, 1980). This genus is widely distributed in caves and interstitial waters from the Mediterranean region and the eastern Atlantic (Azores and Madeira), but it has never been reported from North America or the West Indies. The discovery of *Pseudoniphargus* in Bermuda ranks as one of the most significant biological discoveries yet made in Bermuda's caves.

In November 1981, while conducting water sampling in the cave, divers saw no evidence of animal life in the entrance section of the pool nearest to the dumping site. However, when penetrating about 100 m back into the underwater cave at the lowest levels, a large amphipod, possibly *Pseudoniphargus*, was observed and a caridean shrimp, *Typhlatya iliffei* Hart and Manning, was collected. The water quality, as evidenced by underwater visibility, appeared somewhat better in this section of the cave at depths of 15 to 20 m than in the entrance area and dissolved oxygen levels were possibly higher.

BOD and dissolved oxygen

BOD levels in the upper 10 m of the water column of Government Quarry Cave are 10–60 times higher than those in Church Cave with the maximum again occurring in the region of the halocline. As with the normal caves, this is probably due to the trapping of particulate debris on the pycnocline, but it probably also includes organic matter released from submerged portions of the rubbish pile. In the surface waters oxygen levels are slightly lower than saturation (70–90%) but fall rapidly to zero at the halocline and only slowly begin to recover at depths below 10 m. Hydrogen sulphide is present in all samples from the anoxic region.

Nutrient chemistry

Nutrient concentrations in the surface waters are generally similar to those in unpolluted caves, although nitrite, ammonia and phosphate concentrations are somewhat higher. In the oxygen depleted sub-surface waters, the effect of the redox change on nitrogen speciation is apparent. Nitrate is removed by denitrification and there is an associated ammonia maximum. In deeper waters, there is a nitrite maximum which may result either from partial oxidation of the ammonia—although this is not very likely at the low (3%) oxygen level present—or from partial denitrification of the small amounts of nitrate present.

A phosphate maximum co-exists with that of ammonia. Presumably, the source of the phosphate, and at least some of the nitrogen, is the breakdown of the BOD. Silicate is not affected by the dumping or associated anoxia.

Trace metals

The concentrations of all the metals (except nickel) are higher in the surface waters of the dumping area. Cadmium, copper and zinc are 1–4

times higher while iron and manganese are 3–100 times higher. Cadmium and copper concentrations then fall to very low levels within the anoxic zone, probably due to precipitation of their insoluble sulphides. Zinc and nickel show evidence of both removal in the anoxic zone and input from the dumped material producing complex profiles. Iron and manganese concentrations increase dramatically to several hundred $\mu\text{g}/\text{litre}$ because of mobilisation of their more soluble lower oxidation states from both dumped material and sediments.

Transport of the pollutants

The tidal transfer of water between caves primarily occurs at depth, so that many pollutants, such as the metals which are removed in the anoxic zone or at the oxic/anoxic interface, are not transported. Thus, metal and nutrient concentrations in those caves adjacent to the dumping site are approximately normal. However, the anoxic conditions observed in nearby Shop, Horseshoe and Staff Quarters Caves, which have probable submarine connections to the Government Quarry Cave, provide evidence that the BOD loadings at least are transported.

DISCUSSION

The unique sensitivity of the marine cave environments in comparison to open water marine environments arises from two distinct features. First, there is no light—and hence no photosynthesis—so that all chemical processes are either inorganically or bacterially mediated. Without photosynthesis, no *in situ* source of oxygen exists. Secondly, the restricted connections of the caves to the open waters inhibits mixing and gives rise to very long residence times of the water within the caves. Since dissolved oxygen concentrations of the deeper cave waters cannot readily be replenished by mixing with surface or open sea waters, naturally occurring oxygen sags are found in all deeper cave waters. Organic pollution is extremely serious in these cases since it inevitably leads to oxygen depletion and, ultimately, anoxia.

The carbon input necessary to consume the dissolved oxygen in the water column of a normal cave and produce anoxic conditions equivalent to those observed in the Government Quarry Cave may be calculated. For Church Cave, the water volume of the pool is about $36\,750\text{ m}^3$

(35 m long \times 35 m wide \times 30 m deep). Taking a summation through the water column to a depth of 30 m, the average dissolved oxygen concentration is 3.13 ml/litre. Similarly, the average oxygen concentration in Government Quarry Cave is 0.94 ml/litre. Thus, an oxygen consumption of 2.19 ml/litre (3.13 minus 0.94) would be required to convert oxygen levels in Church Cave to those observed in Government Quarry Cave. This consumption would require 1.17 mg of oxidisable carbon per litre or 43 kg of carbon for the entire pool. Using our previous estimate for the residence time of about 1 year, an input of 43 kg of oxidisable carbon per year would be necessary. If we underestimated the volume of the cave pool, then the calculated input would be too low, while if we underestimated the residence time, the input would be too high.

Using the measured oxygen sags for Church Cave, we can similarly calculate the natural input of oxidisable carbon to this cave. The difference between our measured oxygen concentrations and those values representing complete saturation throughout the water column is the natural oxygen consumption. This consumption averages about 2.04 ml/litre (5.17 minus 3.13) for Church Cave and corresponds to an input of 40 kg of carbon per year. Thus, an approximate doubling of the already low natural input would be all that would be required to produce severe anoxic conditions.

The marine caves of Bermuda are highly sensitive to organic pollution. Only small inputs of the order of twice the natural input can produce anoxic conditions. The BOD from a single dumping incident can be transported by tidal currents and thus result in widespread pollution of entire cave systems. Since many of Bermuda's cave species are endemic and are often restricted to only one cave or cave system, pollution of these habitats can result in the extinction of entire species.

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