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Bahamian blue holes theme issue

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Cave and Karst Science

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Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

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Front Cover:
Stargate Blue Hole, North Passage, at a depth of 36m. Below the divers the cave walls plummet to a depth of more than 75m, where huge tumbled boulders block the continuing fracture. *Photo by Bill Stone.*

Back Cover:
Rob Palmer, after surfacing from a dive in Sanctuary Blue Hole, holding a recovered Arawak Indian skull. *Photo by Chris Howes, FRPS.*

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INTERNATIONAL BLUE HOLES RESEARCH PROJECT

1987 PROJECT MEMBERS

Rob Palmer, Ian Bishop, Judith Calford, Neil Cave, Stuart Clough, Dr James Carew, Dr Peter Glanvill, Bill Hamilton, Chris Howes, Dr John Hutchinson, Ian Kelly, Dr John Mylroie, Rob Parker, Brad Pecel, Dr Bernard Picton, Dr Peter Smart, Richard Stevenson, Paul Steward, Dr Bill Stone, Pat Stone, Robert Trott, Dr David Whiteside, Dr Fiona Whitaker, Sharon Yskamp.

Film Crew: (Oxford Scientific Films, England & Moana Productions, Hawaii): Sarah Cunliffe (Director), Paul Atkins (Cameraman), Grace Niska (Sound Recordist).

Reconnaissance: Rob Palmer, Dr Peter Smart, Dr Mary Stafford-Smith, Sue Wells, Dr Fiona Whitaker.

Royal Patron: H.R.H. The Duke of Kent, KG.

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The Andros Project was supported by a great many companies and individuals on both sides of the Atlantic, and only through this generous support was it possible to mount the Project at all. Too often, this assistance goes unrecognised, but these individuals and organisations are every bit as responsible for the success of the Andros Project as are those of us who had the good fortune to be at the "sharp end". Our heartfelt thanks go to those listed below, and to all others who contributed in any way to the success of the venture.

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Finally, deepest thanks are extended to Mr Zainal Mohebi, for his special support of the Project.

Plate 1. The Andros Project team.

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EDITORIAL

Dave Lowe and John Gunn

This thematic issue of *Cave and Karst Science* contains some of the results of karst exploration and study carried out as part of the Andros Project in the Bahamas. The papers, written by colleagues and friends, provide a small but fitting tribute to the life of Rob Palmer, and the work that he inspired. Before the introductory paper, which also provides the guest editorial background normally associated with thematic compilations, the valediction below offers a brief, but evocative, insight into the man and his motivation.

Vale - Rob Palmer (1951 - 1997)

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It is with profound sadness and regret that I sit here with my PC, surrounded by books, maps, pictures and memories. Rob's books sit to my right and inside the cover of his recent publication, "An Introduction to Technical Diving", the flowing handwritten entry brings it all back: *"- to remind you of cold and muddy days down Southern Stream!"*

When we first met, Rob lived in the North, I in the South. We were the same age, enjoyed the same interests and had pursued the same career - education. The connection was caving, and from the outset it was clear that Rob possessed a burning passion for discovery and adventure. He had a real zest for life; a deep love of music, mountains and wilderness and, as many of us will know, a keen and willing ability to communicate these enthusiasms. With all the flare of the showman he moved from one discipline to the next, expanding his portfolio of skills, building bridges and establishing an intricate network of lifelong connections.

He commenced cave diving in 1976 at a time when cave divers were still regarded with considerable awe, dare I say as elitists; dedicated extremists working at the very limits of human endurance. This combination of the physical and the mental, the wilderness aspect and the cold, unforgiving nature of the enterprise was to present the ultimate challenge. Rob embarked upon this activity the hard way, on second or third rate equipment, proceeding by trial and error, learning fast. There were few people to approach for advice or training and very few sources of specialist equipment. This was the "cobble it together yourself" era, a time when memories were fresh with a series of tragic accidents in the field.

Love of the wild untrodden wilderness had already stimulated interest in other more remote corners of the globe. So it was that in the summer of 1976 he made a significant cave dive at the head of the Grotte de la Cigalère - a challenging site just to reach, let alone dive.

He moved to South Wales soon after and complemented his new-found underwater interest with a love of the sea. The dreamer and romantic facet of his personality became apparent at an early stage:

"Below a cloud of bubbles, a young diver moved through waving fronds of kelp, tracing the broad leaves of the underwater forest with a gloved hand. Flicking a fin to turn a sponge-encrusted boulder and slide in free-fall into a narrow gully he came face to face with a grey seal cub. Across the misty underwater afternoon, two mammals faced each other across a rich and mystical landscape. To one, the alien, the encounter was a touch of forgotten magic that tugged at his soul. To the other, the wary regard of the hunted vied with the curiosity of the inquisitive. The cub was the first to break contact, turning in nervous urgency to flick off with broad strokes of her tail. The human, feeling strangely empty, stayed in the kelp gully for some time, watching the grey distance where the seal had disappeared, as though it had taken the magic of the underwater world into a new and different sea beyond the mist."

Exploratory, environmental and conservational issues ran hand in glove, and he became a committed member of the *Friends Of The Earth* and the *Marine Conservation Society*. Between work and sleep he also found time to run Brecon folk club for a while, and provided immense colour by playing, among other instruments, the tin whistle - often dressed in a kilt!

The recording skills required by an explorer are not inconsiderable and Rob demonstrated his grasp of these qualities time and again. He assimilated cartographic skills at an early date and complemented them with fine artistic flare. At Ingleborough Cave, for example, the cave survey now reveals names such as *"Radagast's Revenge"* and *"Bilbo's Battery"*- inspired by the magical world of Tolkien's *"Lord of The Rings"*. Name-play was another forté. Who but he would have embellished the map of the extensive underwater complex at Roaring Well (Ireland) with local village names, to generate points such as *"Ardfinnan's Reward"*? His surveys were distinctive, and his photographic skills also displayed great talent.

By 1980 sights were set upon an expedition to the blue holes of the Bahamas. With flare and driving ambition, Rob was the obvious choice to lead this venture. It seemed that everything in his life had led to this moment. Despite the tremendous organisational difficulties the outcome was to signal a milestone in cave diving history. The 1980s were to present a series of truly fascinating, quite incredible, ventures in this 'island paradise'. These are recounted fully in his subsequent books *"Blue Holes of The Bahamas"* and *"Deep into Blue Holes"* - epic tales to stir the imagination of any reader. On the initial expeditions, for example, the longest penetration of any undersea cave in the world was achieved, and alongside this, valuable scientific work was undertaken and a series of films produced. The credit for all of this is attributable squarely to Rob.

Fired by immense powers of imagination Rob strove quietly to turn dreams into reality. The Bahamian environment exerted a magnetic attraction, and by the mid 1980s he set up the Andros Project. This was to be an international scientific and exploration expedition that was to run for several years. The aim was simple - to find out as much as humanly possible about this intriguing cave environment - but the amount of co-ordination and organisation required was immense. His leadership skills were by now well honed, and his ability to acquire the necessary equipment was almost legendary. The sheer depth of some of the blue holes gave cause for concern, and it was perhaps inevitable that he should be drawn towards the concept of re-breathers. The expedition of 1987 saw the team adopt this technology at a number of sites, and a depth of 96m (320 feet) was attained in Stargate. Rob had seen the future.

Back in the UK, indeed around the world, Rob was putting the new era of technical diving squarely on the map. Following Rob Parker's epic push at Wookey Hole in the summer of 1985, Rob took advantage of some spare Trimix and in December 1985 this was used to reach the then deepest point in any British cave sump - a depth of 64m at Gavel Pot in Yorkshire. The latter half of the 1980s was to feature the *"Lost River Project"* at Gough's Cave, Cheddar. Again, it was Rob who was to co-ordinate and make the major advances, reaching the current limit of exploration in May 1990 -400m into Sump 3, beyond a maximum depth of 58m at the start of the final dive.

Life beyond exploration may not have been easy, but Rob never lost sight of his dreams. His work in technical and diver training circles -latterly associated with the UWATEC re-breather "Atlantis" - books, and other freelance work all served to establish a viable career by the later 1980s. By now he had fallen in love with the Bahamas, to where he returned on a regular basis. In the early 1990s he set up the Blue Holes Foundation with his wife Steffie, and in the summer of 1995 he finally moved to Grand Bahama to live. For the future the aim was to develop a research station. From the Bahamas he could make his pioneering forays into the deep with relative ease. In 1996 a series of expeditions took place, results of which included, for example, reaching a depth of 119m at Lusca's Breath Blue Hole, now the third deepest site in the Bahamas.

Rob was very much a self-made man who had carved a long, and at times very difficult, path to well-earned success. Rob had a way with words, be they on paper or presented at a crowded lecture theatre. He was a brilliant communicator. He had become one of the leading and most respected voices of technical diving, and a comfortable future was seemingly assured.... He lived life to the full, and I feel privileged to have shared some entertaining and magical moments in his company.

To Rob exploration and adventure was an avenue to a higher plane and it is fitting, I feel, to conclude with a few of his own words:

> *"There are few more rewarding experiences than offering all you have to the altar of chance and skill, committing life itself to the walk along the wire, and emerging whole on the other side. The world smells more vibrant, the colours bear a richer, truer glow, you are so utterly aware of it all. and of its astonishing worth."*

We will miss you Rob.

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The blue holes of the Bahamas: an overview and introduction to the Andros Project

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INTRODUCTION TO THE BAHAMAS

The Bahamas archipelago stretches some 1400km from the coast of Florida to Hispaniola (Fig.1). Approximately half of the total area of 260,000km^2 comprises extensive low-relief banks, flooded by sea water to a shallow depth (generally less than 10m). Deposition of shallow water carbonate sediments has been continuous since the Jurassic, forming a thick sequence (at least 6km) of shallow-water limestones, dolomites and evaporites resting on the subsiding continental basement. Deep water channels and re-entrants separate and dissect the steep-sided flat-topped banks, with two large coalesced platforms in the northwestern Bahamas (the Great and Little Bahama Banks) and a series of smaller isolated platforms in the southeast. Hundreds of islands, over 30 of them inhabited, are formed where the surface of the banks rises above present sea-level. They comprise predominately Pleistocene marine limestones and aeolianites, the latter commonly forming ridges up to 30m high on windward coasts. Surface drainage is absent, but extensive tidal creek systems dissect many islands, and inter-dune swales may be occupied by fresh to hypersaline ponds and lakes. Beneath the sallow vadose zone, lens-shaped bodies of fresh (or brackish) water are separated by a transitional mixing zone from groundwaters of near sea-water salinity.

The Bahamas has a tropical marine climate, characterised by persistent Trade Winds, a warmer rainy season in May to October and a cooler dry season in November to April. There is a marked climatic gradient from the cooler wetter northwest (mean annual temperature 24°C and rainfall 1550mm) to the warmer drier southeast (mean annual temperature 27°C and rainfall 690mm). The whole archipelago lies within the North Atlantic hurricane belt. On the four northern islands (Grand Bahama, the Abacos, New Providence and North Andros) forests of caribbean pine and palmetto palm are well developed. Farther south, drier conditions give rise to relatively dense mixed tropical broadleaf coppice of high diversity, whereas at the southern extreme vegetation degenerates into low scrub (Campbell, 1978). At all latitudes mangrove swamps are developed along low-lying coastal areas.

BLUE HOLES: MORPHOLOGY AND GENESIS

While most of the landforms in the Bahamas, including dune ridges and tidal flats, are constructional in origin, the exposed limestones surface is subject to erosional lowering, which also affects the underlying rock. Chemical weathering is ubiquitous and gives rise to karren, dissolution pipes and shallow subsurface channels, and surface pits locally called 'banana holes'. However, the most conspicuous features of karstic dissolution in the Bahamas are the entrances to underwater caves, known as 'blue holes'. This local term is derived from the intense blue colour of the deep water commonly found in the cave entrances (Agassiz, 1894). These entrances, which may lead to extensive underwater cave systems at depth, open both from the subaerially exposed surface of islands (inland blue holes) and from the submerged shallow banks (marine or ocean holes). Mylroie *et al* (1995) classify blue holes according to their mode of formation. However, many blue holes are polygenetic and, therefore, in this paper they are identified according to their distinctive morphology (Palmer, 1986; Whitaker, 1992; Whitaker and Smart, 1997a). Three main types are distinguished: predominantly vertical circular shafts or 'cenotes', laterally extensive, predominantly horizontal, cave systems, and vertically extensive linear caves developed on bank-marginal fracture systems.

Cenotes

Named after similar features found in the Yucatan (Reddell, 1977), these are generally 50 to 100m-deep vertical shafts, although Deans Hole, Long Island, reaches a depth of 202m (Wilson, 1994). From circular entrances typically 50 to 150m in diameter, cenotes tend to bell out at depth. A few have open horizontal passages leading off at depth, but these are generally blocked by breakdown. The upper 20 to 30m of the cenote walls are commonly crumbly and rotten, indicating locally high rates of dissolution. Below this the walls are planar and overhanging, with blocky cliffs suggestive of collapse. Whereas cenotes are present on most Bahamian islands, they are a particular feature of Andros. The distribution of cenotes appears to be independent of topography, but the linearities apparent on North Andros may reflect joint/fracture patterns, or the lines of major conduits into which collapse has occurred.

Early workers attributed development of these deep shafts to meteoric dissolution, within a thick vadose zone, at times of Pleistocene low sea-level (Agassiz, 1894). This demands a widespread impermeable seal, such as calcrete, that would enable water to shed laterally to points of concentrated recharge. Dissolution would be enhanced by continued input of organic material into topographic lows, as proposed on a smaller scale for banana holes development (Smart and Whitaker, 1988). Alternately, cenotes may result from enlargement of water-filled cave voids by phreatic dissolution, followed by collapse when sea-level lowering decreased the buoyant support of rock walls (Palmer and Williams, 1984; Smart, 1984).

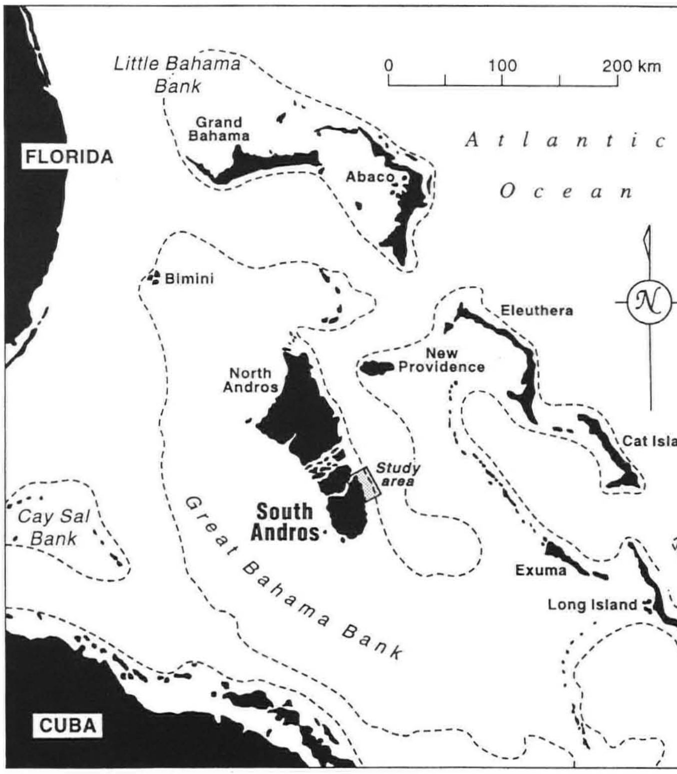

Figure 1. Location of the Bahamas Banks and Andros Island.

Laterally-extensive caves

Roof collapses provide access to laterally extensive horizontal cave systems, termed *'lens-based'* caves by Palmer (1986). The most extensive of these is Lucayan Caverns, Grand Bahama, one of the longest underwater caves in the world, with over 14km of surveyed passage (Williams, 1980). Such caves appear to develop preferentially around the island margin and, from a maze-like complex of passages adjacent to the coast, reduce to a smaller number of sub-parallel passages inland. Passages tend to be small (average 2 to 3m diameter) and, although some cross sections suggest modification by vadose entrenchment, most are circular or elliptical, indicating a predominantly phreatic origin. Passages are developed at one or more horizontal levels, although in places active upward stoping has enlarged and displaced an open void upward, resulting in stepped ceilings with planar (bedding plane) bedrock surfaces, and breakdown covering the original floor.

Development of such horizontal systems is probably related to dissolution at the water table and/or fresh-salt water mixing zone, during periods of enduring sea-level high stands. Above modern sea-level there are numerous subaerial caves, mostly less than 100m in length (Vogel *et al*, 1990; Mylroie *et al*, 1991), with Conch Bar on Middle Caicos, the longest known subaerial cave, exceeding 3km (P L Smart *et al*, unpublished survey). Characteristically they comprise oval or linear chambers with a maze of radiating smaller passages either looping back on one another or terminating abruptly in blank walls. Located within Pleistocene dune ridges, these caves are interpreted as having formed during earlier sea-level high stands at the distal margins of the palaeo-freshwater lens, where vadose-phreatic and fresh-salt water mixing zones are superimposed (Mylroie and Carew, 1990). Many horizontal passages in the present phreatic zone are occupied by the fresh-salt water mixing zone, where waters are undersaturated with respect to calcite, and wall-rock dissolution is active (Smart *et al*, 1988; Whitaker and Smart, 1998). However, the existence of a cavernous void serves to localise the position of the mixing zone, and the original void may considerably pre-date the modern groundwater hydrology (Whitaker, 1992).

Fracture-guided caves

Fracture-guided caves comprise predominantly vertical linear systems developed on major fracture systems that run sub-parallel or perpendicular to the steep margin of the carbonate bank. Passages are laterally continuous, with an average width of 2 to 5m (but may exceed 20m), and have been explored to depths of almost 100m. The vertical bedrock walls are rough but mostly planar, and show evidence both of dissolution and of spalling. Passages roofs are either bedding plane ceilings or collapsed boulders jammed within a narrow but continuing fissure. Fallen blocks of wall-rock up to several metres in diameter form a jumbled mass on the floor and, in places, bridge across the passage. Although they are of neo-tectonic origin, dissolution (predominantly in the fresh-salt water mixing zone) has enlarged the fracture voids and also developed tubular and elliptical passages along bedding planes. Spalling of wall-rock sheets parallel to the fracture walls occurs, particularly below the base of the present mixing zone, especially during periods of low sea-level. These voids appear identical to some of the larger neptunian dykes and fissures recorded in the geological literature (Smart *et al*, 1987).

In addition to the bank-marginal fracture system on the east coast of South Andros, which forms the focus of this volume (Fig.2), similar fracture systems have been reported in the Pleistocene deposits of North Andros (Daugherty *et al*, 1986), Grand Bahama (Heath and Palmer, 1985; Smart *et al*, 1988) and the Exuma Cays (Curran and Dill, 1990; Aby, 1994). The controlling fractures can be traced laterally for tens of kilometres across the shallow bank and island surfaces. They are commonly vertical, multiple and complex, but show no evidence of significant vertical displacement. On land, some fractures have been enlarged by surface dissolution, resulting in rifts more than 1m in width, with surficial karren development. These fractures may be surface indications of deep graben structures that control deep-water channels such as the Tongue of the Ocean, or they may result from basal undercutting, and/or lateral unloading, of the bank margins (Whitaker and Smart, 1997b; Carew *et al*, 1998).

EXPLORATION AND INVESTIGATION OF THE BLUE HOLES OF SOUTH ANDROS

On South Andros Island more than 60 blue holes have been explored and surveyed (Palmer *et al*, 1998a) using specialised cave diving techniques pioneered by George Benjamin (1970, 1984) and later developed by Rob Palmer (1984, 1985, 1989). Exploration of these caves began in the late 1950s when a team led by Canadian diver and photographer George Benjamin explored and documented ocean holes off the east coast of Andros Island. The team focused on a series of fracture-guided holes in South Bight (just north of South Andros Island), and developed many of the cave diving techniques still used in blue holes exploration. Benjamin's explorations ended in the early 1970s, following a number of fatalities, and exploration halted for 10 years until the arrival of British cave divers under the leadership of Rob Palmer. Two expeditions to North Andros in 1981 and 1982 climaxed in the exploration of Conch Sound for 1,150m, at the time the longest submarine cave in the world, and inaugurated a programme of academic research (Palmer, 1984). After two years working on Zodiac Caverns at the eastern end of Grand Bahama (Palmer, 1985a, 1985b), an 'Operation Raleigh' team under Palmer's leadership returned to South Andros. Working largely inland, a number of entrances along a major fracture system were catalogued and explored, including Stargate and Elvenhome. Recognising the exploration and scientific potential of the fracture caves, in 1986 Palmer organised a five-man reconnaissance, and a year later the Andros Project, the first major integrated scientific study of the Andros blue holes.

The Andros Project involved a total of 28 people in the field over a two month period, including specialist divers, paramedics and decompression specialists, biologists and earth scientists, and a crew from Oxford Scientific Films, plus logistical, medical and photographic support (Plate 1). Work concentrated on the bank-marginal fracture system on the east coast of South Andros, with additional work by a small scientific team on North Andros. Palmer describes the expedition vividly in his book *'Deep into Blue Holes'* (1989).

On South Andros a total of 11 marine and 31 inland blue holes were visited (Fig.2), with underwater exploration of all but 14. All major caves were surveyed, to no more than BCRA Grade 3 underwater, but to Grade 4/5 subaerially. Seven sites proved to exceed 70m in depth, with a maximum depth of 98m reached in Stargate. All blue hole sites visited on South Andros are described in Appendix 2 of this volume (Palmer *et al*, 1998a).

The Andros Project pioneered the use of mixed gas for deep cave diving, with 36 man-dives to depths in excess of 60m for exploration and collection of speleothem samples for age dating (see Smart *et al*, 1998). Two techniques were employed (Palmer, 1988). In collaboration with Carmellan Research, and as part of an experimental deep diving research programme, modified Rexnord Mk 16 units using high PO_2 in the breathing mix were employed. This was the first use of mixed gas re-breathers in underwater caves, and gave a depth potential of 150m. Secondly, open-circuit SCUBA using heliox (20% oxygen, 80% helium) was used, with shallow decompression on oxygen.

Rob Palmer's enthusiasm and underwater expertise provided a catalyst for the wide-ranging scientific investigation of the blue holes. The geology and geomorphology of the surficial carbonate rocks and the bank-marginal fractures that host the caves have been investigated (Carew and Mylroie, 1988; Carew *et al*,1998), and the fracture system appears analogous to neptunian dykes preserved throughout the rock record elsewhere (Smart *et al*, 1988). The caves have proved to be important repositories of scientific information. Speleothems preserve a record of geological and environmental changes (Dill, 1977; Gascoyne *et al*, 1979; Richards *et al*, 1994; Smart *et al*, 1998), and Arawak Indian artefacts and remains have been recovered (Mack and Armelagos, 1992). In addition to giving direct access to the interior of the Bahamas banks, the blue holes provide routes for rapid groundwater circulation. The consequent enhanced groundwater

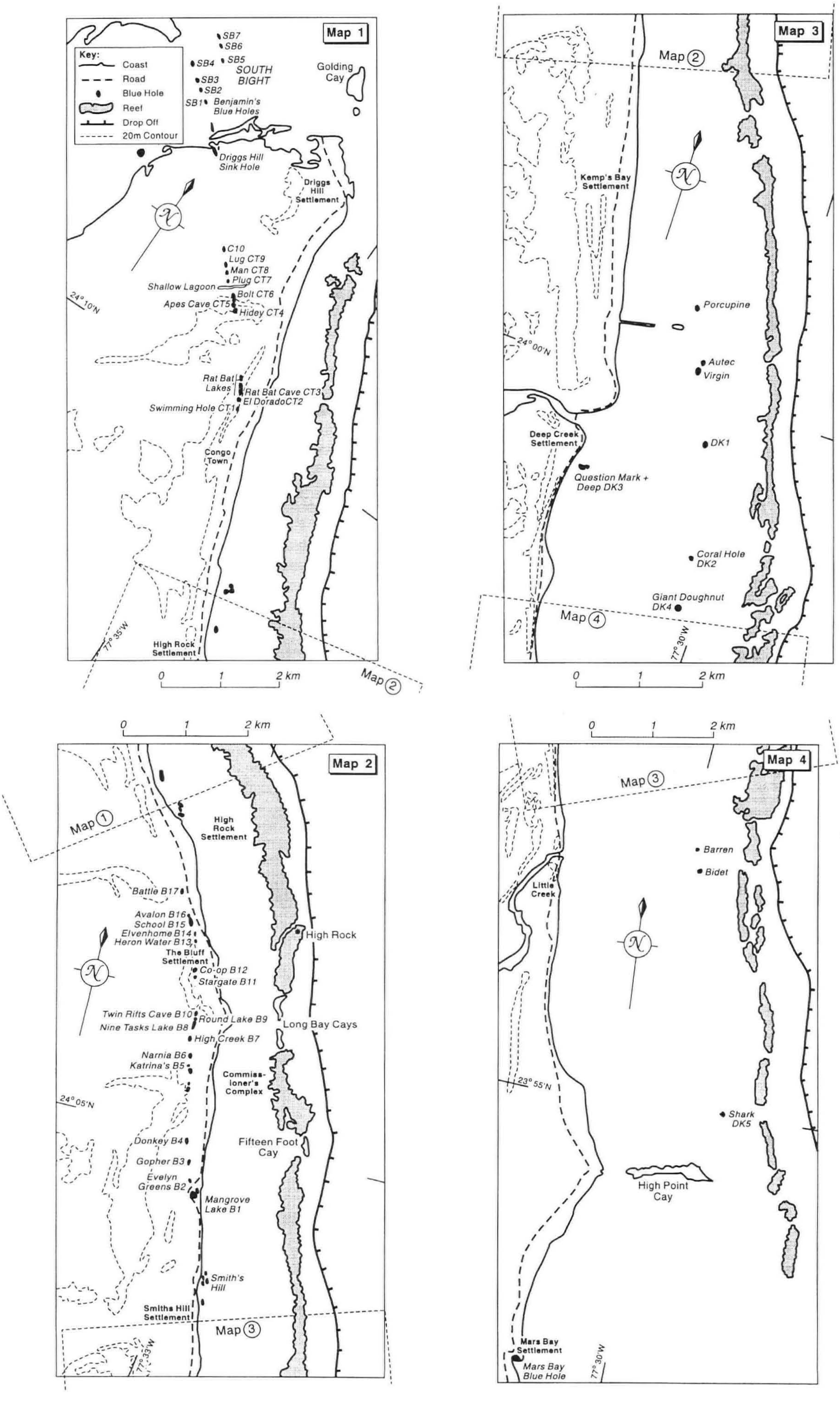

Figure 2. Detailed maps of the bank-marginal fracture system on the east coast of South Andros Island, from South Bight in the north (Map 1) to Mars Bay in the south (Map 4), showing location of blue holes.

mixing and import of surface-derived organic matter substantially modify the geochemistry and diagenetic potential of the groundwaters (Smart *et al*, 1988; Whitaker and Smart, 1990, 1997b and 1998; Whitaker *et al*, 1994), the study of which is giving new insights into the diagenetic processes that affect young carbonates.

Both inland and marine blue holes contain a distinctive biota that changes with increasing distance into the caves (Palmer *et al*, 1998b). Within marine holes, tidally-driven currents and associated sediment flux are major controls, and the caves and smaller vents form loci for development of coral patch reefs, originating the term *'doughnut holes'* (Warner and Moore, 1984; Trott and Warner, 1986; Palmer *et al*, 1998c). Inland holes display a marked vertical stratification of organisms present, apparently reflecting the distribution of salinity and dissolved oxygen (Palmer *et al*, 1998c). This, together with other factors (Hutchinson, 1998), gives rise to significant macrofaunal variations between individual inland holes.

Since 1987 work has continued on material and data collected by members of the Andros Project, advancing understanding of the fracture system caves and their associated marine and terrestrial habitats. Assisted by Palmer's diving expertise, earth scientists based at Bristol University have continued fieldwork across the northern Bahamas (see summary in Whitaker and Smart, 1997a). Rob Palmer and his wife Stephanie Schwabe moved to the Bahamas in 1995 and established the Blue Holes Foundation, to explore, survey and promote conservation of the caves. Now, ten years after the original Andros Report (Palmer, 1988), this volume draws together the results and interim conclusions from some of this work, in memory of Rob Palmer, providing a tribute to his hard work, his infectious enthusiasm and his friendship.

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The geology of South Andros Island, Bahamas: a reconnaissance report

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Abstract: The surficial rocks of South Andros Island consist almost entirely of the Grotto Beach Formation (French Bay and Cockburn Town members), that was deposited during the last interglacial sea-level highstand (oxygen isotope substage 5e ~125 ka). Scattered transgressive-phase aeolian calcarenites of the French Bay Member are the oldest rocks exposed on the island and offshore cays. At High Cay, these aeolianites are truncated and encrusted by fossil corals of the Cockburn Town Member, at elevations of up to 2m. The entire sequence is capped by a single terra rossa palaeosol. The majority of the island below 5 to 6m elevation consists of ooid shoals and lagoonal deposits of the Cockburn Town Member. All higher ground consists of aeolianite ridges. The more significant aeolianite ridges trend approximately parallel to the shore of the Tongue of the Ocean, but lie 100m to 1km or more inland. At all localities the rocks are covered by a palaeosol or its remnants. Whereas modern sediments are common, there are few lithified Holocene rocks (Rice Bay Formation). Rocks demonstrably older than the Grotto Beach Formation (i.e. Owl's Hole Formation) are absent. The island surface has been modified extensively by karst processes. Karst features range from an extensive epikarst with small pits, to banana holes, blue holes and flank margin caves. Most blue holes are developed along a fracture zone that is parallel to the bank margin. Locally, fracturing has produced graben-like features and roofed collapses. Small flank margin caves are found on the banks of the numerous tidal creeks that penetrate into the island. Banana holes are abundant, and locally form very dense concentrations of more than 1000/km^2. Pit caves are restricted to aeolianite ridges and the higher ooid shoals (above 4m). South Andros Island surface geology and karst development is similar to that found throughout the Bahamian archipelago, but the geology is less diverse. The one exception is the many deep and complex blue holes that exist along the bank-margin fracture zone.

INTRODUCTION

The field work for this study was undertaken in July 1987 as part of the British-organized Andros '87 Project that was inspired and co-ordinated by Rob Palmer. The Project was a multi-disciplinary exploration and scientific investigation of the geology, geochemistry, and biology of blue holes on South Andros Island, Bahamas (Palmer, 1988, 1989). A preliminary geologic reconnaissance based on that field work was published two years later (Carew and Mylroie, 1989), but did not include analysis of a large suite of field samples. Co-author Stephanie Schwabe examined these samples as part of her MSc degree at Mississippi State University (Schwabe, 1992). She presented that work at the Sixth Symposium on the Geology of the Bahamas at the Bahamian Field Station on San Salvador Island in June 1992 (Schwabe *et al*, 1993). It was at that meeting that she met Rob Palmer, and within a year they were married. Rob Palmer had a major influence on the lives of the three co-authors, who are pleased to present the results of work that he made possible, as part of this memorial volume.

The Bahamas are famous as a site of modern carbonate deposition, and much research on carbonate geology has focussed on the archipelago. Only in the last two decades, however, has significant attention been paid to the surficial geology of Bahamian islands.

The physical stratigraphy of the Bahamas consists of three formations that can be recognized in the field (Fig. 1). The Holocene Rice Bay Formation overlies a terra rossa palaeosol that separates Holocene from Pleistocene rocks. The Rice Bay Formation is subdivided into the Hanna Bay Member, comprising rocks formed during the last 3,000 years when sea-level was approximately at its current position, and the North Point Member, consisting of aeolianites that have allochem radiocarbon ages in the 5,500 to 4,500 year range, and can be seen to dip below modern sea-level. The next older formation is the Grotto Beach Formation, which was deposited in the late Pleistocene, during the last interglacial or oxygen isotope substage 5e, ~131-119 ka (Chen *et al*, 1991). This formation can also be divided into two members. The French Bay Member consists of aeolianites deposited during the transgressive phase of the last interglacial sea-level highstand. The succeeding Cockburn Town Member consists of rocks from the still-sand and regressive phases of the last interglacial. In places elsewhere in the Bahamas, the Grotto Beach Formation can be seen to overlie a terra rossa palaeosol that separates it from the older Owl's Hole Formation. The Owl's Hole Formation is defined as all rocks exposed on Bahamian islands that are older than the Grotto Beach Formation (i.e. older than oxygen isotope substage 5e). Intertidal and subtidal facies of the Owl's Hole Formation are presumably below sea-level as a result of slow isostatic subsidence, and known exposures of the unit

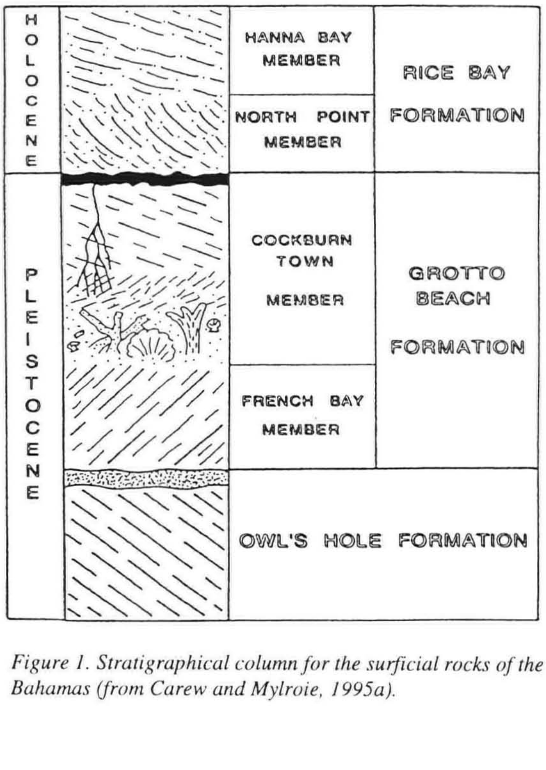

Figure 1. Stratigraphical column for the surficial rocks of the Bahamas (from Carew and Mylroie, 1995a).

are solely of aeolianites. Lack of aeolianite superposition has made field differentiation of Owl's Hole Formation aeolianites produced by older sea-level high stands impossible (e.g. stage 7, ~220 ka, stage 9, ~330 ka, or stage 11, ~440 ka). Only on Eleuthera Island has it been possible to recognise Owl's Hole aeolianites from multiple glacio-eustatic sea-level events prior to the last interglacial (Kindler and Hearty, 1995). A more detailed discussion of Bahamian stratigraphy can be found in Carew and Mylroie (1995, 1997).

The geology of South Andros Island is, as might be expected, similar to that found elsewhere in the Bahamas. This study revealed that, despite the large size of the island, South Andros lacks the variety of geological features found on many other Bahamian islands, and only the Grotto Beach Formation (with minor Rice Bay Formation outcrops) is exposed there. In contrast to the relatively simple surficial geology, the island has numerous blue holes of great depth and complexity. It is those blue holes that attracted Rob Palmer to South Andros to initiate the long and productive scientific campaign of the last 15 years. The observations reported here, and their subsequent interpretation, reflect data gathered during a single field season and, as a result, the discussion is somewhat generalized.

METHODOLOGY

Field investigation consisted of walking all available coastal exposures along the east coast of South Andros Island from Driggs Hill to Mars Bay (Fig.2), and sampling all exposures of interest. All the offshore cays from Goulding Cay to High Cay (Fig. 2) were also visited, using a Zodiac inflatable boat, and the exposed rock investigated. All quarries and pits, road cuts, and some blue holes were examined. Additionally, the rocky exposures inland along the banks of Deep and Little creeks (Fig. 2) were studied, together with representative inland palaeo-dune ridges in eastern South Andros. Finally, all macroscopic (enterable) subaerial caves were investigated, and mapped where possible. Eighty-eight rock samples were collected for further laboratory investigation. Of these, 51 samples from the aeolian ridges were prepared for petrographical analysis as part of Schwabe's thesis work on Bahamian aeolianites (Schwabe, 1992; Schwabe *et al*, 1993). The collection strategy was to obtain as broad a cross section of sample types (aeolian, coral, shoal, etc.) and locations as was possible, to guide more specialized work in the future. Work remains to be done on the non-aeolian samples.

RESULTS AND DISCUSSION

Holocene deposits

Unlike many other Bahamian islands (eg Eleuthera, Great Inagua, Long Island, New Providence, San Salvador), there are essentially no lithified Holocene deposits of the Rice Bay Formation on South Andros. The exceptions to this are some beachrock and a few scattered, weakly cemented back-beach deposits at a coastal location just north of Deep Creek (Fig.2), which meet the criteria to be identified as Hanna Bay Member rocks. Unconsolidated modern sediments comprise beach and back-beach, shallow subtidal lagoon, offshore shoal, and creek channel facies, as well as lowland mangrove marsh and grass flat environments.

The offshore shoal that parallels much of the southern half of South Andros Island is composed primarily of 0.5 to 1mm-diameter ooids. The lagoon that lies landward of this shoal contains a variable mixture of ooids, bioclastic fragments, foraminifera, peloids and aggregate grains, with variable amounts of micrite. Casual observation indicates that ooid content of lagoonal sediments diminishes with distance landward from the shoal, and the beaches consist of calcarenites that show virtually no ooid content. The sediments of the creek channels, marshes, and grass flats that occupy much of the low-lying interior of this primarily flat island were not investigated.

Pleistocene rocks

Offshore Cays

The outcrops found on the offshore cays comprise subtidal ooid shoal deposits, and in-situ reef corals and associated facies of the Grotto Beach Formation. There are a few larger cays (e.g. High Cay) that have outcrops of aeolian facies rocks that extend to about 15m above present sea-level. The in-situ corals extend to approximately 2m above present sea-level.

For most of the relatively flat, low-lying cays, it is not possible, to determine by field examination whether steeply dipping (25°-30°) cross beds are part of a shoal or are truncated aeolianites. At some locations on these cays, there are relatively coarse, shelly, layers and herring-bone cross-bedded horizons associated with these steeply dipping beds. Consequently, it is believed that most of these deposits were part of a series of shoals (or perhaps a continuous shoal analogous to the modern one) that occupied this area during the late Pleistocene.

At a few locations, such as High Cay (Fig.2), subaerial aeolian accumulations formed islands along the eastern margin of South Andros when sea-level was higher than at present. These aeolianites exhibit a truncation surface that is directly covered by rocks of subtidal facies, with no evidence of an intervening palaeosol. The simplest explanation of these outcrops is that deposition of the aeolianites occurred during the transgressive phase of that sea-level highstand, which would make them part of the French Bay Member of the Grotto Beach Formation. As sea-level continued to rise towards the peak of the highstand, coastal processes produced the truncation surfaces that

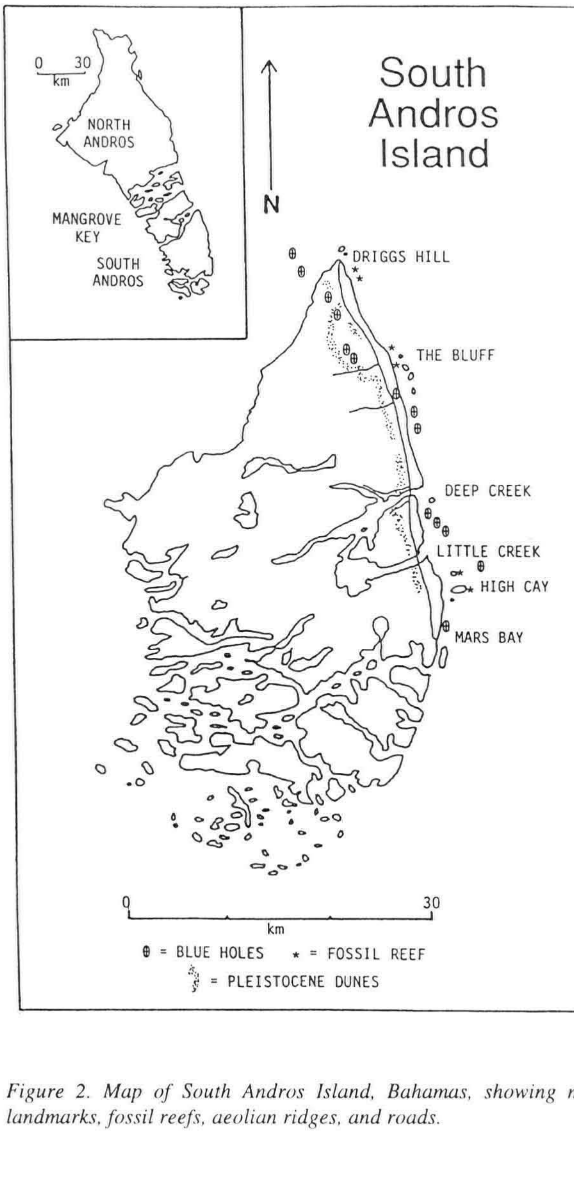

Figure 2. Map of South Andros Island, Bahamas, showing major landmarks, fossil reefs, aeolian ridges, and roads.

Plate 1. Cave passage developed into fossil reef facies at The Bluff, South Andros Island. Circular black dot in the centre of the picture is a camera lens cap. Note Acropora cervicornis above and to the left of the lens cap.

became encrusted with fossil corals of the Cockburn Town Member (Fig.3).

Coastal Outcrops

Most of the coastal outcrops are low-lying (0 to 2m above sea-level). They exhibit textures and compositions assignable to subtidal, shoal, beach, or reef deposition. At a few notable localities, particularly The Bluff (Fig.2), there are coastal cliffs that reveal subtidal facies rocks low in the section, and these grade successively into beach and back-beach dune facies rocks that extend to 10m above present sea-level. That entire sequence fits the criteria necessary for assignment to the Cockburn Town Member.

Outcrops along The Bluff settlement are particularly well exposed. At the northern end of these cliffs there are caves that provide access into the interior of a well-developed coral reef complex (Plate 1). Numerous taxa of corals can be seen, and conspicuous among them are *Acropora cervicornis*, *Montastrea annularis* and *Diploria* sp. Along the cliffs lateral to these reef deposits, the rocks comprise a variety of subtidal deposits, including ooid shoals and mixed bioclastic-ooid subtidal sands. Subtidal facies rocks extend to approximately 5m above sea-level, where they grade into beach facies rocks that are succeeded by rocks of back-beach dune facies at 10m elevation, extending inland to aeolian ridges up to 20m above sea-level. The outcrops are capped by a terra rossa palaeosol/calcrete, or its remnants.

Pits and quarries

All pit and quarry exposures within a few metres of sea-level are assignable to the subtidal facies of the Cockburn Town Member. Exposures at higher elevations reveal beach and dune facies rocks. A particularly noteworthy exposure was seen at Driggs Hill, where excavation of a new harbour was underway in 1987. Behind coffer dams, excavation below sea-level revealed rocks of a complex subtidal facies, composed of coral patch reefs surrounded and entombed by subtidal sands. Those deposits extend several metres above present sea-level. At present, that portion of the outcrop below sea-level is flooded. A terra rossa palaeosol/calcrete, or its remnants, caps all natural exposures.

Roadcuts

One major and several minor north-south roads are close to and parallel with the eastern shoreline. There are also a few short and two long east-west roadway/tracks (eg Blister Rock Road) that provide limited access to the island interior. Road cuts on the north-south roads intersect rocks of a variety of facies depending upon road elevation. Exposures representing rocks of subtidal, shoal, beach, and dune facies can be seen. At The Bluff settlement the north-south roadcuts provide exposures of beach to back-beach facies rocks mentioned above.

Roadcuts on east-west roads reveal mostly transverse exposures of north-south elongate aeolian ridges that are primarily oolitic. Only the east-west road to Black Point settlement (just north of Deep Creek, Fig.2) exposes rocks of facies other than aeolian. There, a sequence of exposures beginning at the eastern end of the road represent the subtidal facies of the Cockburn Town Member. Inland along the road, and up-section, an oolitic aeolian ridge outcrop occurs at the western termination of the road. All outcrops are capped by a terra rossa palaeosol/calcrete, or its remnants.

Creeks

The margins of Deep Creek and Little Creek (Fig.2) were investigated by utilising an inflatable boat and making short inland treks at appropriate and accessible locations. The creeks are tidal channels, not fresh-water streams. These waterways provided another avenue for exploration westward into the island's interior. Exposures seen near the eastern ends of the creeks revealed subtidal oolitic and oolitic-bioclastic facies rocks of the Cockburn Town Member. In some cases, rocks of demonstrable subtidal shoal facies extend to 5 or 6m above present sea-level.

At more westerly locations, the creeks sequentially truncate the interior north-south aeolianite ridges. There, subtidal deposits may crop out from the water level to several metres above it, followed by beach through dune facies rocks in succession to a dune ridge crest 12 to 15m above water level. All the dune facies rocks are oolitic. Outcrops are all capped by a palaeosol/calcrete, or its remnants. Most of the island's interior is a flat lowland plain covered by marsh, swamp, algal and grass flats with rocky "islets" of bedrock exposed sporadically. These areas were not investigated.

Petrography

The 50 thin-sections revealed that the rocks of South Andros Island are dominated by ooids (Table 1). Of the 50 samples, 44% are oosparites,

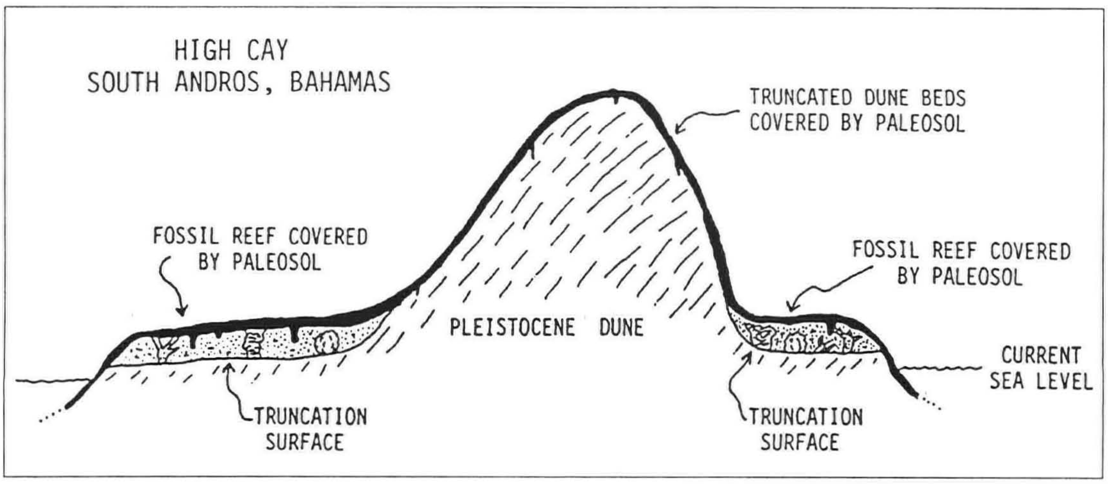

Figure 3. Diagrammatic representation of the geology on High Cay. The truncation of the transgressive-phase aeolianite was followed by growth of coral as sea-level continued to rise to its stillstand peak. All surfaces were subsequently modified by karst processes and palaeosol development.

24% are peloosparites, 8% are oopelsparites, 8% are micrites, 8% are pelsparites, 4% are pelmicrites, 2% are biosparudites, and 2% are other carbonate lithologies. Descriptions of all samples can be found in Schwabe (1992) and Schwabe *et al* (1993). No other Bahamian island that the authors have investigated has shown such a preponderance of oolitic material, although the work of others on North Andros Island (Boardman and Bergstrand, 1988; Boardman *et al*, 1993) indicates similar lithologies there.

XRD analyses of four samples indicates that whereas some aragonite remains (7 to 16%) in the ridge allochems, most material has inverted to calcite (Table 2). The amount of surviving aragonite is much less than was found (commonly 35 to 43% aragonite) in aeolianites of similar age on San Salvador Island (Vogel *et al,* 1990). It is possible that the wetter climate of South Andros, compared to that of San Salvador, may have promoted a greater amount of aragonite inversion to calcite. One sample contains a small amount of dolomite, but none contain gypsum.

Throughout the Bahamas, lowland plains at 7m elevation or less are common. Wilson *et al* (1995) designated this feature on San Salvador Island as the "Sangamon Terrace", and attributed its origins to be the result of subtidal and intertidal depositional processes that were active during the +6m sea-level highstand of the last interglacial (oxygen isotope substage 5e, ~125 ka). The rocks exposed on and in the terrace are generally those of the Cockburn Town Member of the Grotto Beach Formation. They are commonly ooid-rich, as are the aeolianites associated with them. The rocks below 6m elevation on South Andros Island show similar characteristics; that is, they can be assigned to the Cockburn Town Member.

On other Bahamian islands, aeolianite ridges deposited during sea-level highstands older than the last interglacial (Owl's Hole Formation)

Sample name	oolith	peloid	clotted micrite	algae	grape-stones	forams	shell frag-ments	other grains	total bio-clasts	sparry cement	micrite cement	whisker cement	arg. cement	inter-particle porosity	intra-particle porosity	total porosity	Rock name
Andros Island	49	14	0	0	0	0	0	0	0	26	0	0	0	11	0	11	Oosparite
AN87-1	58	2	0	0	0	0	0	0	0	26	0	0	0	13	0	13	Oosparudite
AN87-2	50	5	0	0	0	0	0	0	0	33	0	0	0	11	0	11	Oosparite
AN87-3	32	0	0	0	0	0	0	0	0	46	0	0	0	13	9	22	Oosparudite
AN87-4	55	4	0	0	1	1	0	0	1	26	0	0	0	12	1	13	Oosparudite
AN87-5	52	0	0	0	0	0	0	0	0	30	0	0	0	15	0	15	Oosparudite
AN87-6	44	0	0	0	0	0	0	0	0	29	0	0	0	23	4	27	Oosparite
AN87-7	58	1	0	0	0	0	0	0	0	30	0	0	0	10	1	11	Oosparudite
AN87-8	49	0	0	0	0	0	0	0	0	47	0	0	0	1	3	4	Oosparudite
AN87-9	35	0	0	0	0	4	0	0	4	54	0	0	0	3	4	7	Oosparite
AN87-10	51	0	0	0	0	0	0	0	0	30	0	0	0	5	14	19	Oosparite
AN87-11	36	18	0	0	0	0	0	0	0	44	0	0	0	0	2	2	Oosparudite
AN87-12	30	25	0	0	4	*	*	0	*	36	0	0	0	4	1	5	Oopelsparudite
AN87-13	7	7	0	0	0	4	0	0	4	5	76	0	0	1	0	1	Oopelmicrite
AN87-14	51	2	0	0	3	0	0	0	0	34	0	0	0	5	5	10	Oosparudite
AN87-15	48	0	0	0	0	0	0	0	0	39	0	0	0	4	9	13	Oosparudite
AN87-16-1	40	4	0	0	1	0	2	0	2	40	0	0	0	10	3	13	Oosparudite
AN87-16-2	48	0	0	0	0	0	0	0	0	37	0	0	0	15	0	15	Oosparudite
AN87-16-3	55	0	0	0	0	0	0	0	0	43	0	0	0	1	1	2	Oosparudite
AN87-17	33	0	0	0	0	0	0	1	1	34	0	0	0	4	27	31	Oosparudite
AN87-18	52	0	0	0	0	0	0	0	0	31	0	0	0	3	14	17	Oosparudite
AN87-19	41	14	0	0	0	0	0	0	0	29	3	0	0	8	5	13	Oosparudite
AN87-20	0	*	0	0	0	0	0	0	0	0	100	0	0	*	0	*	Micrite
AN87-21	0	*	0	0	0	0	0	0	0	0	100	0	0	*	0	*	Micrite
AN87-22-1	0	0	0	0	0	0	0	100	100	0	0	0	0	0	*	*	Biosparite
AN87-22-2	0	0	0	0	0	0	0	100	100	0	0	0	0	0	*	*	Biosparite
AN87-23	*	46	*	0	0	0	0	0	0	18	13	0	0	23	*	23	Pelsparite
AN87-24	5	24	0	0	0	0	0	0	0	6	45	0	0	19	1	20	Pelmicrite

Table 1. Petrographical data from 51 ridge samples, South Andros Island.

usually have peloidal and bioclastic lithologies (Schwabe *et al*, 1993). Also, Holocene aeolianites of the Rice Bay Formation on San Salvador Island contain poorly-developed ooids only low in the section, and the rocks are primarily peloidal and bioclastic. Though there is a full complement of Grotto Beach rocks present on South Andros Island, rocks of the earlier Owl's Hole Formation are not exposed, and lithified Holocene Rice Bay Formation rocks are nearly non-existent. Thus, peloidal and bioclastic rocks that commonly occur on other Bahamian islands are absent on the surface of South Andros Island.

FRACTURE ZONES

In 1987, behind the Batelco offices, south of The Bluff settlement, a large area had been cleared by slash and burn (Plate 2). This area exposed part of the fracture zone that trends sub-parallel to the coast, and along which the majority of the island's blue holes are developed. The cleared area provided a relatively long, line-of-site view of the fracture zone, which is usually buried in vegetation and very difficult to see. The cliffs that form the margins of this graben-like fracture zone (Fig. 4) expose oolitic, subtidal and shoal facies rocks of the Cockburn Town Member. Narnia Blue Hole is located along the western margin of this fracture zone. The "graben" block itself is cut by many small fractures and joints, some of which have been infilled with palaeosol material called caliche dikes (Fig. 4). The fractures are oriented sub-parallel to the trend of the eastern margin of the Andros portion of the Great Bahama Bank, and therefore nearly parallel to the orientation of the Tongue of the Ocean (TOTO).

Whitaker and Smart (1997a) provide a more detailed review of the origin of the fractures, which is simplified here. The fractures may represent the result of three factors: 1) a surficial expression of the crustal fractures thought to be the source of an original horst and graben topography of the Bahamas region, that is expressed today as platforms with linear embayments (Mullins and Lynts, 1977); 2) oversteepening of the bank margin by headward-eroding turbidity currents (Hooke and Schlager, 1980) and upward growing reefs (Schlager and Camber, 1986) which leads to spalling of blocks into the TOTO; and 3) the release of uncompensated lithostatic pressure as a result of proximity of the depths of the TOTO, with the subsequent fracture development parallel to the TOTO, especially during glacio-eustatic sea-level lowstands (Daugherty *et al*, 1987).

The failure of bank margins has been proposed as a mechanism to explain fracture patterns on some Bahamian islands, such as North Andros (Daugherty *et al,* 1987), San Salvador (Mylroie, 1988), and New Providence islands (Carew *et al*, 1996). Mullins and Hine (1989)

Sample name	oolith	peloid	clotted micrite	algae	grape-stones	forams	shell frag-ments	other grains	total bio-clasts	sparry cement	micrite cement	whisker cement	arg. cement	inter-particle porosity	intra-particle porosity	total porosity	Rock name
AN87-25-1	16	27	0	0	0	0	0	0	0	38	0	0	0	3	16	18	Peloosparudite
AN87-25-2	47	13	0	0	0	0	0	0	0	37	0	0	0	2	1	3	Oosparudite
AN87-26	7	28	0	0	0	0	0	0	0	49	0	0	0	10	6	16	Pelsparudite
AN87-27	29	27	0	0	1	0	0	0	0	32	0	0	0	9	2	11	Oosparudite
AN87-28	25	31	0	0	2	0	0	0	0	32	0	0	0	10	0	10	Peloosparudite
AN87-29	15	23	0	0	0	0	0	0	0	41	0	0	0	18	3	21	Peloosparudite
AN87-30	14	33	0	9	0	0	0	0	0	30	0	0	0	14	0	14	Peloosparudite
AN87-31	20	49	0	0	0	0	0	0	0	24	0	0	0	7	0	7	Peloosparudite
AN87-32	23	27	0	0	1	0	0	0	0	32	0	0	0	10	12	22	Peloosparudite
AN87-33	31	43	0	0	1	0	0	0	0	22	0	0	0	3	0	3	Peloosparudite
AN87-34	*	*	0	0	0	0	0	50	0	10	0	0	0	20	20	4	Biosparudite
AN87-35	7	34	0	0	0	0	0	0	0	57	0	0	0	1	1	2	Pelsparite
AN87-35-A	0	6	0	0	0	0	0	0	0	12	75	0	0	7	0	7	Pelmicrite
AN87-36	10	20	0	0	0	0	0	0	0	60	0	0	0	3	7	10	Peloosparudite
AN87-37	14	56	0	0	0	0	0	0	0	26	3	0	0	1	0	1	Peloosparudite
AN87-38	5	65	0	0	0	0	0	0	0	15	*	0	0	15	0	15	Pelsparite
AN87-39	25	23	0	0	0	0	0	0	0	61	0	0	0	11	5	16	Oopelsparudite
AN87-40	30	31	0	0	0	0	0	0	0	36	0	0	0	3	0	3	Peloosparudite
AN87-43	22	35	0	0	0	0	0	0	0	31	0	0	0	12	0	12	Peloosparudite
AN87-44	24	12	0	0	0	0	0	0	0	49	0	0	0	3	12	15	Oosparudite
AN87-45	20	23	0	0	0	0	0	0	0	31	0	0	0	14	12	26	Peloosparite
AN87-46	*	*	0	0	0	0	0	0	0	*	1	0	0	*	*	*	Micrite
AN87-47	*	*	0	0	0	0	0	0	0	*	1	0	0	*	*	*	Micrite

Table 1 (continued). Petrographical data from 51 ridge samples, South Andros Island.

	Calcite	Aragonite	Dolomite
AN87-40	84.40	15.60	0
AN87-43	90.08	7.83	2.1
AN87-44	88.55	11.45	0
AN87-45	84.62	15.38	0

Table 2. XRD data (% mineral) from four selected ridge samples, South Andros Island.

Plate 2. Narnia Fracture Zone, South Andros Island. Scarp running along the length of the picture is the west side of the "graben" seen in Figure 4. Rob Palmer is the figure to the right, the dark area in front of the other figure (JLC) is an entrance to a blue hole.

proposed that the large-scale, scalloped shape of many Bahamian island margins was the result of major bank-margin failures. The fractures penetrate rocks at least as young as 125,000 years old, suggesting that their present surficial expression is relatively recent.

Yet another possibility is suggested here. Perhaps the grabens and associated fractures represent structures developed from the stoping of large, collapsed dissolution voids at depth. Such an origin would require a mechanism for the development of very large dissolutional voids subparallel to the bank margin. That mechanism could be the interaction between outward discharging freshwater and inward encroaching marine waters. Mixing of marine and fresh water produces very dissolutionally-aggressive groundwater and that has been well documented (Back *et al*, 1986; Mylroie and Carew, 1988; Smart *et al*, 1988). Those conditions would produce a zone of high dissolutional aggressivity parallel to, but just inward from, the platform margin. Such dissolution would weaken the bank margin, thereby promoting margin failure as a result of oversteepening and/or uncompensated lithostatic pressure, as discussed earlier. Regardless of how the bank-margin fractures originated, once they formed they would be expected to become a favoured flow path for groundwater in the island. This flow would create a preferred site for dissolution at depth, which has been subsequently expressed at the surface as a graben-like fracture system.

CAVES

Cave development in carbonate islands is linked to the position of the freshwater lens. The modern fresh-water lens can be seen to discharge along the coast of South Andros today, as shown in Plate 3, its elevation tied to modern sea-level. Many caves exist on South Andros Island that are subaerial at present. These caves developed by dissolution in a fresh-water lens that was higher in elevation than today, when sea-level was higher, most likely during the last interglacial (~125 ka). The cave morphologies indicate that these caves formed according to the flank margin model of cave development (Mylroie and Carew, 1990). The caves consist of simple phreatic chambers with inwardly radiating tubes that developed in the zone of mixing between discharging fresh water and encroaching marine water. A survey of South Deep Creek Cave, a typical flank margin cave, shows the main features of this type of cave development (Fig.5, Plate 4). The cave has a large central chamber that occurs on the margin of a ridge. That chamber has been breached by recent surface erosion. A single phreatic tube leads inward into the ridge core, and ends abruptly. Caves of this type are common throughout the Bahamas (Mylroie *et al*, 1991, 1995a).

South Deep Creek Cave was the largest flank margin cave found on South Andros Island, but a number of smaller caves were located and mapped, including Deep Creek Cave, Archways Cave, Little Creek Cave, and the Cluster Caves (Fig.6, Plates 5 and 6). The generally small size of these caves may reflect explorational bias; that is, larger undiscovered caves may occur but were not found. South Andros Island lacks the large, complex aeolian ridges found on many other Bahamian islands. The small caves may reflect the limited fresh-water lenses available during the last interglacial (~125 ka), when these small ridges would have been the only land masses present.

Some of the flank margin caves are developed in rocks of the Cockburn Town Member of the Grotto Beach Formation, which requires that the rocks were deposited and then invaded by a fresh-water lens during that same sea-level highstand. That situation suggests

Figure 4. Map and cross section view of the Narnia Fracture Zone, located halfway between The Bluff and Deep Creek (see Figure 2).

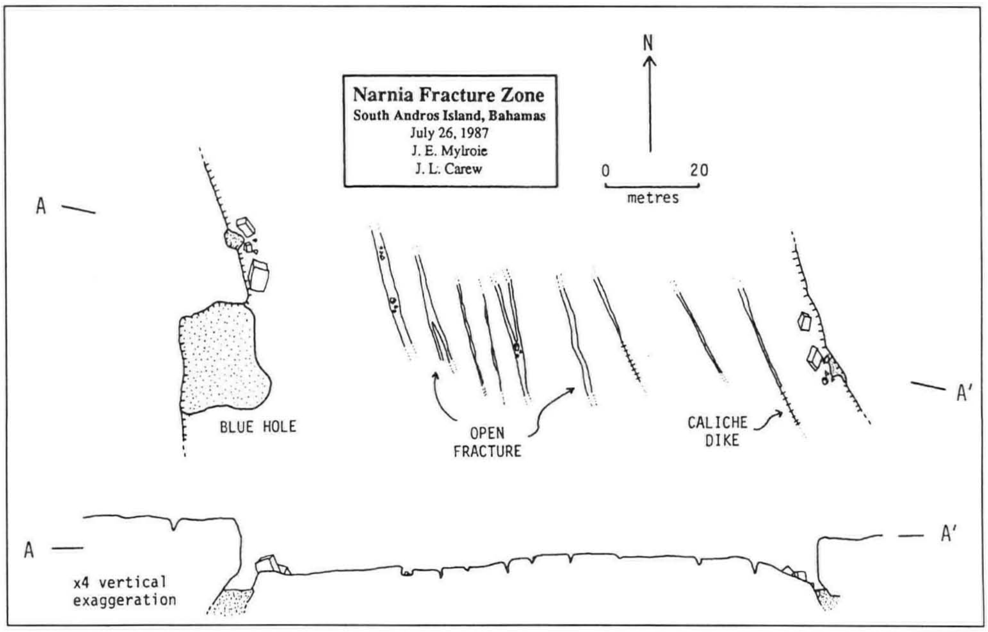

Plate 3. Beach on South Andros Island, south of Driggs Hill, showing the fresh-water lens discharging (on either side of JLC) from the bedrock and flowing across the beach to the sea.

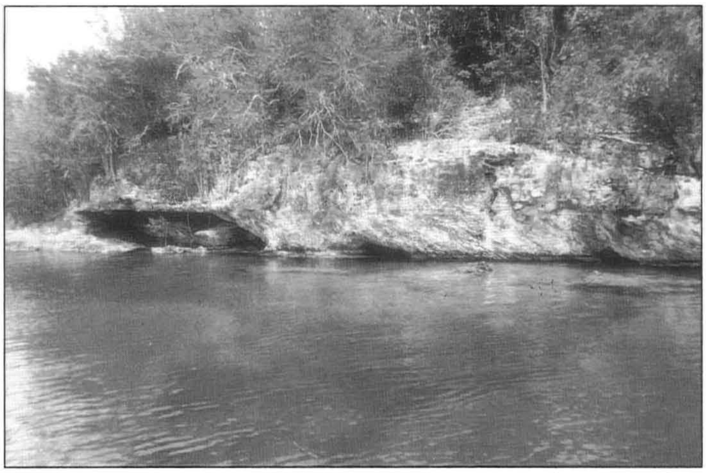

Plate 4. Entrances of South Deep Creek Cave, South Andros Island, Bahamas (see Figure 5), where Deep Creek cuts through an aeolian ridge.

two possibilities by which the cave development could have occurred. One idea, proposed by Harris *et al* (1995) for banana hole development on San Salvador Island, is that as sea-level began to regress during the last interglacial highstand, there was a significant pause after a drop of a few metres from the peak of that highstand. Such a sea-level condition would allow the "Sangamon Terrace" to become exposed, creating the land necessary for meteoric catchment and the development of a fresh-water lens. The flank margin caves developed over a period of a few thousand years, then continued fall in sea-level as oxygen isotope substage 5e ended would have left the caves subaerially exposed. The limited time window for cave development at the altitudes they occupy today could explain their relatively small size, as well as their location in Cockburn Town Member rocks.

Another scenario is that these smaller caves may have developed as a result of a minor sea-level fluctuation within the last interglacial, as has been reported for geological relationships seen at Hunts Cave on New Providence Island (Mylroie *et al*, 1991). According to this scenario, ooid shoal and beach deposits were laid down during the initial sea-level highstand during oxygen isotope substage 5e. Then these deposits, in which the caves were later developed, were partially lithified when subaerially exposed during a brief, limited, drop in sea-level during the middle of the substage 5e highstand at about 125 ka. A second, later highstand introduced a fresh-water lens into these rocks that produced only small caves in the limited time available. Support for a minor sea-level fluctuation during the last interglacial has been reported from relationships seen in fossil coral reefs in the Bahamas (White *et al*, 1997). A problem with this scenario is that it requires that the second pulse of sea-level elevation during the last interglacial could not have been as high in elevation as the first pulse, otherwise the rocks would be flooded by sea water and no fresh-water lens could form.

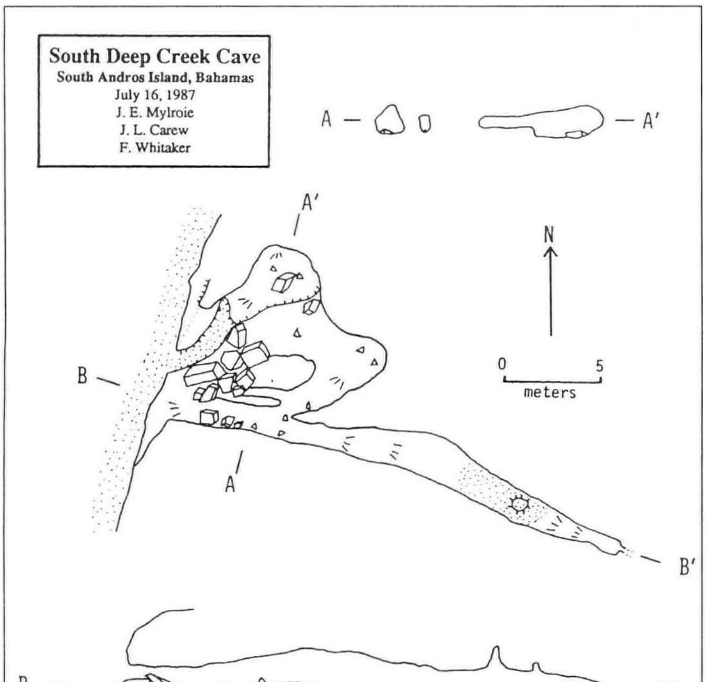

Figure 5. Map and cross section of South Deep Creek Cave, located on the south bank of Deep Creek where it cuts through the aeolian ridge.

The rocks containing South Deep Creek Cave could be a transgressive aeolianite of the substage 5e sea-level highstand, in which case the cave could have developed in a fresh-water lens during the entire duration of the last interglacial highstand, regardless of whether there were a minor sea-level fluctuation or not. Such a situation would explain South Deep Creek Cave's larger size relative to the other flank margin caves studied.

A different type of cave development seen on South Andros Island is shown in Fig. 7 and Plate 7. Rat Bat Cave is a feature produced by stoping upward from a large, deep fracture. Instead of producing a graben-like feature seen elsewhere on South Andros Island, the fracture zone passed upward into an aeolian ridge that had sufficient mechanical strength to bridge the void produced by the collapse. The fracture is marked by a series of linear blue holes on either side of this ridge. The plan and cross sectional views of Rat Bat Cave show that the cave has regions of collapsed rock. This type of cave development is unusual in the Bahama islands, but is common on Bermuda (Mylroie *et al*, 1995a).

Blue holes probably have polygenetic origins, including development from bank-margin fractures, stoping of deep-seated voids, and flooding of vadose pit caves by glacio-eustatic sea-level rise (Mylroie, *et al*, 1995b). However, blue holes associated with the bank-margin fractures are by far the most numerous on South Andros Island. Whitaker and Smart (1997b) provide further discussion of the blue holes of South Andros Island.

Banana holes are very common in the Bahamas, and South Andros Island is no exception. These partially to completely collapsed phreatic voids are located in the lowland terrains of South Andros (the Sangamon Terrace of Wilson *et al*, 1995). They range from a few metres to 10m in diameter and are 1 to 5m deep. Crude estimates of the density of banana holes on South Andros Island indicate local abundances of up to 1,000/km^2. A study conducted on San Salvador Island indicates that their abundance can exceed 3,000/km^2 (Harris *et al*, 1995). Banana holes result from mixing of vadose and phreatic waters at the top of a very shallow fresh-water lens. This dissolution produced numerous voids with thin bedrock roofs during the close of the last interglacial. As noted above in the discussion of flank margin

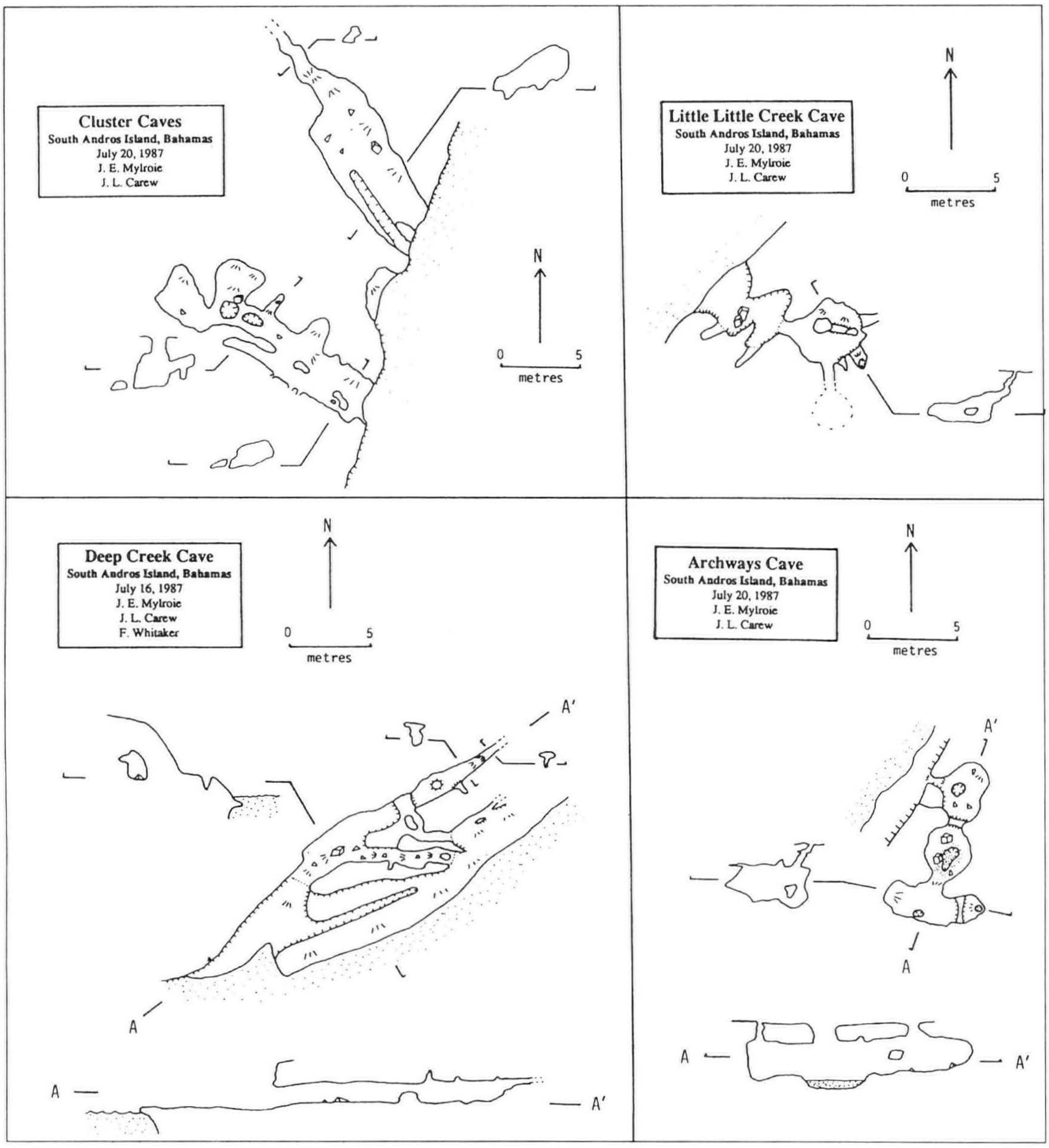

Figure 6. Maps of four small caves on South Andros Island. The Cluster Caves are located about 1km inland on the north bank of Little Creek. Little Creek Cave is located about 500m inland on the south bank of Little Creek. Deep Creek Cave is located only a few hundred metres inland on the north bank of Deep Creek. Archways Cave is located about 1.5km inland on the south bank of Little Creek.

caves, Harris *et al* (1995) argued that this dissolution took place as sea-level migrated slowly from its peak elevation of 6m during the last interglacial, exposing the Sangamon Terrace and allowing a fresh-water lens to develop just beneath the new land surface. If these conditions persisted for the last few thousand years of oxygen isotope substage 5e, then the voids could have developed. Since then, loss of buoyant support of the void roofs as the fresh-water lens followed sea-level down at the end of substage 5e initiated ceiling collapse. This collapse has continued to varying degrees, forming banana holes that display the variety of collapsed and partially collapsed expression seen today. The airport runway on South Andros Island has experienced numerous collapses as a result of ceiling failure of banana holes hidden beneath the surface (Mylroie and Carew, 1997).

Pit caves (Pace *et al*, 1993) are common on aeolianite ridges throughout the Bahamas, and were common on some aeolianite ridges on South Andros Island. They are extensions of the epikarst into the subsurface, where they act as drains that carry surface and subcutaneous water into the island. These pit caves compete for surface recharge, and commonly have their flow pirated by newer pit caves. Piracy results in a complex of pit caves where the number of pits seems to exceed the number the water budget could possibly account for (Mylroie *et al,* 1995a, Mylroie and Carew 1995).

SUMMARY AND CONCLUSIONS

Virtually all of the rocks exposed on South Andros Island appear to have been deposited during a single sea-level highstand that reached about 5 to 6m above present levels. That highstand was associated with the last interglacial, or oxygen isotope substage 5e, 131-119 ka (Chen, *et al*, 1991). All of these rocks can be assigned to the Grotto Beach Formation. The aeolian facies are predominantly oolitic, and the bulk of the island below 5 to 6m elevation comprises a suite of subtidal deposits consisting of ooid shoal and shallow lagoon deposits. In a few places these subtidal deposits can be seen to grade upward into beach and dune deposits. There is possible evidence, in the form of small flank margin caves found in substage 5e ooid-shoal facies rocks, of a minor sea-level fluctuation during Substage 5e.

Only one terra rossa palaeosol is exposed on South Andros, and it is found to cap depositional, as well as truncated, bedding surfaces of Pleistocene rocks. The palaeosol varies from a relatively thin brownish layered calcrete, to thicker palaeosols with in-filled dissolution features (fossilised epikarst). This palaeosol on Grotto Beach Formation rocks represents the late Pleistocene-Holocene transition (Carew and Mylroie, 1995a, 1997). No outcrops of the older Owl's Hole Formation were observed, and Holocene rocks were limited to beachrock and one weakly-cemented outcrop of the Hanna Bay Member of the Rice Bay Formation.

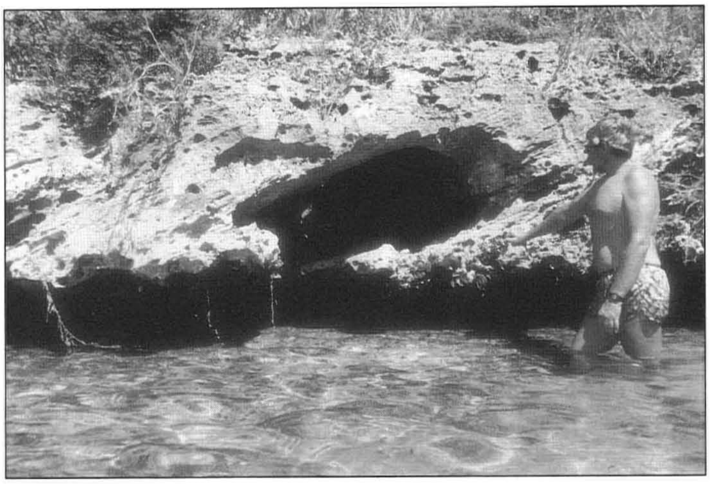

Plate 5. Entrance to the southerly of the two Cluster Caves, South Andros Island (see Figure 6).

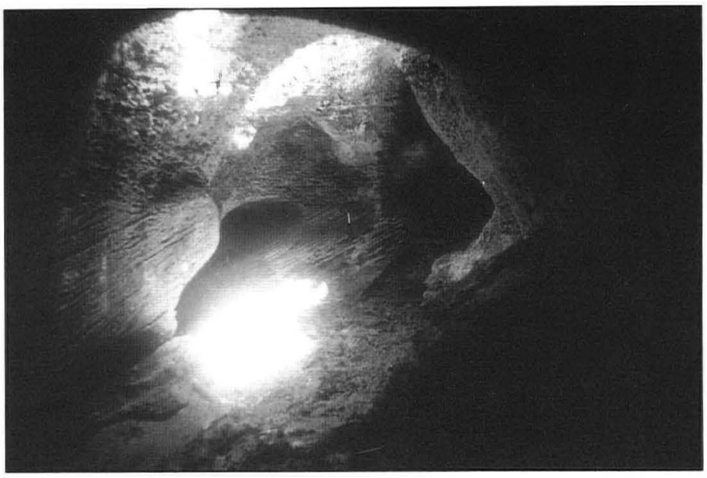

Plate 6. Interior of the southerly of the two Cluster Caves, South Andros Island, under skylights at the end of the cave (see Figure 6). Rock hammer at the centre of the back wall for scale.

On South Andros, there are only a few fossil coral reef outcrops, but their locations suggest that a string of patch to bank-margin reefs existed along the eastern margin of South Andros during the last interglacial. Some of them now crop out at least 2m above current sea-level.

The larger north-south trending aeolian ridges are developed subparallel to the bank margin (see Fig.2). Their relationship to other facies cannot usually be observed, but where exposures are good, the aeolianites grade downward into rocks of intertidal facies. All these aeolianites are assigned to the Cockburn Town Member. The offshore cay aeolianites formed during the transgressive-phase of the last interglacial sea-level highstand (French Bay Member). At the peak of that highstand, most of the platform was flooded and these ridges probably formed a series of cays at that time. On some of those cays, wave action carved a shallow platform on which corals grew during the peak of the substage 5e sea-level highstand.

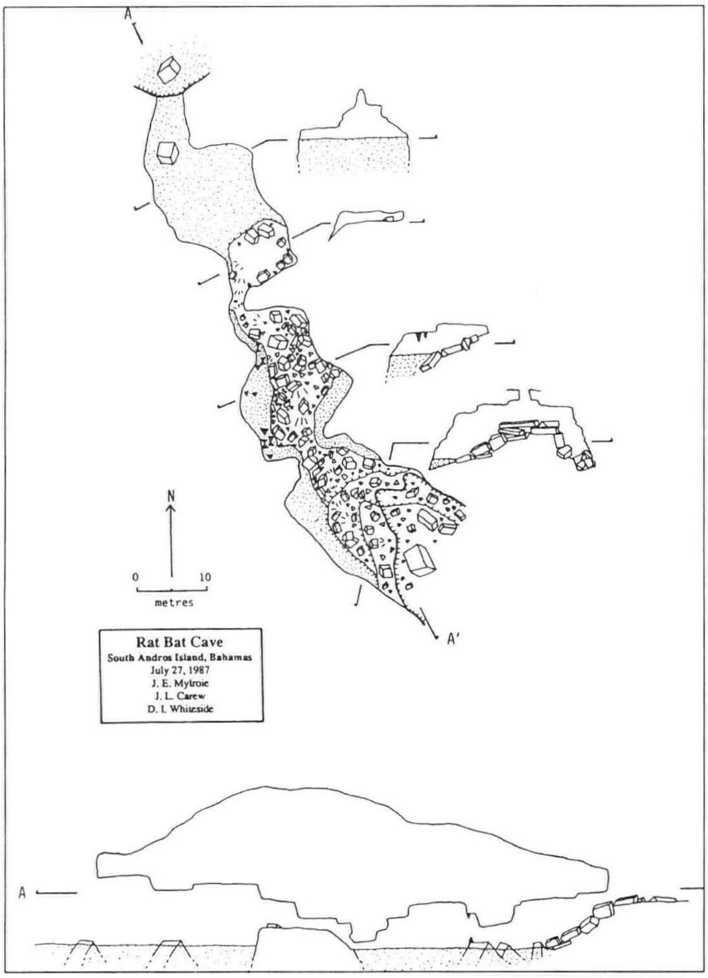

Figure 7. Map and cross section of Rat Bat Cave. This cave appears to have developed by upward collapse from a void at depth along a fracture zone. This cave lies approximately 1km inland between The Bluff and Driggs Hill.

The blue holes are primarily developed along a fracture system that lies sub-parallel to the eastern bank margin. The fractures are problematical as they occur in a supposedly tectonically stable area. Their development suggests a complex interaction between dissolutional process and perhaps failure of the platform edge into the Tongue of the Ocean.

The subaerial caves of South Andros Island are similar to those known from other carbonate islands. Some, such as the flank margin caves and the banana holes, are dissolution caves that developed during a sea-level that was higher than at present. These caves indicate that sea-level was variable during substage 5e, either as a minor lowstand near the middle of the highstand, or as a prolonged pause during the final regression from the substage 5e sea-level highstand.

Pit caves, which developed in the vadose zone independent of the fresh-water lens, are common. Additionally, there are stoping or collapse caves on South Andros Island. These were produced by upward progradation of a collapsing bedrock ceiling. These stoping caves are found in the graben-like fracture system and associated blue holes.

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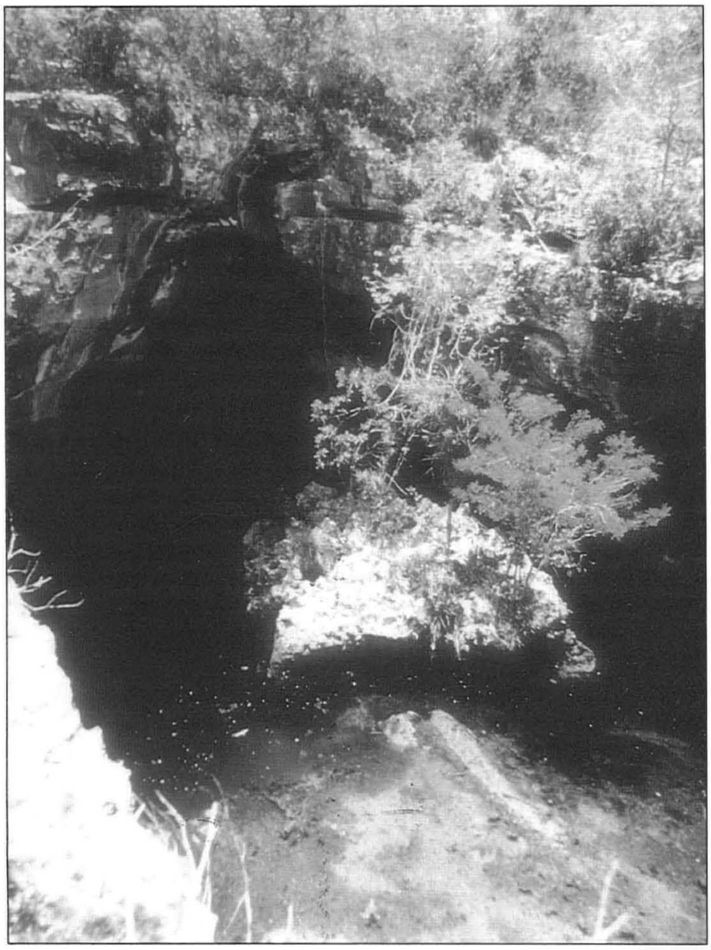

Plate 7. North entrance to Rat Bat Cave, South Andros Island. Breakdown block in the foreground is 3m by 4m. Water depth ranges from less than 1m in front of the block to great depths immediately behind the block (see Figure 7).

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Uranium-series ages of speleothems from South Andros, Bahamas: Implications for Quaternary sea-level history and palaeoclimate

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Abstract: Speleothem samples were collected from fracture-guided blue holes on South Andros Island using mixed gas diving techniques. Uranium-series ages were determined using alpha-spectrometric and, for selected samples, thermal ionisation mass-spectrometric analysis. *In situ* speleothem was absent below 57m depth suggesting that sea levels have fallen below this depth for only a limited period (although dissolution associated with present-day groundwater chemistry may also be a contributing factor). The oldest samples collected dated from Marine Isotope Stage (MIS) 6, and form false floors associated with oolitic sediments previously emplaced within the cave void. This implies latest ages of MIS 7 for the cave, and MIS 9 for the host rock. The general pattern of sea-level for MIS 4/3 defined by speleothem ages parallel the progressive lowering demonstrated by global ice volume records. Estimates of high-stands derived from Barbados and from earlier work in the Huon Peninsula agree well with the constraints provided by Bahamas speleothem, but the global ice volume and more recent estimates are somewhat lower. Speleothem growth on South Andros ceased before flooding of the caves by rising sea-levels, probably related to a regional decrease in precipitation associated with the discharge of melt-water into the Gulf of Mexico. Cessation of growth in MIS 6 may also be controlled by palaeoclimate, and suggests an early commencement of deglaciation.

INTRODUCTION

Studies of Quaternary sea-levels have depended primarily for chronological control on the uranium-series dating of fossil corals preserved in Quaternary reefs. In stable areas such as the Bahamas, Quaternary reefs that formed at sea-stands lower than present sea-level are not exposed. Studies are thus limited to the dating of Quaternary sea-levels similar to or higher than present, such as the early studies of Neumann and Moore (1975), who dated Marine Isotope Stage (MIS) 5 deposits in the Bahamas. More complete records of Quaternary high-stands are obtained in areas of active tectonic uplift, such as the Huon Peninsula (Chappell, 1974, 1983) and Barbados (Bard *et al*, 1990a; Gallup *et al*, 1994). However, estimation of palaeo sea-levels from uplifted reefs in such areas is subject to uncertainties associated with the rate and constancy of uplift with time (Bloom and Yonekura, 1985). Such uncertainties are much less important in stable areas such as the Bahamas where rates of subsidence are very much lower (0.01 - 0.02m/ka, compared to 1.5 – 2.0m/ka for uplift in the Huon Peninsula). A further problem with the coral reef record is that the timing and duration of low-stands cannot be determined; a discontinuous sea-level record is thus preserved, which cannot readily be compared with that derived from continuous data such as the deep sea foraminifera oxygen isotope record (Chappell and Shackleton, 1986).

Spalding and Matthews (1972) were the first to recognise the potential of underwater caves for the dating of Quaternary sea-levels. Subsequently, with the assistance of pioneer blue hole diver George Benjamin, Gascoyne *et al* (1979) obtained speleothem samples, from a depth of 45m in Benjamin's Blue Hole in the Bahamas, that were dated by uranium-series techniques. Further samples were obtained during the early British diving expeditions to North Andros (Gascoyne, 1984). Speleothems with distinctive morphology indicating subaerial growth (e.g. gravitational forms such as stalactites and stalagmites) provide unequivocal evidence that at the time of deposition sea-level was below the sample elevation. Under ideal conditions they provide an oceanic dip-stick, commencing growth as sea-level falls, and stopping when the cave becomes flooded by the rising sea-level. They therefore fulfil the three criteria for sea-level age/altitude data (Van der Plassche, 1986); the meaning of the evidence is clear, the elevation is defined and the age can be determined accurately and precisely by uranium-series dating. In many ways the speleothem record from underwater caves is complementary to that from raised reefs, in that it may provide useful information on rates of rise and fall of sea-level, and the elevation of low-stands, but has more limited potential to define timing of high-stands.

The complementary nature of the speleothem and other records of sea-level was well illustrated by the study of Harmon *et al* (1983) working in Bermuda. Like the Bahamas, this island is also stable, yielding reliable palaeo-elevation estimates. However in Bermuda samples could only be obtained over a restricted depth range (to 11.5m below present sea-level) because of the limited thickness of the limestones hosting the caves from which the speleothem samples were obtained. In this respect the Bahamas offers much greater potential, divers reporting accessible caverns to depths in excess of 202m (Deans Blue Hole, Long Island), and the carbonates continue to much greater depths (>2km).

METHODS

In 1985, Rob Palmer conceived the Andros Project, which was to focus on exploration and scientific study of the recently discovered blue holes of South Andros Island. A research proposal was prepared to the Natural Environment Research Council for the collection and analysis of a suite of speleothem samples from the well-decorated and deep caves that were known to be present in the expedition area. This was supported enthusiastically by Nick Flemming, and received commercial sponsorship from a number of sources, including Carmellan Research who offered to provide access to closed-circuit rebreather diving equipment that would permit safe sampling to depths in excess of 200m, well beyond the 120m estimated for the last glacial sea-level low-stand. This was the first time that such an extended sampling programme utilising cave diving had been undertaken, and the first time that mixed gas rebreathers had been used in caves. In fact, mixed gas diving proved to be very demanding logistically. It was necessary to train open-water divers to work in cave conditions, and cave divers to use the rebreather systems safely. Bail-out and in-water decompression facilities were required in the event of failure of the experimental rebreather systems, together with on-site recalculation of decompression schedules, and a portable decompression chamber. Large volumes of helium and oxygen breathing gases were also needed, in addition to two high volume high pressure compressors, one of which drove a Haskel booster pump for high pressure mixed gas fills.

A maximum of three or four samples could be collected on each dive. Where possible foundered samples were collected with care being taken to locate the original growth position. Sample elevation was recorded (±0.1m) using Aladdin depth-indicating dive computers. Subsequently these figures were corrected for the different proportions of fresh and saline water in the overlying water column to give true depth. Where possible the true base of the sample was collected, although the importance of this was perhaps not recognised by the non-scientific divers involved in sample collection using the rebreather systems. The majority of the samples collected were stalagmites because their predominantly columnar growth is much simpler to section using a rock saw for analysis than stalactites, which have concentric growth around a circular core. In addition to the submerged samples, a limited collection of subaerial samples was also obtained.

On return to Bristol, samples were sawn longitudinally, photographed, and the internal growth structure recorded. Samples that were porous, showed evidence of recrystallisation, or contained detritus were rejected. Sub-samples of 50 to 100g were cut from the top and base of samples selected for uranium-series analysis. The sub-samples were weighed and dissolved in 6M HCl. A ferric chloride carrier and precisely measured quantity of $^{229}Th/^{236}U$ spike was added and left overnight to equilibrate. U and Th were then co-precipitated by addition of NH_4OH, the precipitate recovered and redissolved in 6M HCl. Iron was then separated by liquid extraction with 4-Methyl penton-2-one, the sample evaporated to dryness and dissolved in 9M HCl. U, Th and residual Fe were then separated using AG 1 X 8 ion exchange resin. Uranium was retained on the first column while Th was eluted in 9M HCl, Fe was removed in 7M HNO_3 and finally U recovered in 0.1M HCl. The thorium solution was then converted to nitrate form in 7M HNO_3 and separated from Fe on a second exchange column, from which it was eluted using 2M HCl. Both U and Th were electroplated onto stainless steel planchettes from $(NH_4)_2SO_4$ electrolyte in a standard cell to produce uniformly distributed thin sources for alpha spectrometry. Sources were counted in a four channel Canberra alpha spectrometer with Canberra 7404 silicon surface barrier detectors and a Series 35 PLUS multichannel analyser. Counting times were sufficient to obtain >10,000 counts for the major isotopes of interest (^{238}U, ^{236}U, ^{234}U, ^{230}Th and ^{229}Th).

During the course of this research, thermal ionisation mass spectrometry was developed for determination of uranium-series isotope concentration and ratios (Edwards *et al*, 1986). Some critical samples were thus re-dated at the University of Minnesota Isotope Laboratory using this technique, which both enables very much smaller sample size to be employed, and achieves very much higher precision than is possible using alpha spectrometry. Analytical methods are as described by Chen *et al* (1986) and Edwards *et al* (1986), isotope ratios being determined using a Finnigan MAT 262 RPQ mass-spectrometer. Further details are given in Richards (1995).

RESULTS

The majority of the South Andros collection are from Stargate Blue Hole (n = 34), with three samples from Sanctuary and two (courtesy of J Mylroie) from Rat Bat Cave (Palmer *et al*, 1998). One bag of samples collected during the deep-diving was lost (although recently this has been recovered and is held by the Blue Holes Foundation). The depth distribution of speleothem samples collected is shown in Fig. 2. There was a paucity of samples from immediately beneath the surface, there being little in the way of passage or alcove development off the main shaft at this point (Fig.1). Coverage was then good to -45m, with limited speleothem between -45 to -57m, where the deepest *in situ* sample was collected. Despite extensive searching and the cave continuing to a low point of -96m, no further *in situ* speleothem was observed beneath this depth. Gour pools at a depth of –80m have been reported from Avalon (Palmer *et al*, 1998), although this remains unconfirmed and they were not sampled. Six subaerial samples were obtained, but only two were selected for dating, the others being tufaceous and/or detritally contaminated.

There is a marked contrast in the internal morphology of present day subaerial speleothems collected on Andros (and more generally in the Bahamas) and those recovered from the submerged caves. The former are typically densely banded with layers of dense calcite separated by more porous bands, often showing evidence of corrosion, and distinctive colour differentiation (Plate 1a). The majority of submerged samples are relatively poorly banded, and completely free of gross internal corrosion (some samples from within the mixing zone show etching of the external surfaces). They are typically dense white pure calcite with an absence of detrital material (Plate 1b). In contrast to samples collected from marine blue holes (Gascoyne, 1984), the Andros collection is not affected by either encrusting organisms such as serpulid worms, or borers such as polychaete worms and molluscs. The tip of stalagmite AN-87-27-3 does have a bored surface (Plate 1c). This is also true of the surface of the inner growth phase of AN-8723-2, which is part of a complex drapery at a depth of 57m, and shows a hiatus separating two distinct growth phases. The inner core is orange brown calcite (probably with a high organic content), and the outer more densely banded white calcite.

A total of 35 alpha spectrometric ages were obtained, four of which were greater than 100 ka. The analytical precision of the ages based on counting statistics is good and is much higher than in earlier studies. For samples <100 ka the average 2σ uncertainly is 9.6%, but this reduces to 6.6% if 6 samples with chemical yields less than 10% are excluded. For samples >100 ka, the age uncertainty is much higher (11.4%) due to the decreased gradient of the relationship between age and $^{230}Th/^{238}U$. Of 13 paired top and bottom analyses only 1 sample showed a reversal in ages suggestive of post-depositional alteration and that the isotopic system had not remained closed. One sample, a subaerial Holocene speleothem from Rat Bat Cave had a $^{230}Th/^{232}Th$ ratio significantly less than 20, all other samples have a minimal detrital component. Finally, there is good agreement between the alpha spectrometric and high precision mass spectrometric determinations performed more recently on selected samples (Table 1a).

Because of the significant sample size required for alpha-spectrometric analysis, the actual ages of growth initiation and

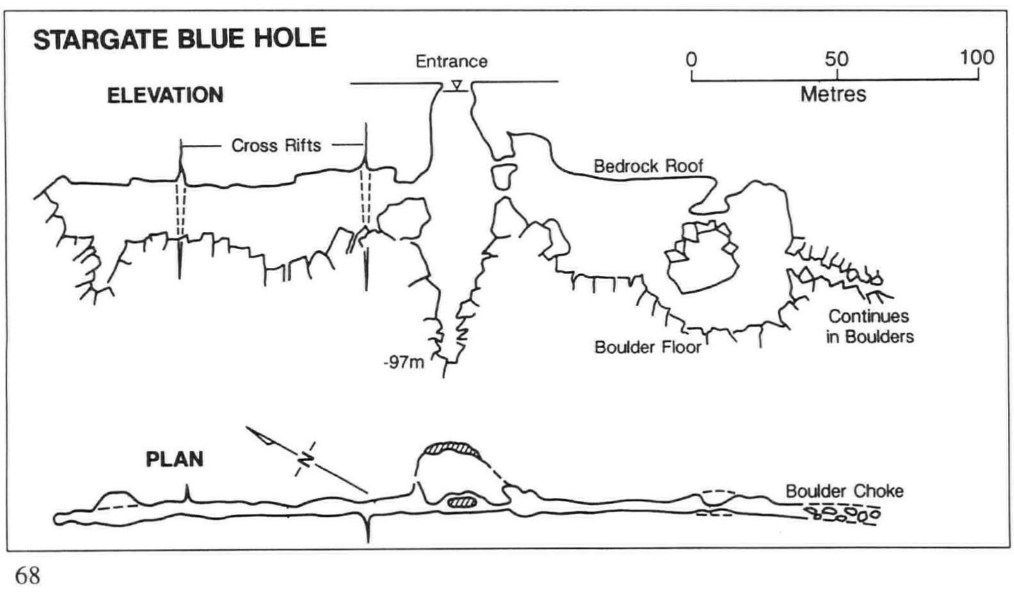

Figure 1. Plan and section of Stargate Blue Hole, South Andros.

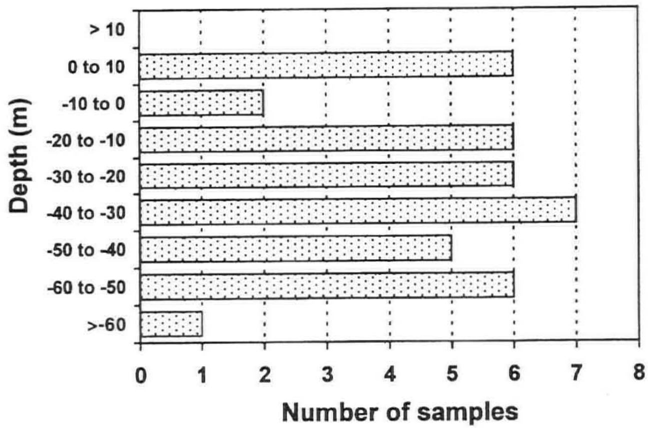

Figure 2. Depth distribution of speleothem samples collected from S. Andros.

cessation may be significantly older and younger, respectively, than the determined uranium-series age. The timing of initiation and cessation of growth phases was determined by assuming linear extension rate between the mean ages and centres of the sub-samples along the growth axis of the speleothem. In fact, because of the relatively rapid growth, differences between extrapolated initiation and cessation ages, and dated sample ages were generally less than analytical uncertainty (Table 1a). This is, however, not always the case, and some caution is needed in interpreting speleothem growth/sea-level history data where significant extrapolations are made, particularly for older samples (see for example Lundberg and Ford, 1994). Note also that the improvements made possible by mass-spectrometric dating (AN-87-23-3 Table 1a) enable much smaller sub-samples to be cut from very close to the inner or outer surface.

Also shown in Table 1 are ages determined for whole growth phases (1b, where the thickness of the growth phase is so small that only one sample may be cut, giving a mean age), and unpaired top and bottom ages (1c and 1d, for which paired analyses have not been completed). Finally in Table 2 the ages of the penultimate interglacial growth phases preserved in only three of the Andros collection are presented. Note the major improvement that is achieved by mass-spectrometric analysis of these older samples.

INTERPRETATION

Penultimate glacial speleothem growth: implications for sea-level history and cave antiquity

It has not been possible to determine the earliest age for speleothem deposition in Stargate, as the morphology of the stalactitic drapery from AN-87-23-6 is complex, and the earliest growth phase cannot readily be defined. Two stratigraphically related samples best define the cessation of growth (AATI and AAT2 from AN-87-23-6 at -49.1 m) at 149.2 + 6.2 - 5.8 ka, which may be related to rising sea-level at the end of MIS 6. Less precise alpha spectrometric analyses for AN-87-27-3 (-39.7m) give similar figures (mean 145 ka), and are comparable within error with the duplicate analysis for the youngest dated sample in flowstone DWBAH determined by Lundberg and Ford (1994) of 142 ka (mean of three determinations with 2σ errors c.10 ka). Richards *et al* (1994) report similar cessation ages (149 – 152 ka) to those from Stargate for a flowstone sequence from Grand Bahama, which is very similar to DWBAH.

These ages are all much earlier than mass-spectrometric ages for the commencement of the stage 5e high-stand (typically 130 ka, Stirling *et al*, 1995; Chen *et al*, 1991), and infer either that sea-level rose to the high-stand very slowly, or that speleothem growth ceased before sea-levels inundated the caves (the latter possibility will be considered further below). In fact, there does not appear to be any association between cessation age and depth (Table 2), and the slow rates of sea-level rise suggested (1 – 2m/ka for the youngest and shallowest samples) are relatively low compared with typical rates in excess of 5m/ka for the last deglaciation (Bard *et al*, 1990a). Lundberg and Ford (1994) suggested that this disparity was simply related to the difficulty in obtaining reliable uranium-series ages for DWBAH (sample H) immediately below the hiatus. They therefore employed linear extrapolation of the growth for the whole MIS 6 growth phase from the last dated sample (sample 10) to the stage 5e hiatus. This yielded a flooding date of c.130 ka. However, it is possible that growth was non-linear, as is suggested by the much more rapid growth calculated for the sequence of sub-samples 10/F/G/H immediately below the hiatus. The significance of the MIS 6/5 cessation is discussed further below, but clearly more work is needed on a wider spectrum of samples to determine the nature and timing of the sea-level rise associated with the last deglaciation.

Speleothem growth during the penultimate glacial provides constraints on antiquity of Stargate Blue Hole and information on cave development. Sample AN-87-27-3 developed as a speleothem capping on sediment infilling an existing cave void. This sediment is now largely removed, but is preserved as cemented remnants, locally associated with speleothem false floors. The upper surface of the sediment body, defined by the vestiges of the false floor, slopes relatively steeply (c.10m/50m) from the entrance shaft down into South Passage, suggesting that the sediment entered via the present entrance (no sediment was observed in North Passage, but a careful survey was not undertaken). The sediment comprises a cream-coloured cemented oolitic limestone, although the oolites have been largely removed by subsequent dissolution. It could either have entered the cave by marine transport as an oolite shoal prograding over the pre-existing island under high sea-level conditions, or may represent a regression of sea-level with mobilisation of high-stand marine sediments by aeolian processes. Deposition was almost certainly sub-aqueous as the surface of the deposit is not at the sub-aerial angle of repose, suggesting some reworking and transport to the south in the cave (the same direction as observed under present day conditions - Whitaker and Smart, 1998).

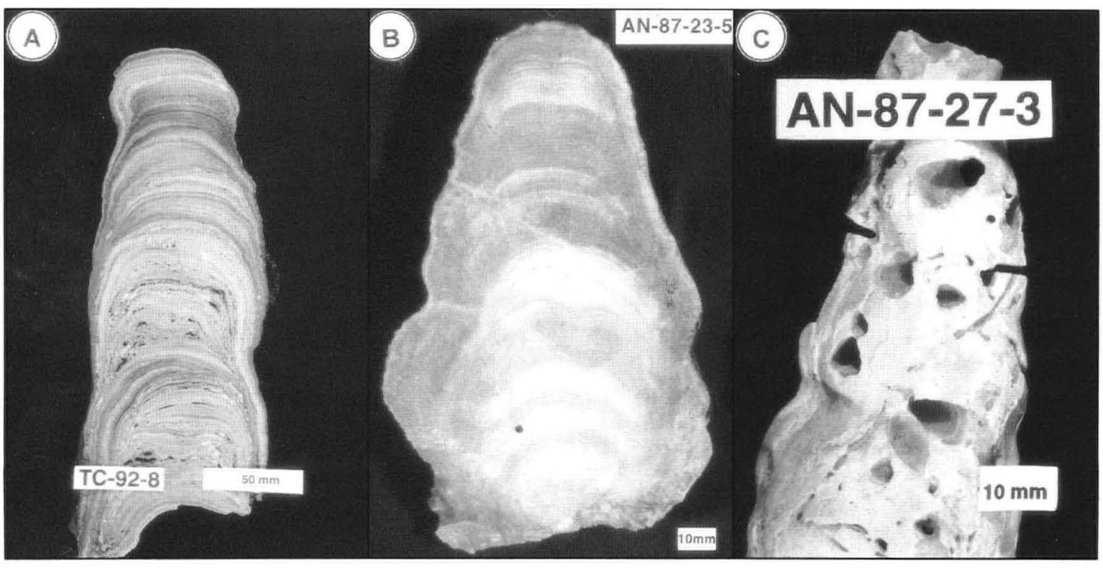

Plate 1.
A. Holocene subaerial speleothem from Conch Bar Cave, Middle Caicos. Note dense layering with many voids and brown colouration (?organic matter).
B. Last-glacial submarine speleothem from 50.5m depth in Stargate Blue Hole, South Andros. Note dense pure white calcite.
C. Tip of submarine speleothem pre-dating the last interglacial from Stargate Blue Hole showing evidence of marine boring.

Table 1 a) Initiation and cessation, b) whole growth phase, c) unpaired basal and d) top ages (ka) of speleothems from South Andros after the last interglacial (errors are 2σ). Starred analyses by mass spectrometry.

a)

Sample	Depth (m)	Basal sub-sample age	Extrapolated initiation age	Top sub-sample age	Extrapolated cessation age
AN-87-23-2	-54.9	19.3 ± 0.4	19.2 ± 0.4	18.9 ± 0.2	18.9 ± 0.4
AN-87-23-3	-51.8	19.6 ± 1.1	23.5 ± 6.0	17.4 ± 1.7	16.3 ± 3.1
AN-87-23-3*		21.7 ± 0.2	21.8 ± 0.2	18.5 ± 0.2	18.4 ± 0.2
AN-87-23-5	-48.8	19.7 ± 1.3	20.1 ± 1.8	16.9 ± 1.2	16.3 ± 1.8
AN-87-26-5*	-47.3	18.7 ± 0.3	18.7 ± 0.3	16.8 ± 0.2	16.8 ± 0.2
AN-87-26-11	-16.2	35.5 ± 1.8	36.6 ± 6.9	32.7 ± 11.9	32.2 ± 14.2
AN-87-27-2	-37.5	39.3 ± 0.9	39.4 ± 0.9	22.2 ± 5.9	20.0 ± 6.5
AN-87-28-1	-36.5	40.6 ± 0.1	40.7 ± 0.1	39.9 ± 0.1	39.9. ± 0.1
AN-87-28-2	-38.0	31.0 ± 4.5	36.2 ± 15.0	25.8 ± 5.8	23.1 ± 11.2
AN-87-28-4	-36.5	29.8 ± 2.1	30.5 ± 3.3	27.8 ± 1.2	27.6 ± 1.5
AN-87-28-7	-16.1	55.3 ± 2.1	57.3 ± 2.6	39.7 ± 1.6	34.6 ± 2.8

b)

Sample	Depth (m)	Whole Growth Phase Age
AN-85-k-A1	-25.0	19.1 ± 1.5
AN-87-1-3i	+0.2	69.1 ± 3.0
AN-87-1-3ii	+0.2	19.1 ± 1.0
AN-87-23-6	-50.3	20.1 ± 1.0
AN-87-26-3	-56.4	19.2 ± 2.0
AN-87-27-4	0.0	26.7 ± 3.2

c)

Sample	Depth (m)	Basal Age
AN-87-1-2	-12.9	32.6 ± 2.0
AN-87-26-8	-6.6	40.1 ± 4.8
AN-87-31-1(i)	-26.0	47.7 ± 1.1

d)

Sample	Depth (m)	Top Age
AN-87-28-5	-28.7	15.9 ± 2.3
AN-87-31-1(ii)	-26.0	23.6 ± 1.2
AN-87-41	+0.3	2.2 ± 0.6

Table 2. Ages (ka) of speleothem samples from South Andros Island prior to the last interglacial (errors are 2). Starred analyses are by mass spectrometry, alpha spectrometric analyses for AN-87-23-6 have low chemical yield, giving poor precision.

Sample		Depth (m)	Age
AN-87-23-2	(A)	-53.6	129.5 ±0.9*
AN-87-23-6	(AA) T1	-49.1	149.2 +6.2/-5.8
	AAT2		162.1 ±1.7*
	ABT1		171.6 +4.0/-3.9*
	C		150.3 +28.6/-23.3
	A		132.1 + 5.0/-13.4
AN-87-27-3	E	-39.7	146.6 +15.0/-13.4
	B		143.3 +11.6/-0.5
DWBAH[1]	10	-15	138.9 +10.5/-10.0
	10r		144.1 +10.5/-9.4
	F		143.0 +3.5/-2.9
GB-89-25-5A[2]	B	-18.1	149.2 ±1.7
	DDT1(A)		151.6 ±1.5
	BGT1		156.8 ±2.1
[1].Lundberg and Ford (1994) [2].Richards *et al* (1994)			

Attempts to obtain a uranium-series date from the residual cements in the sediment proved unsuccessful, but the c.145 ka ages on AN-87-27-3 indicate that the latest this deposit could have been emplaced is late MIS 7 (or the MIS 7/6 boundary). The Stargate Blue Hole void was clearly extant at this time, suggesting the latest the cave could have formed is at the main stage 7 high-stand (c.200 ka). Clearly, the carbonate rocks hosting the void were lithified and subject to brittle fracture by that time, implying an earlier period of subaerial diagenesis and cementation (MIS 8 or earlier). The wall rock itself is therefore MIS Stage 9 at the latest. This extended time scale for sediment deposition on South Andros contrasts significantly with the chronology proposed by Carew *et al* (1998) on stratigraphical grounds. This discrepancy echoes the wider debate regarding the antiquity of Bahamian surficial sediments and landforms in the literature (see contrasting views in Vacher and Quinn (1997) and earlier discussions of Hearty and Kindler (1993)).

Last glacial speleothem deposition: implications for sea-level history

The earliest dated speleothem growth on South Andros for the last glacial period is a whole rock analysis from the inner brown growth phase of a subaerial speleothem 0.2m above present sea-level (69.1 ± 3.0 ka). In the dated submarine samples the earliest growth commenced at 57.3 ± 2.6 ka in AN-87-28-7 (-16.1m). This is much later than has been reported for samples from somewhat greater depth on Grand Bahama Island (79.4 ± 1.8 ka at -18m; Richards *et al*, 1994). This growth phase on Grand Bahama (which continues to 16 ka) was interrupted at 63.3 ± 1.8 ka by a prominent hiatus defined by a linear array of fluid inclusions and slight colour change. Growth recommenced at 59.9 ± 0.5 ka, in agreement with the date from South Andros. However, unlike earlier hiatuses in the Grand Bahama sequence, there was no deposition of iron on the hiatus surface. It is therefore not certain that the hiatus represents a drowning event. Rather it may relate to changes in palaeoclimate (considered below), or simply a random cessation of deposition due, for example, to migration of the ceiling drip.

Fig. 3 shows the depth distribution of last glacial speleothem growth with time for South Andros samples, together with two samples from Grand Bahama (Richards *et al*, 1994; Lundberg and Ford, 1994). The dark shaded area is based on mean age plus 2σ error for commencement of growth and mean minus 2σ error for cessation. It defines, on the most conservative basis, a zone in which MIS 4/3 sea-levels must fall. The lighter shading employs a less conservative definition, using the mean age. At 40 - 50 ka these two zones diverge significantly because of the high uncertainties associated with AN-87-28-2 (Table 1). The resolution of the boundary between the shaded 'permitted' zone and the white 'prohibited' zone into which Quaternary sea-levels cannot have risen is determined by the frequency of samples with depth.

There is a general pattern of later commencement of growth with increasing depth (Fig.3) that agrees in its general form with sea-levels predicted from the stable isotopic composition of foraminifera in deep-sea cores by assuming a linear relation between global ice volume ($\delta^{18}O$) and sea-level calibrated using an MIS 2 low sea-level of –120m. The data used in Fig. 3 are from a Norwegian Sea core for which temperature effects are thought to be minimal (Labeyrie *et al*, 1987). The maximum sea-levels defined from the global ice volume lie below the prohibited zone defined from South Andros speleothems for the complete duration of the last glacial. Note that the predicted brief high-stand at c.60 ka (uncertainty in elevation c.± 4m) could indeed be responsible for the Grand Bahama hiatus described above. Other estimates from global ice volume, such as that of Shackleton (1987), suggest rather lower sea-levels (for example c.–50m for the 60 ka high-stand), indicating the uncertainties inherent in such predictions.

The second source of sea-level information included for comparison in Fig. 3 is from uranium-series dating of coral reefs. The most securely defined sea-level high-stand dated by high-precision uranium-series analysis of corals is that associated with MIS 5a from Barbados (Bard *et al*, 1990a; Gallup *et al*, 1994). Both the elevation of this (-13 to –18m) and the timing (83.3 ± 0.3 ka) agree well with the 79.7 ± 1.8 ka commencement of speleothem growth at –18m on Grand Bahama (Fig.3). This is believed to confirm the reliability of the constraints on sea-level placed by the speleothem dating.

Because of the low uplift rates, reefs associated with MIS 4 sea-level low-stand are not represented on Barbados, and the record from the Huon Peninsula provides the only alternative source of sea-level estimates for this period. Fig. 3 plots elevation estimates (derived from Aharon and Chappell, 1986) that were dated by alpha spectrometry (note the age of the IIIa reef crest has not been dated, and the timing of this phase is defined by a radiometric age on the transgressive phase). There is good agreement between the speleothem and these early Huon estimates, with a general tendency for the constraining elevations from the speleothem data to be higher than the coral reef derived figures (+4.9 ± 1.7m, n=5). This may simply reflect either the limited availability of speleothems with depth, or the typical difference in elevation between reef crest corals and high water (which would prevent speleothem growth) of c.4m (Curran *et al*, 1989).

The Huon terraces have however received more recent attention following a major expedition in 1988. Stein *et al* (1993) undertook high precision uranium-series dating of samples from the MIS 5e reef.

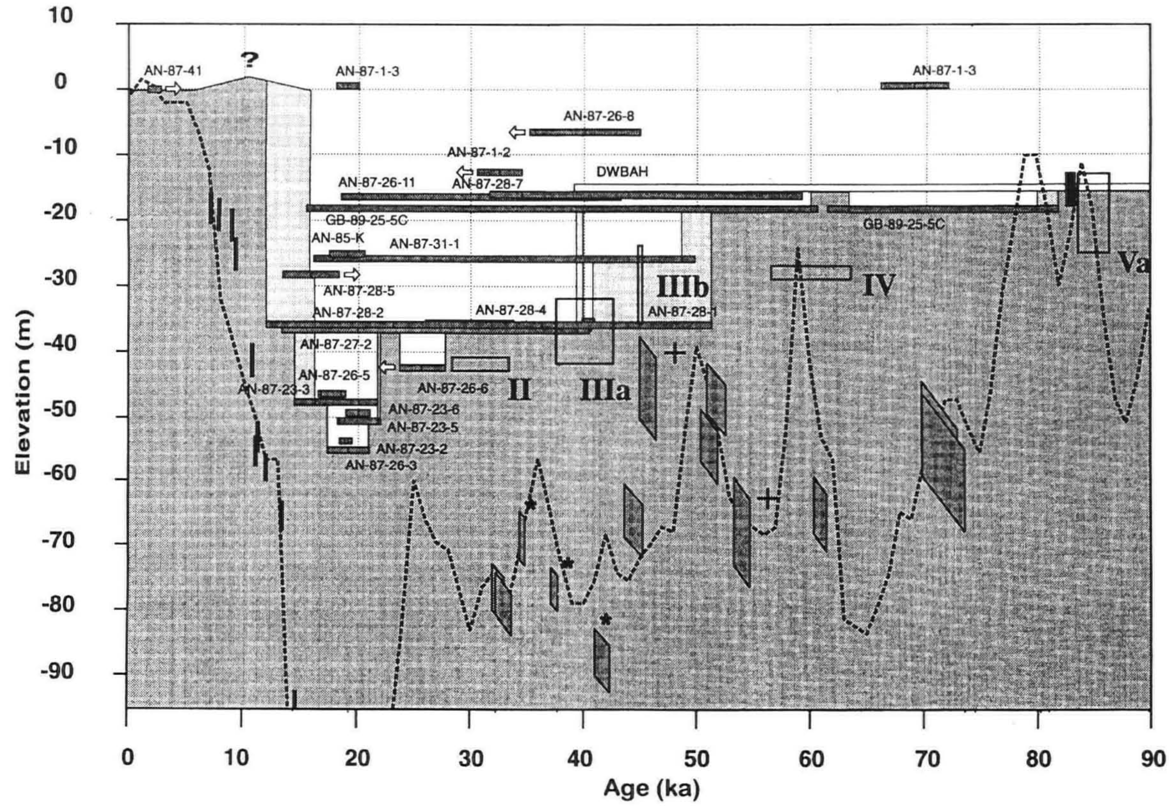

Figure 3. Age/sea-level elevation curve based on speleothems from South Andros. Horizontal bars represent periods of active deposition defined by top and basal ages of individual samples (individual ages marked by vertical line, ±2σ errors define end of bar. Bars with arrows are top or basal ages only. Also included are results from two speleothems from Grand Bahama, GB-89-25-5C (Richards et al, 1994) and DWBAH (Lundberg and Ford, 1994). For comparison, estimates of age and elevation for high sea-stands based on ages of coral reef terraces are illustrated; Huon Peninsula reefs II to Va from Aharon and Chappell (1986: rectangles) are 1σ uncertainty in height and alpha-spectrometric age, and from Chappell et al (1996: shaded trapezoids for individual samples with errors based on 2σ alpha and mass spectrometric age uncertainty and uplift rate); and mass spectrometric ages on Barbados corals from Gallup et al (1994: dark rectangle 2σ uncertainty for mass-spectrometric analysis). Also shown is post-glacial sea-level rise from mass-spectrometric analysis of Barbados corals (Bard et al 1990a: bold vertical bars), and sea-level predicted from ice volume record from the Norwegian Sea (Labeyrie et al, 1987: dashed line). For explanation of shaded areas and symbols see text.

Of 12 corals dated only 5 were found to provide reliable ages due to the often subtle effects of diagenesis. The ages clustered into two groups at c.134 and c.118 ka, with no intermediate ages, although Chen *et al* (1991) working from well exposed reefs in the Bahamas suggest that sea-level remained relatively high and constant during this time. Both erosion and variation in uplift rate were suggested as possible explanations. Although apparently collected from reef front positions, and at less than 10m from the reef crest, the sea-levels inferred from the c.134 ka samples were below –40m. This requires a remarkably rapid sea-level rise (40m/2ka) to the high-stand defined by the Chen *et al* (1991) Bahama reef data. In a subsequent study of the MIS 4/3 raised reefs (trapezoids, Fig.3), Chappell *et al* (1996) suggested that they no longer considered that individual samples could be used to define a reef crest, but rather represent independent estimates of sea-level, which can be from positions intermediate between low- and high-stands. However there is an implicit association between any systematic errors in age and in predicted elevations. For instance, samples for the IIa reef yielded ages between 34.8 and 42.2 ka (much greater than the 2σ analytical error of 0.2 - 0.3 ka). When combined with the assumption of linear uplift rate this gives a systematic age/depth shift of c.25m (starred, Fig.3). Further examination of the Chappell *et al* (1996) data, together with other analyses of Huon samples (Grun *et al*, 1992) show that consistent dating of the Huon reefs is difficult. For example, adjacent samples (crosses Fig.3) give ages that vary by as much as 10 ka. The results of Chappell *et al* (1996) are not at variance with the speleothem data from South Andros reported here; all fall into the acceptable (shaded) area of Fig.3. However, given the poor reproducibility and other difficulties that have been reported in the dating of the Huon complex, we consider the Bahamas speleothem growth constrained sea-level curve to be a more reliable constraint for Quaternary sea-level data.

As discussed previously, a second advantage of submerged speleothems for the definition of Quaternary sea-levels is that active growth may define the extent and duration of low-stands. However, the speleothem data described here are somewhat disappointing in this respect. Two deep samples, AN-87-23-6 (-53.6m) and AN-87-23-2 (-49.1m) show evidence of multiple growth phases, and one would expect speleothem growth to be represented for the periods of low sea-level preceding the Huon Terrace II and IV high sea-stands (Fig.3). However, despite extensive growth at shallow depths, none is recorded in either these or single phase samples from similar depths during MIS 3 and 4, suggesting that sea-levels did not fall to the extent indicated by the other record. Some caution must however be placed on this interpretation, as it is not certain that there is not a significant lag between sea-level fall and the commencement of speleothem growth, or that other factors are responsible for non-deposition. For the Stage 5a high-stand, there was a minimum delay of 3.6 ka between commencement of speleothem growth at –18m on Grand Bahama (Richards *et al*, 1994) and the dated high-stand on Barbados (Gallup *et al*, 1994). Given the limited duration of the low-stands implied by the Huon record, such a lag could preclude significant speleothem growth during MIS 3 and 4, but this would not be the case for the $\delta^{18}O$ derived curve, which predicts much longer subaerial exposure. Furthermore, no speleothem growth is observed below c. –55m during MIS 2, although some 10 ka elapsed between the fall in sea-level (defined by speleothem data) and the post-glacial sea-level rise (Bard *et al*, 1990a), and sea-levels are thought to have fallen below –100m at this time. A possible explanation lies in the modern geochemistry of waters in Stargate (Whitaker and Smart, 1997, 1998). Below -43m saline groundwaters are strongly reducing and bacterial oxidation of organic matter entering from above occurs by sulphate reduction generating H_2S. Subsequent oxidation of H_2S generates acidity, which attacks both wall-rock and speleothem, leading to direct dissolution of the latter and also detachment from the commonly vertical walls of the fracture-controlled void. This suggestion is confirmed by the recovery of highly corroded/etched fragments of speleothem from breakdown that forms the floor of the blue hole at –70 to -80m.

Post-glacial speleothem deposition: implications for palaeoclimate

The post-glacial sea-level rise constrained by the cessation of speleothem growth is much more rapid than the decline of sea-level towards the glacial maximum (Fig.3). However, although the data parallel the sea-level rise determined from the dating of corals (Bard *et al*, 1990a), there is a systematic deviation between the two records, with the South Andros speleothem curve leading the coral data by c.5.5 ka, or more correctly c.35m. This cannot simply be explained by differences in the sensitivity of the two indicators to the position of sea-level (as discussed above). Nor is it easy to envisage a process that could progressively terminate speleothem deposition in advance of rising water level in a vertically extensive vadose zone. In fact, an alternative view is that speleothem growth was terminated by an event other than rising sea-level. Closer examination of the data shows that there is no depth dependence of cessation age, some shallow samples such as AN-85-K (-25m) terminating relatively early (as indeed did subaerial deposition in AN-87-1-3 from +0.2m; 19.1 ± 0.1 ka). The mean cessation age calculated from the extrapolated and top only ages is 18.6 ± 2.7 ka (n=7), a timing coincident with the marked climatic changes that drove deglaciation. In fact the cessation ages from Grand Bahama included in Richards *et al* (1994) are significantly younger than those for South Andros (mean 14.8 ± 2.2 ka). This difference may possibly reflect the much shallower (<20m) depth of the Grand Bahama samples, but could also be related to regional differences in palaeoclimate between the two areas that are separated by some 200km.

A second observation suggests to us that speleothem growth on South Andros is climatically controlled. In Table 1 four of the six whole phase analyses are for the period 19 - 20 ± 1.5 ka, and of the 10 paired analyses, four define a rapid growth phase during this same period. This pattern is confirmed in Fig. 4, in which the frequency of actively growing speleothems is plotted. The curve is prepared by determining the frequency distribution of initiation and cessation ages using the distributed error frequency method (Gordon *et al*, 1989), which considers uncertainties in the age determinations. The frequency of actively growing samples is ten, derived by subtracting the cumulative frequency curve of initiation ages from that of cessation ages in 50 year time steps (Richards, 1995). Minor peaks and troughs are associated with the contribution of individual high precision analyses within the quite small data set. However, there is a general pattern of increased speleothem growth from 60 ka to 40 ka, a minor peak at c.30 ka, and a major peak at 20 ka. We do not believe that this major peak simply reflects the greater depth of unsaturated zone for speleothem deposition as sea-level fell, because (as discussed above) other periods of probable low sea-levels such as MIS at c.70 ka are not marked by enhanced deposition.

It is stressed above that for stalagmite deposition to occur, sea-level must be below the site of deposition in the blue hole. However, there must also be sufficient recharge (precipitation minus actual evapotranspiration) to cause flow into the cave void, and a sufficiently high soil (or ground air) CO_2 concentration to raise calcium carbonate concentrations above those at equilibrium with an atmospheric value (0.0003 atm). Finally, the cave void must be well ventilated, or CO_2 concentrations may build up preventing degassing of percolating groundwater. This is unlikely to have been a problem in Stargate, as we have already demonstrated than an open entrance was present prior to MIS 6.

At present on North Andros the pCO_2 of soil air (0.0074 ± 0.0037 atm - Smart and Whitaker, 1988) and vadose percolation waters (0.0040 ± 0.0018 atm - Whitaker, 1992) is sufficient on degassing to precipitate speleothems. However, inspection of caves such as Morgans Bluff Cave (North Andros) and Rat Bat Cave (South Andros) indicates there is very little present-day speleothem deposition. Observations during the summer wet season suggest that this is due to an absence of drip water. In this area annual precipitation is approximately equal to the potential evapotranspiration (1340 and 1175mm/a on North and South Andros respectively), although effective evapotranspiration is probably much lower (c.800mm/a). We hypothesise that the relatively high intergranular and vuggy permeability of the Bahamian limestones retains both sufficient capacity and capillarity to accommodate present-day rates of recharge without lateral diversion to open cave voids. There have not, however, been any studies of actual recharge processes in this type of carbonate to confirm this suggestion.

Other sources of evidence for the terrestrial last glacial climate of the area are now considered. These are unfortunately quite limited. Records of the terrestrial last glacial palaeoclimate for the study area are few. Pollen in a core from Sheelar Lake, Florida indicate dry cold and windy conditions between 23,880 and 18,500 yr BP (26.5 and 21.5 ka using the calibration of Bard *et al,* 1990b), but above this there is a hiatus in the core that lasted until 14,600 yr BP (17.2 ka) (Watts and Stuiver, 1980). The latter could either be associated with regional lowering of the piezometric surface in the Floridian aquifer during maximum glacial sea-level depression (Kutzbach and Wright, 1987), or to regional aridity. General circulation models of the last glacial maximum indicate that the Laurentide ice sheet had a significant orographic effect, causing the jet stream to bifurcate over North America, with a strong branch flowing around the southern edge of the ice sheet. The NCAR/CCM model used by Kutzbach and Wright (1985) suggests that over much of southeast USA, effective rainfall was a little less than today due to lower sea-surface temperatures, and the influence of subsiding air at the exit of the summer time jet core. Further to the south, over much of the Caribbean, latest estimates (Kutzback *et al,* 1998) suggest that summer rainfall was increased by 0.5 - 1.0mm/day. Using the NASA/GISS model, Rind and Peteet (1985) reported that increased precipitation affected much of the northeast Atlantic seaboard of the USA (including the Bahamas), as frontal systems were intensified in the area of strong temperature gradient between the ice sheet and the ocean. Effective precipitation in the Bahamas may then have been as much as 2mm/day greater than present, equivalent to nearly doubling of the mean annual precipitation for South Andros. Such an effect would clearly increase vadose groundwater flux, and may have been sufficient to exceed capillary flow routes, allowing copious speleothem deposition to occur in well-ventilated cave voids. Although several general circulation models support the suggestion that precipitation was higher at the last glacial maximum, the prediction of precipitation by such models is generally recognised as poor. Further palaeoclimate data are needed from field studies in the Bahamas to confirm these suggestions of increased last glacial precipitation.

Overpeck *et al* (1989) have suggested that, following the last glacial maximum, meltwater entering the Gulf of Mexico via the Mississippi may have caused a dramatic local cooling, strengthened western Atlantic trade winds and a significant decrease in precipitation in the Gulf region. Geological data from North America (Teller, 1990) and stable isotope data from foraminifera in sediments from the Gulf of Mexico (Kennet and Shackleton, 1975; Leventer *et al,* 1982) suggest that the inflow of cold melt water began at 16,000 yr BP (18.6 ka). This is in very good agreement with the cessation of speleothem growth on South Andros (18.6 ± 2.7 ka). Using 11,000 yr BP orbital parameters and land-ice conditions, and a 6°C reduction in Gulf sea-surface temperatures, the NASA/GISS model predicts c.2mm/day reduction of precipitation in the Bahamas area (Overpeck *et al,* 1989). Similar results are reported for a range of reduced temperature by Oglesby *et al* (1989) using the NCAR/CCM model. The abrupt cessation of speleothem growth on South Andros therefore appears to be in response to a major decrease in effective precipitation associated with the initiation of deglaciation in North America.

DISCUSSION AND CONCLUSIONS

It appears that Pleistocene speleothem growth in the Bahamas is highly sensitive to variations in precipitation. These are caused by changes in atmospheric circulation and moisture associated with the growth and decay of the Laurentide ice sheet. Throughout much of the glacial period speleothem growth has not been limited on South Andros, suggesting wetter conditions than present (and permitting reliable recording of past sea levels). During the glacial maximum deposition was greatly enhanced, while at the start of deglaciation it terminated abruptly due to the commencement of melt water discharge into the Gulf of Mexico. This could only occur when eastward flow through the St Lawrence River was inhibited by the presence of ice. On the basis of negative anomalies in planktonic foraminifera $\delta^{18}O$ from high resolution cores in the north-eastern Gulf of Mexico, Joyce *et al* (1993) report that major melt-water events also occurred at the cessation of the penultimate glaciation and at the MIS 4/3 boundary. The latter may correlate with the hiatus in the Grand Bahama flowstone between 63 and 59 ka discussed above. The early cessation of MIS 6 speleothem growth reported here is thus potentially of great significance because it suggests that deglaciation may have commenced before or, more probably, was synchronous with the increase of northern hemisphere insolation from the minimum at 141 ka to the maximum at 128 ka (Berger and Loutre, 1991). A similar suggestion has been made by Winograd *et al* (1992) from the stable isotope record of a well-dated vein calcite from Devils Hole, Nevada, and is not at variance with the chronology of the Vostock ice core (Jouzel *et al,* 1993). Given the considerable debate that has resulted from the Devils Hole study, confirmation of the timing of the MIS 6/5 boundary in other samples from the Bahamas would be very worthwhile.

The sensitivity of Bahamian speleothem growth to palaeoclimate does, however, introduce some uncertainty into the interpretation of the sea-level record from speleothem dating. This may be partially overcome if it is possible to demonstrate contemporaneous growth in subaerial or shallow samples at the times of initiation/cessation in deeper samples. In contrast to the coral reef record, where diagenesis can be a problem (particularly in wet areas such as the Huon Peninsula), the dating of this speleothem record is very reliable. This, together with the unambiguous constrains on sea-level imposed by the occurrence of active speleothem deposition, suggests that other sources of sea-level data should be tested against the speleothem constrained sea-level curve before being considered reliable. However, detailed structure is largely absent in the South Andros record because few individual samples show evidence of multiple growth phases, and the potential for dating of low sea-stands has not at present been realised by our study. Although further sampling could overcome this problem, conservation ethics limit the number of samples (and therefore phases at a particular depth) that can be dated. There is a marked contrast here between samples from Grand Bahama, which show extended records with multiple growth phases, and those from Andros. The Grand Bahama samples are, however, from caves with a more limited depth range than those sampled in the fracture-guided blue holes of South Andros. Fracture-guided sites such as Great North Road (Palmer, 1985) are present on Grand Bahama, but reconnaissance suggests speleothem preservation is poor. Thus, at present, any record that over-predicts actual sea-level lowering cannot be refuted by the speleothem constrained curve.

Existing underwater studies discussed here are in many ways scientifically primitive, lacking the development of a detailed geomorphological history of the caves and the sequence of deposits that occur within them, as would be normal in a subaerial system. With the general adoption of technical mixed gas diving pioneered during the Andros Project, this may now be possible. Together with the wider understanding of the types of samples that are most suitable for sea-level studies, it may now be timely to re-examine the South Andros caves.

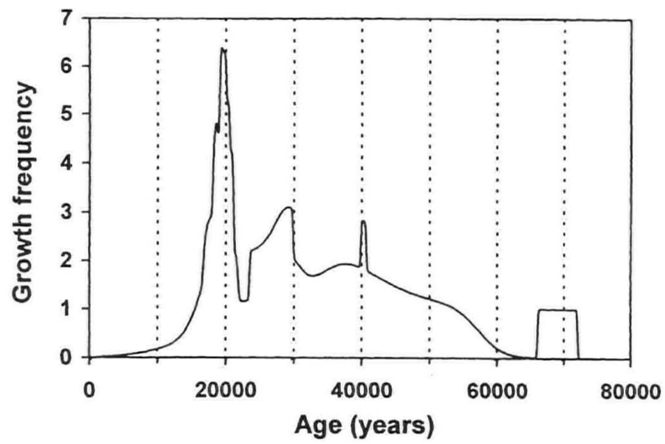

Figure 4. Speleothem growth frequency versus age for South Andros samples.

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Hydrology, geochemistry and diagenesis of fracture blue holes, South Andros, Bahamas

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Abstract: On the east coast of South Andros Island, Bahamas, a major bank-margin fracture system characterised by vertically-extensive cavern systems (blue holes) is developed sub-parallel to the steep-sided deep water re-entrant of the Tongue of the Ocean. In addition to providing a discharge route for meteoric, mixed and geochemically-evolved saline groundwaters, the fracture system hosts a strong local circulation. Tidal pumping along the fracture system causes enhanced mixing within the fracture caves. Within the fracture caves, the salinity of the brackish lens increases, lens thickness decreases and the mixing zone thickens progressively from north to south. This suggests a net southerly flow along the fracture, possibly in response to tidal lags amplified by the complex topography of the offshore reefs and cays. Tidal head also drives exchange between fracture cave waters and pore waters in the surrounding aquifer, affecting up to 200m either side of the fracture.

Blue hole waters are geochemically distinct from those of the surrounding aquifer, due to enhanced mixing as well as ingress of surface derived organic material from open entrances. Carbonate supersaturation at shallow depths results from degassing of CO_2 sourced from photosynthesis beneath open entrances and oxidation of organic matter. Below this shallow zone, waters are undersaturated with respect to aragonite but remain slightly supersaturated with respect to calcite. Waters in the fresh-salt water mixing zone are calcite undersaturated and approach equilibrium with respect to disordered dolomite. Saturation indices are significantly lower than predicted by theoretical mixing calculations, due to *in situ* generation of CO_2 by organic matter oxidation and partial dissociation of H_2S where the organic matter oxidation occurs by sulphate reduction. The redox interface is an important locus for dissolution driven by the re-oxidation of reduced sulphur species.

The product of enhanced groundwater flow, inorganic mixing and organic matter oxidation is the generation of significant diagenetic potential. Pervasive dissolution of both allochems and matrix within the predominantly low-magnesium calcite bedrock occurs. This enhances porosity significantly and, at the macro-scale, produces a characteristic 'Swiss cheese' fretting, particularly in the upper mixing zone. In addition to controlling aqueous geochemistry, bacterially-mediated processes may be responsible for precipitation of an iron-rich crust on the walls in the lower mixing zone. Maximum undersaturation occurs in the lower mixing zone but dissolution is most intense above this, possibly reflecting the distribution of iron-oxides. Although dolomite is not apparent in thin sections, bulk rock analysis reveals minor enrichment in magnesium relative to wall-rock above and below the mixing zone. This suggests localised and limited dolomitisation, possibly influenced by organic matter oxidation by sulphate reduction in the surrounding waters.

INTRODUCTION

Diagenesis is the sum of processes acting on a sediment after deposition, which alter not only the composition and texture of the sediment, but also its porosity and permeability. Diagenesis depends both on aqueous geochemistry, which controls the precipitation and dissolution of mineral phases, and on fluid circulation to supply the reactants and remove the dissolved products. Carbonate sediments are particularly susceptible to early diagenetic modification, as they comprise metastable phases such as aragonite and high-Mg calcite. These are easily converted to low-Mg calcite by meteoric waters, and may also be subject to dolomitisation. In carbonates the degree and distribution of diagenetic change is commonly equally as important as, if not more important than, the original depositional facies in determining porosity and permeability. Carbonates host an estimated 44% of global oil reserves (Roehl and Choquette, 1985) and an estimated 25% of the World's population is supplied largely or entirely with water from carbonate groundwaters (Ford and Williams, 1989). Thus a better understanding of the distribution of diagenetic phenomena is critical for prediction of reservoir properties and sound management of hydrocarbon and groundwater resources.

The Bahama Banks are the largest extant carbonate platform in the World, and provide a natural laboratory for studying the processes of modern diagenesis. The extensive network of flooded caves (blue holes) enables direct access to groundwaters within the interior of the platform. This paper examines the hydrology and geochemistry of groundwaters circulating within a major bank-margin fracture system on the east coast of South Andros Island, Bahamas, and the resulting wall-rock diagenesis. This represents a major part of fieldwork carried out in 1986 and 1987 as part of the International Andros Project, inspired and led by Rob Palmer. Some aspects of this work have been published previously (Smart *et al*, 1987, 1988; Smart and Whitaker, 1988; Whitaker, 1992; Whitaker and Smart, 1997a), and the reader is referred to these sources for more detailed discussion.

METHODS

Hydrology

Vertical distribution of fresh and saline groundwaters was examined at 19 blue holes along the 8km onshore "Bluff Section" of the fracture system (Palmer *et al*, 1998), using specific electrical conductance as a measure of salinity, either profiling down from the surface using a probe with 100m cable, or using *in situ* measurements taken by divers. Groundwater flow was apparent in the upper part of the lens at some inland fracture sites from the orientation of fish and streaming of bacterial filaments, while in ocean holes strong currents could easily be observed and felt by divers. Within the saline waters of Stargate Blue Hole fluorescein dye was released from a point in the centre of the passage at -37m, and periodic qualitative observations were made of direction and extent of dispersion.

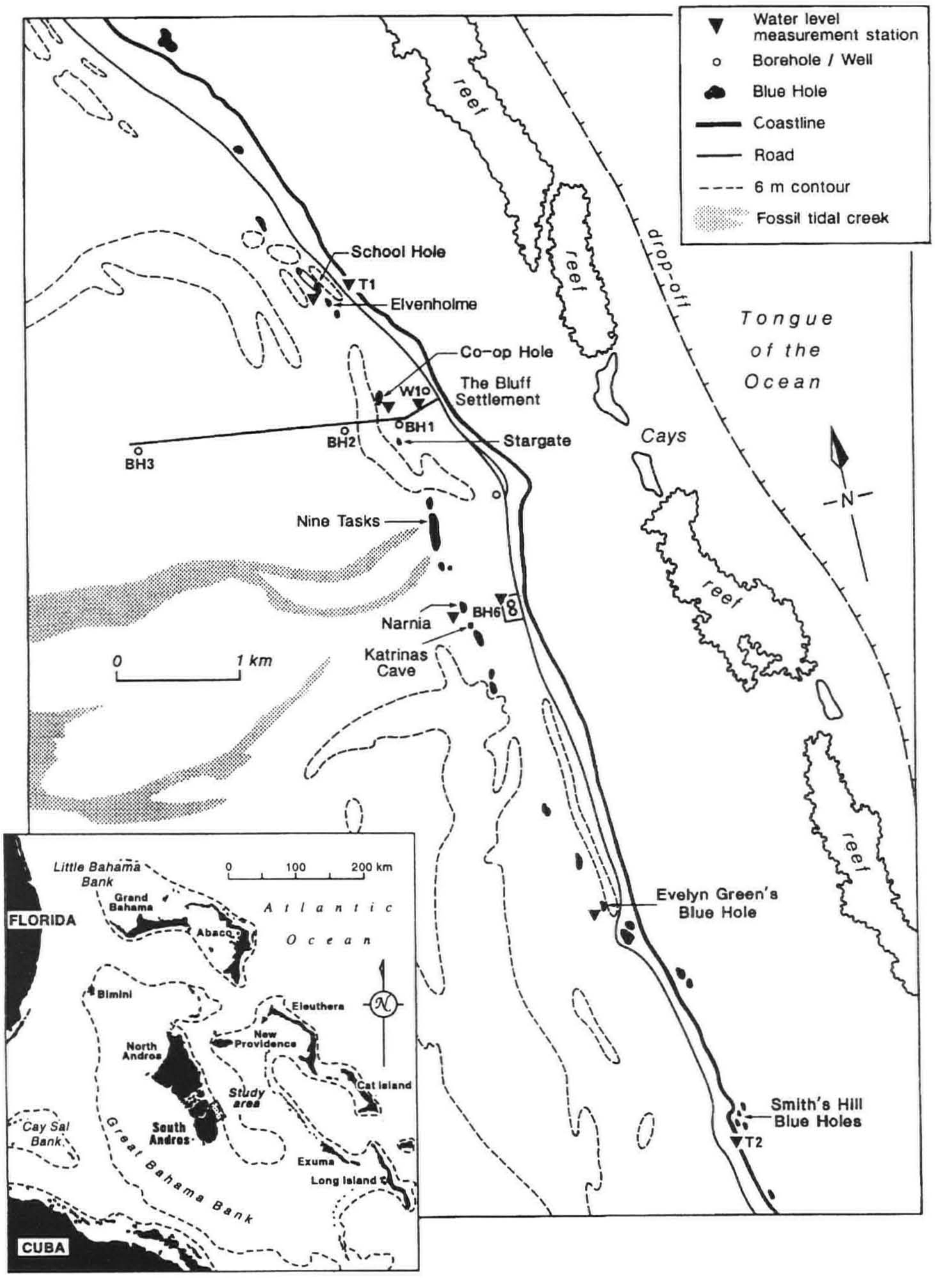

Figure 1. Location map of the study area on South Andros Island, Bahamas showing monitoring sites and the fracture system marked by a chain of blue holes (after Whitaker and Smart, 1997a).

Temporal variations in water level in response to semi-diurnal fluctuations in ocean tidal head were monitored at intervals of approximately 60-90 minutes over a 12-hour tidal cycle. Ocean tides were recorded at coastal sites at both ends of the onshore fracture section (T1 and T2, Fig.1), and groundwater levels were monitored at 4 inland blue holes along the fracture system (School, Co-op, Narnia, and Evelyn Green's blue holes). Temporal variations in the depth of the top of the mixing zone at School Hole, 2.75km from the northern end of the onshore fracture section, and the salinity of waters discharging from the ocean hole immediately offshore of the southern end of the fracture system (Smith's Hill Blue Holes) were measured at the same time. Water-level variations are expressed as a percentage of those at the coast (±5%), defining the tidal efficiency of the site.

Geochemistry

A total of 100 samples of fracture groundwaters, discharges from ocean blue holes and Tongue of the Ocean (TOTO) seawater were collected for geochemical analysis. At five inland fracture sites (3 main sites - Elvenhome, Stargate and Evelyn Green's, and 2 subsidiary sites - Cavalier Canyon and Katrinas Cave) 86 water samples were collected at depth intervals from the surface, through the brackish lens and mixing zone, and into the saline groundwater to a maximum depth of 70m. Sampling depths were targeted using *in situ* measurement of conductance and temperature, and undisturbed samples collected by divers using 7cm-diameter 1.5L plastic tubes, which were filled by forward motion of the diver and capped underwater. Similar techniques were used to sample discharges from 5 ocean fracture blue holes at the midpoint of the rising limb of the tidal cycle prior to reversal of flow direction. In addition, 12 samples of fresh groundwater in the surrounding aquifer were taken from static boreholes and wells using a down-hole sampler.

At the surface, samples were flowed through a closed stirred cell for measurement of pH (±0.02 pH units) using a high precision digital meter calibrated with low ionic strength NBS standard buffers, conductance, dissolved oxygen and temperature. Sub-samples were taken for immediate analysis of alkalinity and calcium by titration, and after pressure, were acidified to pH <2 for later analysis of other major ions by standard techniques (sulphate by turbimetry; chloride by mohr titration, sodium, magnesium, potassium and strontium by atomic adsorption spectrophotometry). All dilutions were weighed and analytical uncertainty was <±1%, except turbimetric sulphate analysis which had an uncertainty of ±4%. Ion balance errors for all samples are <5% and are normally distributed around a mean of zero.

The aqueous speciation model PHREEQE (Parkhurst *et al*, 1980) was used to calculate the PCO_2 with which the waters were in equilibrium, and their saturation state with respect to carbonate minerals. Equilibrium constants for aragonite and calcite were derived from Plummer and Busenberg (1982) and for dolomite (ordered and disordered) from Helgeson *et al* (1981). Geochemical modelling was also used to simulate mixing of two solutions of differing composition between fresh and saline groundwaters, and also the extent of any resulting carbonate dissolution/precipitation. Full details of analytical techniques and geochemical simulations are given in Whitaker (1992).

Diagenesis

A description of the gross wall-rock morphology was made in 3 fracture blue holes (Elvenhome, Stargate and Evelyn Green's) and hand samples collected at vertical intervals of c.1m for petrographical analysis. Samples were impregnated with blue epoxy resin and stained with Alizarin Red-S prior to thin-sectioning. Selected samples were also examined under the scanning electron microscope. Major and trace element concentrations were determined on bulk samples using atomic adsorption spectrophotometry, and crusts on the surface of wallrock samples were analysed by x-ray diffraction.

RESULTS

Hydrology of the fracture system

Groundwaters sampled from blue holes along the onshore section of the bank margin fracture system range in salinity from brackish at the water table to close to that of sea-water at and below depths of 20 to 25m. The salinity profile shown in Figure 6 from Evelyn Green's Blue Hole shows a stratification typical of all sites studied. The brackish lens is relatively homogeneous vertically, although some sites show a gradual increase in salinity with depth, and others have minor steps in the salinity profile. Fracture waters are significantly more saline than the fresh waters sampled in boreholes and hand-dug wells in the surrounding aquifer (generally <1‰, and <4‰, even where over-pumping has led to salinisation of the lens, Whitaker and Smart, 1997). The brackish lens is underlain by a broad mixing zone 3 to 9m thick. Mixing occurs between brackish lens waters and saline ground waters that are geochemically similar to sea water. However, below a 5 to 20m-thick zone of active circulation, more stagnant saline ground waters are geochemically evolved, compared with local TOTO sea water, and in some cases they are of slightly elevated salinity.

Salinity of the brackish lens increases from 3.8‰ at the northern end of the Bluff Section to 9.4‰ at the southern end, with the most rapid increase between 3.5 and 4.0km from the northern end of the fracture (Fig.2a, between Stargate and Narnia blue holes). In association with this, the thickness of the brackish lens diminishes from 20m to 12m southwards along the fracture system (Fig.2b). Although there are only 10 sites where conductivity profiles to the base of the fresh-salt water mixing zone could be obtained, this zone is thinnest at the northern end of the fracture system (3m) and increases southwards to a maximum thickness of almost 9m. These observations are most readily explained by a net southerly flow along the fracture system, with progressive mixing of the brackish lens with underlying saline waters. Maximum mixing occurs at sites where breakdown material infills the fracture at and above the depth of the base of the mixing zone. This may in part explain the marked increase in lens salinity near Nine Tasks (c.4km from the northern end of the fracture), where collapse has been extensive, possibly associated with the interception by the fracture of an east-west oriented fossil tidal creek (Fig.1) that may represent a preferential route of groundwater discharge from the centre of the island.

Support for the hypothesis of a net southerly flow was obtained by direct observation of groundwater movement in the top of the brackish lens at Narnia. Of 7 observations equally distributed over a twelve hour period, 5 showed flow to the south, with northward movement limited to some 3 to 4 hours only (Fig.3). Outflow from Smiths Hills ocean holes at the southern end of the Bluff Section of the fracture system was also more prolonged than inflow (6 versus 4.5 hours). Net southerly flow was also observed directly in the saline waters of Stargate Blue Hole, using fluorescein dye (Whitaker and Smart, 1997a).

Observed semi-diurnal reverses in flow direction indicate that water movement in the system is related to the pumping action of the ocean tides. The net southerly movement could readily be explained by a head differential between sea-surface elevations at either end of the fracture system, in combination with flood currents that are stronger than those on the tidal ebb. In the TOTO the tides are known to be lagged from north to south, and this delay may be amplified on the banks where currents are restricted by the shallowness of the water and the presence of reefs and cays (Fig.1). Flow of seawater into the fracture conduit was observed at the Smiths Hill Blue Holes in response to the inland hydraulic gradient established at high tide, and this flow reversed at low tide. Considerable volumes of water are involved in this "suck and blow" cycle and velocities are such that at many sites diving is possible only at slack water. Volumetric discharges at ocean holes on South Andros were not measured, but at a comparable site on the east coast of North Andros, peak velocities in excess of $0.45ms^{-1}$ have been recorded, with $4.5 \times 10^5 m^3$ exchanged over a single tidal cycle (Whitaker and Smart, 1990, 1993a).

Water levels within the 4 monitored inland fracture blue holes oscillate in response to ocean tides with a tidal efficiency (amplitude of fluctuations relative to those at the coast) that ranges from 45 to 65% (e.g. Fig.3a). There is no discernible lag in the tidal signal (<30 minutes resolution), indicating rapid propagation of pressure waves within the conduit. At School Hole, 1.75km from the northern end of the fracture section, the tidal efficiency is 41% at the water table and 94% at the top of the mixing zone, compared with 25% in an adjacent borehole. Thinning of the lens appears to occur at high tide, with displacement of the brackish lens water into the surrounding aquifer. Using a pump test aquifer transmissivity of 2160 md^{-1} (Cant, 1979), an average lens thickness of 14m over an 8.6km length of fracture system, and measured hydraulic gradient of 1.93×10^{-3} from BH6 to Narnia, it is estimated that 3.7 x 104 m^3 of water is expelled from the fracture voids into the surrounding aquifer over each tidal cycle, affecting a zone up

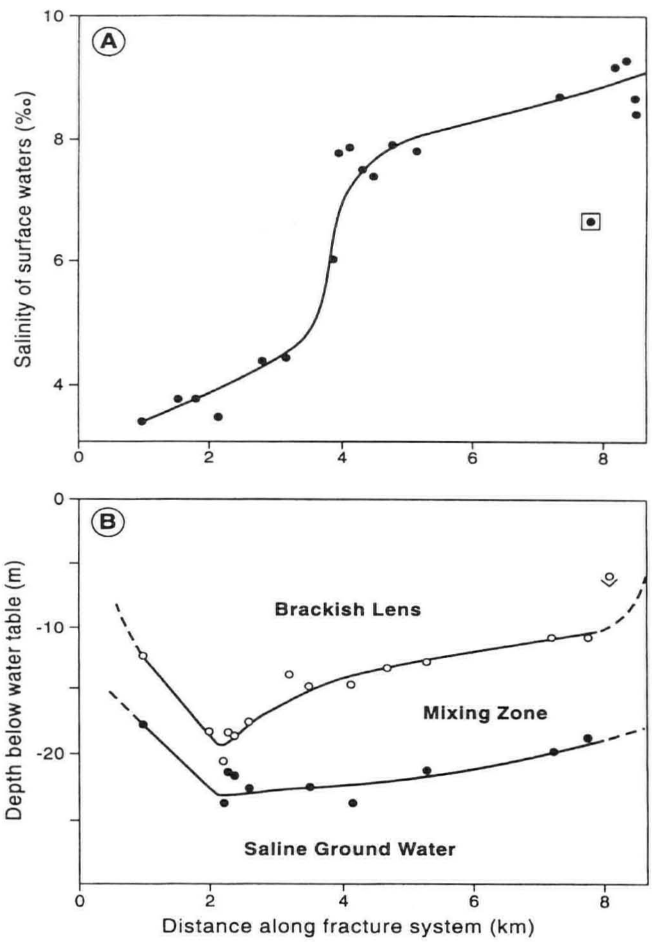

Figure 2 (a) Surface salinity of the brackish lens waters (outlier boxed) and (b) depth of the top and bottom of the mixing zone at blue holes along the fracture system (after Whitaker and Smart, 1997a).

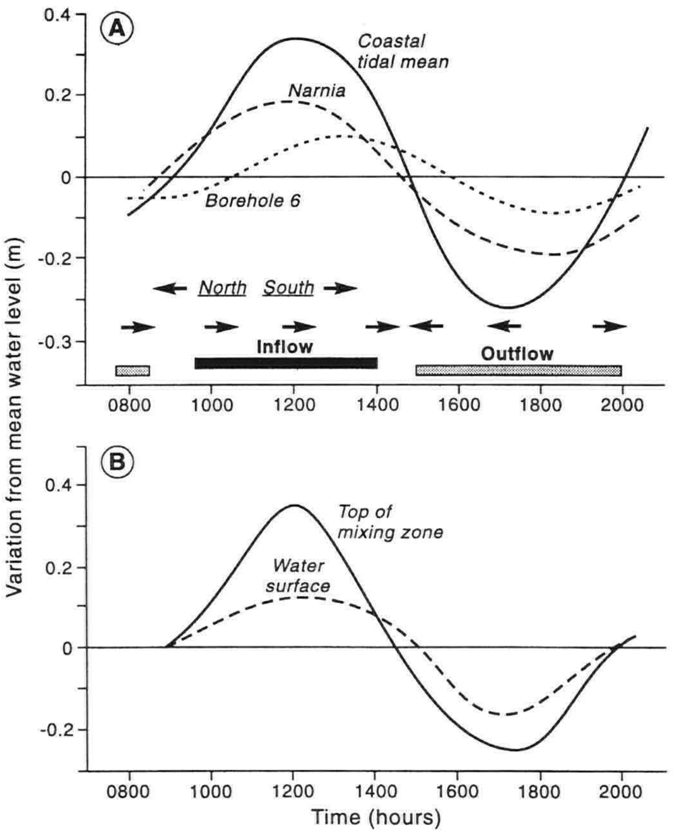

Figure 3 (a) Comparison of water level fluctuations at the coast, Narnia Blue Hole and Borehole 6. Arrows indicate the direction of flow observed in the brackish lens at Narnia, shaded bars show periods of inflow and outflow of saline water at Smith's Hill ocean hole. (b) Fluctuations in elevation of water surface and top of the transition zone at School Hole (after Whitaker and Smart, 1997a).

to 200m wide on either side of the fracture. This tidally-driven pumping may have important implications for diagenesis in the aquifer surrounding the fracture system (Whitaker and Smart, 1997a).

Geochemistry of fracture groundwaters

The brackish lens waters from the surface of the blue holes are degassed, resulting in a high degree of carbonate supersaturation. Below the upper 2 to 3m, PCO_2 increases gradually to an average 0.99%, more than 30 times atmospheric level and comparable with non-degassed fresh waters from the surrounding aquifer. Carbonate saturation decreases with depth through the brackish lens, approaching aragonite saturation but most waters remain slightly supersaturated with respect to calcite. This suggests that carbonate saturation may be controlled by the least stable mineral phase in the bedrock, aragonite, even where this is present in only relatively small amounts (<10% in the upper 10m of the bedrock at Evelyn Green's: Whitaker, 1992). Because of their relatively high magnesium content (from seawater and/or high-Mg calcite stabilisation) all fresh and brackish waters are supersaturated with respect to ordered dolomite. Non-degassed fresh waters may dissolve disordered dolomite, while those in the brackish lens of the fracture approach equilibrium with disordered dolomite.

Vertical mixing occurs between brackish lens waters and underlying saline groundwaters. The saline groundwaters sampled within the fracture system are geochemically distinct from sea water, having a significantly higher PCO_2, lower carbonate saturation and slightly elevated salinity. There is some evidence of depth dependence, with waters 0 to 10m below the mixing zone having a significantly higher calcite saturation index and lower PCO_2 than those from greater depth (Whitaker and Smart, 1997a). Saline groundwaters discharging from ocean blue holes are also elevated in salinity, and their PCO_2 and carbonate saturation are intermediate between fracture saline groundwaters and sea water (Fig.4). Even those discharging from ocean holes more than 10km southward along the submarine section of the fracture, show a significant groundwater component (Fig.4). The fracture system clearly acts as a major discharge route for saline platform groundwaters that may circulate to considerable depth. Studies of blue holes on North Andros (Whitaker and Smart, 1990, 1993a) have demonstrated the existence of a large-scale saline groundwater circulation system, with waters concentrated by evaporation on the shallow bank to the west of Andros flowing east beneath the island.

Geochemical modelling demonstrates that mixing of waters from the base of the brackish lens with shallow saline ground waters (of greater

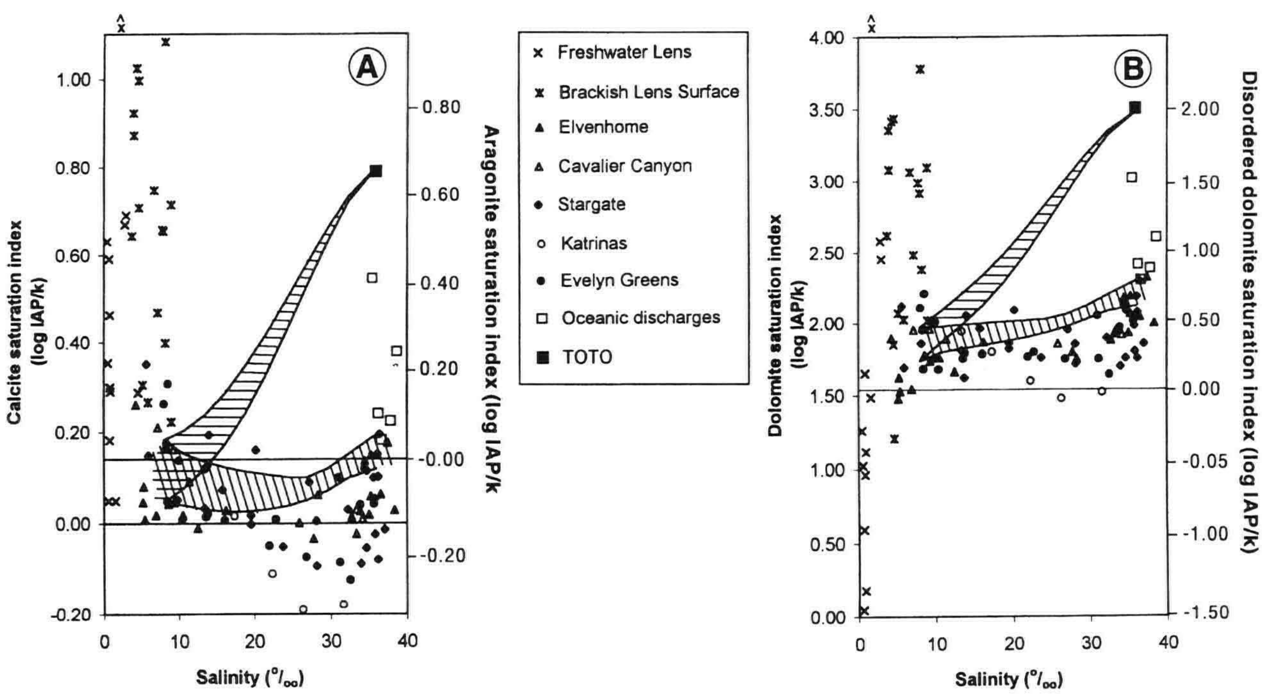

Figure 4. Variation in saturation with respect to calcite and aragonite (a) and ordered and disordered dolomite (b) with salinity for fracture blue hole waters (main study sites identified individually by symbols; crosses show surface samples of brackish lens waters from other sites), freshwater lens from boreholes and wells, discharges from ocean blue holes and TOTO seawater. Range of values predicted for mixing of fracture basal brackish lens waters with saline groundwaters (angled hashing) and TOTO sea water (horizontal hashing) are shown for comparison.

ionic strength and lower PCO_2) is capable of generating aragonite undersaturation, but that all mixtures remain supersaturated with respect to calcite (Fig.4). This contrasts with the classic mixing results of Plummer (1975), which predict maximum depression in saturation within the upper mixing zone. This difference arises from Plummer's use of a sea-water end-member, rather than the saline groundwater used here. Dolomite saturation is predicted to increase through the mixing zone as magnesium concentrations increase with salinity, with all mixtures of brackish lens and saline groundwater supersaturated with respect to ordered and disordered dolomite.

In comparison the real waters shows considerable reduction in saturation through the mixing zone, with a significant number of middle and lower mixing zone samples undersaturated with respect to calcite (Fig.4). Furthermore, the observed trend in saturation index does not mirror that predicted by mixing calculations, but varies systematically through the mixing zone with an initial reduction in the upper part of the mixing zone and more marked peak at the base of the mixing zone. According to the 'Dorag' model of dolomitisation (Badiozamani, 1973) dolomites might be expected to form in the lower mixing zone, where waters are undersaturated with respect to calcite but supersaturated with respect to dolomite. In practice, waters remain supersaturated with respect to stoichiometric dolomite, but the degree of saturation decreases through the mixing zone in parallel with that of calcite. However, all mixing zone waters remain close to saturation with respect to disordered dolomite.

Simple inorganic mixing models are clearly inadequate to account for the patterns of mineral saturation observed in these mixing zone waters. The PCO_2 of mixing zone waters is elevated compared to that predicted from simple mixing of fresh and saline end-members, due to *in situ* bacterial oxidation of particulate and dissolved organic matter, which is predominantly surface derived. Organic matter percolates down through the water column and become suspended in the density gradients within the brackish lens and mixing zone, as well as accumulating on rock ledges and at the bottom of the caves. Within the water this also gives rise to a marked brown colouration and to suspended organic flocculates, comparable to those observed in estuarine mixing zones (Mantura, 1987).

Under oxic conditions, bacterial oxidation of organic matter proceeds by reaction 1:

$$C_6H_{12}O_6 + O_2 \Leftrightarrow 6HCO_3^- + 6H^+ \qquad [1]$$

However, once all dissolved oxygen has been consumed, sulphate becomes the dominant electron receptor, and organic matter oxidation occurs according to reaction 2:

$$C_6H_{12}O_6 + 3SO_4^{2-} \Leftrightarrow 6HCO_3^- + 3H_2S \qquad [2]$$

This is evidenced by depletion of sulphate in the mixing zone by as much as 700 mgL^{-1} relative to the concentrations predicted from conservative mixing with seawater (Fig.5a). Sulphide concentrations mirror the pattern of sulphate depletion, with distinct peaks in the upper mixing zone (particularly in Elvenhome and Cavalier Canyon) and also in the lower mixing zone (Fig.5b). The peaks may be associated with layering of bacterial communities whose vertical distribution within the water column appears to be controlled by salinity and dissolved oxygen gradients. Note that sulphide concentration is orders of magnitude smaller than net sulphate depletion as the latter is a cumulative product of sulphate reduction along the groundwater flow path (see discussions in Whitaker, 1992). Studies of sulphur isotope composition from an inland blue hole on North Andros Island (Bottrell *et al*, 1990) show ^{34}S enrichment of residual sulphate in the mixing zone, confirming the importance of microbial reduction of sulphate in these environments.

Reduced sulphur species produced in the mixing zone are able to diffuse through the water column (as water soluble gaseous H_2S) along a concentration gradient established by reaction with an oxidising agent:

$$H_2S + O_2 \Leftrightarrow 2H^+ + SO_4^{2-} \qquad [3]$$

Reactions 1 (aerobic oxidation of organic matter) and 3 (re-oxidation of reduced sulphur species) are both capable of generating acidity and therefore are likely to drive carbonate dissolution in an organic-rich mixing zone environment. Whereas many studies have concentrated on the potential of reaction 2 (organic matter oxidation by sulphate reduction) to drive carbonate precipitation (Berner, 1971), partial sulphate reduction promotes carbonate dissolution as the impact of the reduction in pH exceeds that of the alkalinity increase (Morse and Mackenzie, 1990; Stoessel, 1992). However, this is less efficient per mole of organic carbon than aerobic oxidation, the latter producing undersaturation equivalent to the combined effect of sulphate reduction and re-oxidation of reduced sulphur species (Whitaker, 1992).

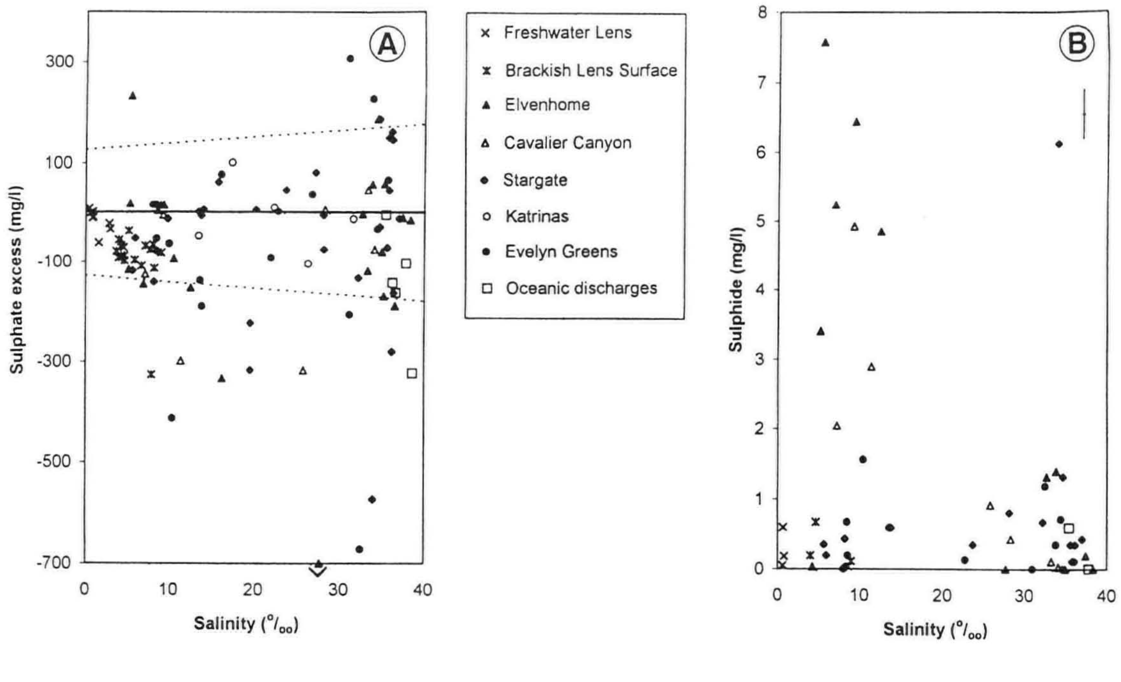

Figure 5. Variation in sulphate excess (a): calculated relative to dilution of local TOTO seawater: $SO_{4\,XS} = SO_{4\,SAMPLE} - [SO_{4\,TOTO} \times (Cl_{SAMPLE}/Cl_{TOTO})]$, *and sulphide concentration (b) with salinity for fracture blue hole waters (main study sites identified individually by symbols; crosses show surface samples of brackish lens waters from other sites), freshwater lens from boreholes and wells, and discharges from ocean blue holes. Dashed lines on (a) show combined analytical uncertainty in calculated sulphate excess; large cross in (b) shows representative analytical uncertainties in sulphide and salinity measurements.*

Maximum dissolution would therefore be expected at the interface between oxic and anoxic conditions, where reactions 1 and 3 may proceed simultaneously.

These processes are of widespread significance as the redox interface occurs throughout the platform at varying depth, dependent upon the rates of input and consumption of oxygen and organic matter (Whitaker, 1992). There appear to be significant differences between individual fracture sites reflecting the proximity and nature of entrances, distance from the coast and direction and rate of groundwater flow. The depth of the redox interface depends upon rate of organic matter oxidation and diffusion of dissolved oxygen along the resultant concentration gradient, and occurs within the brackish lens in Elvenhome, upper mixing zone in Evelyn Green's and lower mixing zone in Stargate. This is reflected in the anomalously low carbonate saturation in the non-degassed brackish lens at Elvenhome (Fig.4). The proximity to the coast of both Elvenhome and Evelyn Green's means that saline groundwaters underlying the mixing zone remain oxic, giving rise to a second redox interface at the base of the mixing zone. Further from the coast the anoxic conditions, which are present at depth throughout the fracture caves, extend up to the base of the mixing zone. These waters are close to equilibrium with respect to calcite, more similar to non-coastal cenote waters (Whitaker *et al*, 1994). In contrast, shallow saline groundwaters in Elvenhome and Evelyn Green's are more supersaturated and, like oceanic discharges, appear to be mixtures of deep saline groundwater and sea water.

Contrasts in the distribution and extent of diagenetic potential between fracture groundwaters and those in the less cavernous surrounding aquifer will be even more marked. Within the aquifer, the reduced efficiency of tidal pumping and circulation decreases the effect of inorganic mixing corrosion, while organically mediated processes are affected by differing rates of input and consumption of dissolved oxygen and organic matter. Evidence from North Andros (Whitaker, 1992) indicates that due to physical filtration much particulate organic matter is retained within the freshwater lens and beneath a shallow redox interface all groundwaters are anoxic.

Diagenesis

The wall-rock of the fracture blue holes reveals a general pattern of alternation between facies characteristic of moderate depth waters on an open platform or lagoon (such as peloidal/skeletal wackestones) and those deposited in a shallow high energy environment (such as peloidal and oolitic grainstones and localised patch reefs). In Evelyn Green's,

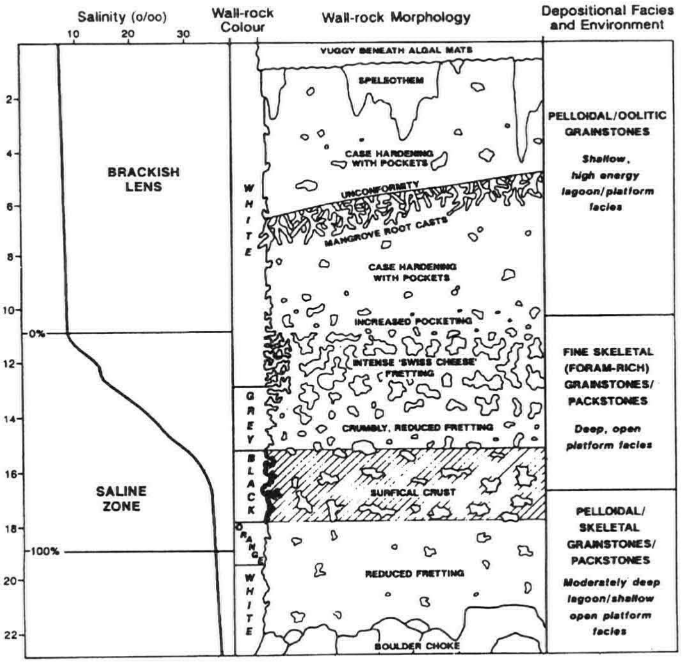

Figure 6. Vertical distribution of salinity, wall-rock colour and morphology, and depositional facies at Evelyn Green's Blue Hole, South Andros (from Whitaker, 1992).

the penultimate shallowing upwards sequence terminates in a shallow dipping unconformity with case-hardened mangrove roots at its base, indicating that deposition was interrupted by a period of subaerial exposure (Fig.6). At other sites there is evidence of sequential periods of cave infill by Pleistocene aeolianites followed by removal by dissolution or collapse, indicating the longevity of the fracture system and associated caves (see also Smart *et al*, 1998).

The early diagenetic history is complex, involving several phases of leaching and cementation, probably in response to Pleistocene sea-level changes. All samples show early meteoric stabilisation of aragonite and high magnesium calcite, with recrystalisation of allochems to low-magnesium calcite, and a variable degree of porosity occlusion by coarse low magnesium calcite cements (Whitaker, 1992). During sea-level low stands a thick vadose zone developed and some of the mouldic porosity became enlarged, forming an interconnecting network of karstic channels and micro fissures. However, below the base of the brackish lens early diagenetic features have largely been obliterated by Holocene mixing zone dissolution.

Dissolution is dominant within the mixing zone, with precipitation of a distinctive iron-rich crust but only minor dolomitisation. The wall-rock is relatively smooth below the present mixing zone, with increased dissolutional fretting and pocketing upwards into the mixing zone, culminating in deep "Swiss cheese" fretting in the upper part of the mixing zone (Fig.6). This is characterised by a ramifying network of dissolutional channels and enclosed vugs of 2 to 3cm diameter (Plate 1). Above the top of the mixing zone there is an abrupt reversion to relatively smooth wall-rock morphology. The changes in morphology do not correlate with changes in the primary depositional texture. Rather, the clear association between wall-rock morphology and the present position of the mixing zone, combined with the geochemical potential of modern mixing zone waters for dissolution indicates that porosity is actively generated within the present mixing zone.

The distribution and degree of dissolutional porosity at the micro-scale largely mirrors the gross wall-rock morphology. Within the brackish lens most samples show well-developed mouldic porosity and there is only limited attack of the low-Mg calcite cement, reflecting the non-aggressive nature of the brackish lens waters (Plate 2a). However, below the lens base all samples show pervasive dissolution of both allochems and matrix (Plate 2b). Dissolution is not restricted to the originally more permeable, coarser limestones, but also occurs in the relatively fine-grained rocks. These microscopic dissolution features are most well developed in wall-rock samples that show the highest degree of surficial fretting. Pervasive matrix dissolution also occurs below the mixing zone, despite slight supersaturation with respect to calcite in modern saline groundwaters. This may represent a former position of the mixing zone during periods of lower sea-level, or may be forming at present, possibly by oxidation of H_2S diffusing downward from the lower mixing zone.

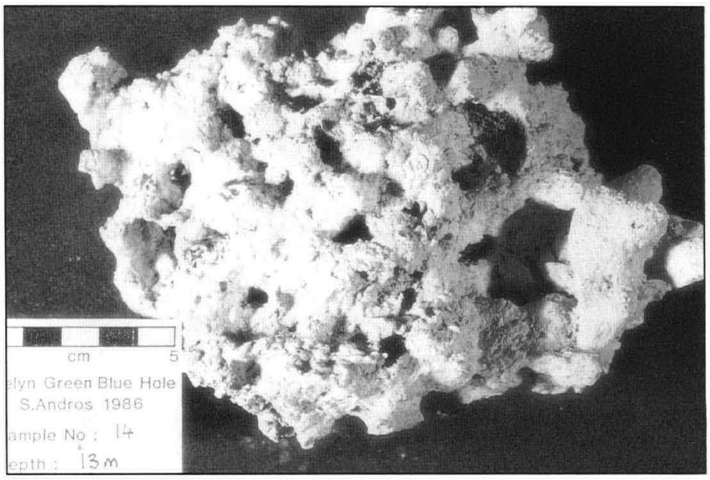

Plate 1. Hand specimen of wall-rock from the upper mixing zone of Evelyn Green's Blue Hole, South Andros, showing distinctive "Swiss cheese" fretting.

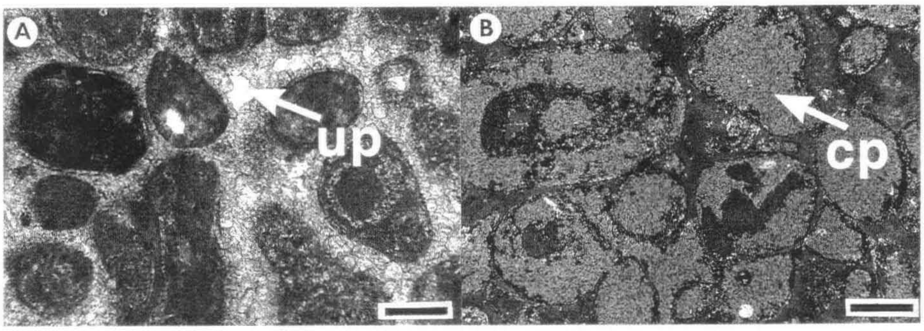

Plate 2. Thin-sections of wall-rock samples from Evelyn Green's Blue Hole, South Andros. Thin sections stained with Alazarin Red-S. Photographs taken under normal transmitted light, porosity in white. Scale bar is 150 microns. (a) Vadose and fresh-water cementation in oolitic/peloidal limestone from the present-day brackish lens. Low magnesium calcite forms fringing cements around ooid grains and replaces the ooids, with partial dissolution of the original aragonitic cortices. (b) Mixing-zone dissolution features in oolitic/peloidal limestone from the lower mixing zone, showing highly corroded low magnesium calcite mosaic and pervasive dissolution of all ooids.

Bulk rock analysis of wall-rock from the brackish lens indicates an average of 8% aragonite (assuming a Sr:Ca ratio of 0.011:1 for aragonite and 0.0017:1 for calcite: Budd, 1988), consistent with equilibration of lens waters with aragonite rather than calcite. Below the top of the mixing zone all aragonite has been dissolved, and calcite becomes the mineral controlling carbonate equilibrium. None of the thin sections examined appear to contain dolomite, apparently attesting to the absence or inefficiency of any mixing zone dolomitisation in comparison to calcite dissolution. However, bulk rock samples are enriched in magnesium in the upper mixing zone and also near the base of the mixing zone, where concentrations are almost twice those in the brackish lens and are also elevated compared to the underlying saline zone (Whitaker, 1992). Thus, minor amounts of dolomite (1 to 2%, assuming a constant Mg:Ca ratio for calcite), may be formed within the mixing zone. Their apparent absence in thin section may be explained by this small scale, highly dispersed or localised distribution, and the limited number of thin sections made. This is supported by observations of magnesium depletion (relative to brackish lens and shallow saline fracture groundwaters) in waters from specific sub-zones of the mixing zone (Whitaker, 1992). There appears to be a correlation between magnesium enrichment in the wall-rock and depletion in fracture ground waters, and waters that are enriched in sulphide and depleted in sulphate, suggesting that oxidation of organic matter by sulphate reduction may play an important role in controlling dolomitisation (Whitaker, 1992). Sparse dolomites observed in thin section at depth in the saline zone appear to have formed in saline waters and are also associated with sulphate reduction (Whitaker *et al*, 1994).

In the lower part of the mixing zone the walls of many blue holes are encrusted by a brown/black iron-rich precipitate that is on average 1mm thick, but locally up to 3mm thick (Plate 3). This consists largely of x-ray diffuse amorphous iron oxides, but gypsum and framboidal pyrite are also present (Plate 4). The acicular crystals of gypsum are derived from pyrite oxidation (Bottrell *et al*, 1990), either when the samples were brought to the surface or *in situ*, as has been reported from mixing zones elsewhere (e.g. Magaritz and Luzier, 1985). The presence of iron oxides confirms periodic exposure to aerobic conditions, possibly due to periodic water level surges or shrinking of the freshwater lens during dry periods. Framboidal pyrite, which comprises 10 to 15% of the crust material, has isotopically light sulphide (Bottrell *et al*, 1990), and forms *in situ* at the base of the mixing zone by bacterial reduction of sulphate. A dense network of filaments appear to be enclosed within the cubic crystals of iron sulphide, and may represent fossil remains of sulphate-reducing bacteria (Plate 4). As iron concentrations in seawater seldom exceed $0.002 mgL^{-1}$, the iron must be derived from particles of aeolian Saharan dust (Glaccum and Prospero, 1980; Eaton and Boardman, 1985), which form the main mineralogical component of modern soils and palaeosols (Foos, 1986). The dust particles are washed down through the vadose zone and oxic lens to the anoxic mixing zone, where surficial iron oxides become mobilised.

Concentrations of iron and manganese in wall-rock beneath the crust co-vary and are elevated most markedly in the lower mixing zone (where the crusts occur), but also in the upper mixing zone, where sulphate reduction also takes place although the surficial crust is not present. Models of mixing under conditions of sulphate reduction in the presence of iron oxides (Stoessel, 1992) suggest precipitation of the crust should counteract dissolutional potential generated by the sulphate reduction. This is in accordance with observations of maximum fretting in the upper mixing zone above the zone of crust formation. This provides further evidence of the clear association between wall-rock diagenesis and the present distribution of organically mediated processes within the mixing zone.

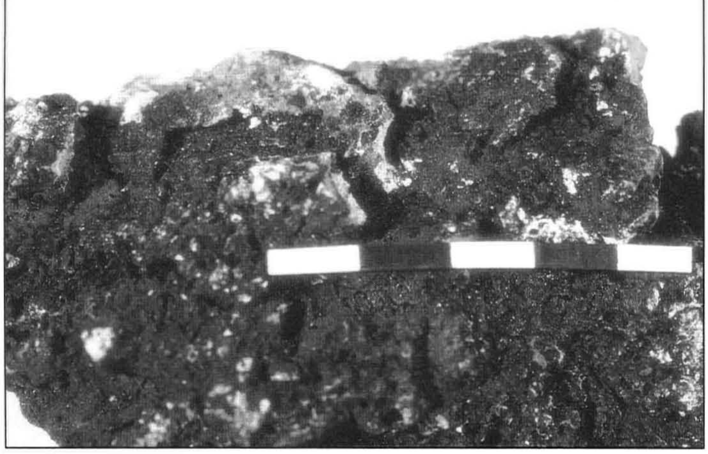

Plate 3. Hand specimen of wall-rock from the lower mixing zone of Evelyn Green's Blue Hole, South Andros. Surface of wall-rock is covered by 1-2mm-thick iron-rich crust. Note much reduced degree of wall-rock fretting compared with upper mixing zone wall-rock in Plate 1.

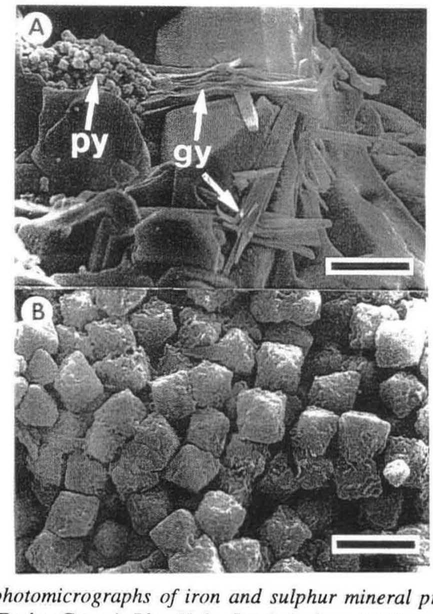

Plate 4. SEM photomicrographs of iron and sulphur mineral precipitates in mixing zone of Evelyn Green's Blue Hole, South Andros. (a) Framboidal pyrite (py) and elongated crystals of gypsum (gy) precipitated in an iron-rich crust at the base of the mixing zone. Note how the gypsum crystals are embedded in the calcite substratum. Scale bar is 5 microns. (b) Close-up of framboidal pyrite showing assemblage of individual cubic crystals enclosing filaments suspected to be of bacterial origin. Scale bar is 2 microns.

CONCLUSIONS

Integrated study of the hydrology and aqueous geochemistry of fracture blue hole waters on South Andros has provided insights into modern diagenetic processes affecting Plio-Pleistocene platform margin carbonates. Mixing occurs vertically within the fracture, between brackish lens and shallow saline groundwaters, and also laterally between fracture waters and groundwaters within the surrounding aquifer. This decreases the carbonate saturation state of the mixed waters and generates the potential for aragonite dissolution. More significant is the dissolutional potential generated by oxidation of organic matter under both oxic and anoxic conditions, which results in calcite undersaturation within the lower mixing zone. Organic matter oxidation by sulphate reduction generates H_2S, which diffuses to the redox interface where re-oxidation occurs, generating additional acidity. The redox interface is an important locus for calcite dissolution throughout the platform, occurring at greater depth in the open water column (within the mixing zone at most blue holes) compared to the aquifer (within the freshwater lens on North Andros: Whitaker, 1992).

Within the fracture, there is an intimate association between present day geochemistry and the long-term record of diagenesis of the wall-rock. Pervasive dissolution of both allochems and matrix enhances porosity, as well as generating distinctive macro-scale "Swiss cheese" fretting in the upper mixing zone. Within the anoxic parts of the mixing zone a distinctive iron-rich crust covers much of the wall, and minor magnesium enrichment suggests localised formation of up to 1 to 2% dolomite (although no dolomite has been seen in thin section). Sea-level has only been close to the present level for the last 2 to 3,000 years (Wanless, 1982), suggesting that water-rock reaction within the mixing zone is occurring rapidly to produce the distinctive diagenetic associations observed.

The blue holes should be viewed as one end-member in a continuum of porosity types from cavernous to intergranular porosity that may exist within carbonate aquifers (Whitaker and Smart, 1997b). These voids vary enormously in terms of groundwater residence time and water:rock ratio. Thus, although the processes operating within the blue holes will differ in rate and distribution from those occurring in intergranular porosity, insights into the nature of these processes have significance for all porosity types within the platform. For example, this study led to recognition of the importance of organic matter oxidation in driving carbonate dissolution, a processes that may also occur at a slower rate in intergranular pores. The more recent studies, inspired by the initial impetus provided by Rob Palmer, have confirmed the significance of these geomicrobiological processes, developing a fruitful new research field beyond the traditional inorganic geochemical diagenetic paradigm.

ACKNOWLEDGEMENTS

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Factors influencing the surface fauna of inland blue holes on South Andros, Bahamas

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Abstract: The macrofauna (particularly insects, molluscs and birds) of the surface waters of a series of inland, mostly anchialine, blue holes (flooded caves and associated lakes) was surveyed. The number of species was small, but the fauna varied considerably between holes. The following factors are evaluated as causes of these patterns: isolation and past inundation of Andros island, difficulty of dispersal between holes, topography (size of hole, water depth, whether ringed by cliffs), the surrounding vegetation, water quality (salinity, dissolved oxygen, nutrients), tidal influence, human disturbance and pollution. Conservation issues are discussed, but generally the surface fauna is shared with far more extensive habitats on Andros. The same conclusion is drawn about the fauna of two subaerial caves associated with blue holes.

INTRODUCTION

Blue holes are the entrances to flooded caves, occurring in the Bahamas both out at sea and inland. Cave diving has revealed a diverse and unusual fauna of crustaceans in these blue holes. For instance, a new class of Crustacea, the Remipedia, was first discovered in 1979 in a blue hole on Grand Bahama (Yager, 1981), and within the last 12 years at least 20 new species of crustaceans have been described from inland blue holes. A phylogenetically related fauna is known from other islands on both sides of the Atlantic, and from the deep sea, but the level of endemism is considered high (Hart *et al*, 1985; Stock, 1986, 1994). Given the limited samples available from such habitats, much remains to be discovered about the ecology and evolutionary history of this fauna, but few would argue that the blue holes have a high conservation value.

This rich endemic crustacean fauna is found at depth, remaining mostly in saline and anoxic waters. It is considered troglobitic and is distinct from the fauna found nearer the entrances to inland blue holes (Cunliffe, 1985; Stock, 1986). Much less attention has been given to the surface-water fauna, and even less to the partially aquatic fauna at the interface with the air. But since the deep-water fauna is fed by a detrital rain from the surface waters, the surface ecology can affect the deep-water ecology. Also, any similar endemism in surface waters would strengthen the case for the conservation of the entire ecosystem. Accordingly in 1987 Paul Stewart and the author surveyed the surface fauna of blue holes in South Andros as part of the interdisciplinary Andros Project. Only inland blue holes were studied, and only from the surface. The study should be viewed as preliminary; the intention is to provide hypotheses to test, and a better idea of the animals upon which to test them.

This paper considers which factors might influence the composition of the surface fauna and why blue holes differ in their faunas. This also provides a means to describe the surface environments of the holes systematically. Initially the range of blue holes visited and the fauna sampled are described; subsequently the fauna of two subaerial caves associated with blue holes is described, and then the conservation issues are reviewed.

SITES VISITED

During July and August 1987 more than 23 inland blue holes on South Andros were visited, most more than once. Appendix 1 of this issue (Palmer *et al*, 1998a) describes each hole. At about half of these the water surface, aquatic vegetation, and bottom sediment were sampled with a fine hand net, looking particularly for aquatic insects and molluscs. The time taken varied, depending partly upon whether the bottom was within reach. Deliberate limitations of this study were that it was rarely attempted to sample more than one metre underwater, the microscopic fauna was not examined, and only general aspects of the flora were noted. Sampling at night, when some crustaceans and fish may emerge from hiding, was not attempted.

Conductivity measurements of surface water were made by Whitaker and Smart (1997a and pers. comm.). These have been converted to estimated salinities; local sea water has a salinity of 36‰, and water with a salinity below 1‰ is conventionally considered fresh.

The blue holes visited are divided into fracture-line and cenote types. The fracture-line blue holes occurred in two chains, the Bluff and Congo Town chains, both aligned along a linear fracture system running adjacent to the east coast. Evidence from salinity measurements, tidal changes, and cave-diving exploration indicates that the fracture-line holes are anchialine, connected underground to each other and ultimately to the sea (Whitaker and Smart, 1997a). In the Bluff chain the marine connection is at the southern end, so that salinity generally decreases northwards (range = 4.2 – 11.8‰; see Table 1). In the Congo Town chain the only known marine connection is to the north, and salinity generally decreases southwards; but all these holes are more saline than any of the Bluff chain (range = 12.9 – 25.9‰). The maximum explored depth of the fracture-line holes is c.100m. The salinity at such depths is comparable with that of sea water, but the upper 15 to 25m is brackish, the transition occurring at the halocline, a mixing zone less than 10m thick (Whitaker and Smart, 1997a, 1998). Along the fracture-line the flooded vertical caves commonly adjoin shallower lakes, and the term "blue hole" is used here to cover both.

Cenote blue holes are circular holes, typically 30 to 150m across. Locally they occur in small groups, but elsewhere they may be several kilometres apart. On North Andros more than 118 have been mapped (Little *et al*, 1973); Smart (1984) compared their hydrology, and Proudlove (1984) made preliminary studies of their biology. On South Andros they occur in the interior, which is difficult to access. Two groups of cenote holes, one approached from Deep Creek (the Iguana Holes), the other from Little Creek, were visited. The Iguana Holes were visited three times, whereas there was only a single hurried visit to the Little Creek site. The freshwater lens beneath the island makes the surface salinity of cenote holes low, except near the tidal creeks (3.3‰ for the second Iguana Hole, but this tasted more saline than the other cenote holes; on North Andros the cenote holes typically had salinities under 5‰, with some below 1‰ - Smart, 1984). The vegetation and relief of the interior are also distinct from those along the fracture lines, as discussed below.

For comparison various other aquatic habitats on the island were also visited. Fossil tidal creeks formed long shallow silted-up depressions, with salinities of 4.9 to 8.7‰ for two west of The Bluff Settlement, but of 25.6‰ for one north of Congo Town that is fed by water from the Congo Town chain of fracture-line blue holes. Two

	surface-salinity (‰)	search	No. of species		*E. b.*	*B. f.*	*N. c.*	*I. r.*	*L. n.*
Congo Town Chain									
Lug Hole	24.9		1		A				
Man Hole	23.4		1		c				
Plug Hole	25.9		1		d				
Bolt Hole	21.6		1		B				
Hidey Hole	18.1		1		B				
Rat Bat Lake	12.9	s	4		A	d	d		
Swimming Hole	13.2	s	0						
Bluff Chain									
Mangrove Hole	9.8		5		d	A	A		
Evelyn Green	11.8	s	6		d	A	A		
Gopher Hole	9.3	s	4		B	A	A		
Donkey Hole		s	4		A	A	B		d
Nine Tasks/Round Lake	8.5		3		d	d	B		
Co-op Hole	5.1		0						
Heron Hole	4.2	s	4					A	
School Hole/Avalon	4.6	s	10		A	d	A	c	d
Battle Hole	4.2	s	12		A			A	
Interior cenote									
2nd Iguana Hole	3.3		5			A	A	c	d
1st Iguana Hole	< 1?		6			d		d	d

Table 1. A list of blue holes where enough time was spent to estimate the dragonfly fauna.
Holes are listed in order along each chain of holes, corresponding roughly to a decreasing salinity. An "s" in the third column indicates whether the sediment was searched for at least 30 minutes for submerged fauna. The next column gives the number of Odonata species observed flying around the blue hole or found as larvae. The other columns refer to the species *Erythrodiplax berenice, Brachymesia furcata, Neoerythromma cultellatum, Ischnura ramburi*, and *Libellula needhami*; the following letters are used as decreasingly certain indicators of breeding:
A = nymphs or exuviae found,
B = oviposition,
c = mating,
d = adult observed.

small muddy potholes near Black Point (NGR TB392 567) had a low salinity (0.3‰) and a rich insect fauna, suggesting that they did not dry up seasonally. Also several flooded quarries along the coast road were carefully sampled. The water in these was rarely more than 1m deep and their salinities ranged from 0.6 to 12.4‰. Another low-salinity habitat (2.7‰) was grassland between the coastal road and the raised line of palm trees, which became flooded after rain and, judging by their fauna of molluscs and amphibians, never dried out completely.

THE FAUNA

Some taxa were searched for specifically, whereas others were merely noted in passing. It is noteable that the macroinvertebrate fauna was not abundant and consisted of relatively few species. Proudlove (1984) also commented on the paucity of the fauna in the surface waters of blue holes on North Andros, as did Breder (1934) of the macroinvertebrates of large freshwater lakes in the interior of Andros. In contrast, the density of Crustacea in the halocline can be much higher (Palmer, 1985). Also much richer is the marine-like fauna and flora reported from the surface of the more-saline inland holes on Eastern Grand Bahama and San Salvador (Cunliffe, 1985; Godfrey *et al*, 1994).

Coelenterata

A small pink hydromedusan (illustrated in Palmer, 1989) occurred in the southern holes of the Congo Town chain, at some sites in spectacular profusion. Based on observations in 1986 Palmer (Palmer *et al*, 1998b) described the size range as 3 to 200mm, but a size limit of 20mm seemed more typical in 1987. It appears to be an undescribed species of *Ptychogena*, related to *P. crocea*, but this genus is not well studied (P F S Cornelius, pers. comm.).

Mollusca

The only bivalve found was *Polymesoda maritima*, abundant in sediment in the Congo Town chain, and in Mangrove Hole at the coastal end of the Bluff chain. Hydrobiid gastropods were abundant along the more saline holes in the Bluff chain (from Mangrove Hole to Nine Tasks Lake); those collected were *Littoridinops monroensis* and a species of *Heleobops*. The gastropod *Cerithidea costata* was found from Mangrove Hole to Donkey Hole, but was also widely distributed along the Congo Town chain. Rat Bat Lake and the waters in the associated cave were the only site where *Neritina clenchii* and *Neritina virginea* were found. Pulmonate freshwater gastropods (Physidae, Planorbidae, Ancylidae, Succinidae) were collected elsewhere on South Andros, but none in blue holes (see Pilsbury, 1930, for a species list from fresh and slightly brackish water on North Andros).

Molluscs are one group that has been thoroughly sampled in blue holes elsewhere in the Bahamas. Edwards *et al* (unpublished) sampled quantitatively across three anchialine sites on San Salvador (salinities 20 to 26‰). The bivalves collected live were *P. maritima* and *Anomalocardia auberiana*; the gastropods were *C. costata*, *Batillaria minima*, *Cerithium minima* and *Melampus coffeus*. Four other mollusc species occurred dead in the sediment, and adjacent blue holes with a marine salinity had additional species (Godfrey *et al*, 1994). Cunliffe (1985) also listed other molluscs in Sagittarius, a saline (20‰ at surface, 27‰ at -2m) anchialine cave and associated lake on Grand Bahama; *C. costata* was again present.

Crustacea

No systematic collections were made. However, the conspicuous shrimp *Macrobrachium lucifugum* was common at the surface of School Hole, the most polluted site, but not seen elsewhere. Its habitat in other parts of the Caribbean is reported as caves and anchialine sites (Hobbs, 1994), which does not suggest an association with pollution. A species of *Hyalella*, a freshwater amphipod genus, occurred at least in Nine Tasks Lake and Battle Hole.

Pelagic ostracods were noticed in several fracture-line holes, and dead ostracod carapaces formed much of the sediment in some holes. Ostracod assemblages from sediment cores in San Salvador blue holes are described by Crotty and Teeter (1984).

Land crabs are common throughout the coastal strip, so their presence around the fracture-line blue holes is unremarkable. However, in North Andros, Farr and Palmer (1984) noted numerous land crabs at the base of blue-hole lakes 15m underwater, so they could be important predators in this ecosystem.

***Odonata* (dragonflies and damselflies)**

A special study was made of this group. Exuviae were searched for around most holes, live nymphs were found in some holes, and it was also noted whether adults were ovipositing. From this evidence at least seven species were breeding in blue holes: *Ischnura ramburi*, *Neoerythromma cultellatum*, *Anax junius*, *Brachymesia furcata*, *Erythrodiplax berenice*, *Macrodiplax balteata*, *Tramea onusta*. Table 1 shows the strong effect of salinity on diversity. *E. berenice* could breed even in the most saline holes, but the next two most tolerant species were not found breeding in salinities higher than 9.8‰. No dragonflies were observed around Swimming Hole and Co-op Hole, despite each being visited twice in suitable conditions. The probable reason is that both lack shallows. The richest blue hole was Battle Hole (12 species), the least saline of the fracture-line holes, with extensive shallows, algae and overhanging vegetation. In comparison, several of the quarries filled with shallow fresh or weakly brackish water had 14 or 15 species frequenting them. In total 26 species were observed on South Andros, with indications of breeding for 16.

***Heteroptera* (bugs)**

Water striders were abundant on many blue holes. The following genera of aquatic bugs were collected, most only from Heron, School and Battle Holes, the least saline of the fracture-line holes sampled: *Limnogonus*, *Trepobates* (2 species), *Rheumatobates*, *Hydrometra*, *Buenoa*, *Pelocoris*, *Microvelia*, *Merragata*. In several species the adults collected were wingless and so must have bred on these holes. The fauna of non-blue-hole sites included extra species.

***Coleoptera* (beetles)**

Many species of aquatic beetle were collected from such freshwater sites as quarries, but they were seen in only four blue holes: a diving species at Battle Hole, and small gyrinids (whirligig beetles) on Swimming Hole, Nine Tasks Lake, and School Hole. Specimens from the latter site were of the genus *Gyrinus*, as were specimens collected from a rock pool alongside a cenote hole. In his paper on aquatic beetles of the Bahamas, Young (1953) remarks on a characteristic community of beetles found in brackish water, but this clearly did not occupy the blue holes visited during this project.

***Diptera* (flies)**

Adult Nematocera (midges and mosquitoes) in abundance utilised the shade and still air afforded by the fracture-line blue holes, but to what extent blue holes are used as breeding sites was not assessed.

Arachnida

Red water mites (Hydracarina) were observed on the surface of several holes, as also seen by Proudlove (1984) on blue holes in North Andros, and by Breder (1934) on inland freshwater lakes. Two species were collected. There was also at least one species of spider walking on the surface of School Hole.

Fish

Most holes contained small fish but, without a seine net, only incomplete sampling was possible, and the collections made are unavailable at the time of writing. The greatest diversity of fish species was observed in the saline waters at the northern end of the Congo Town chain, and this fauna contained larger forms, including a large eel. The most widespread fish were mosquito fish (*Gambusia*) and *Cyprinodon*. South Andros is the type locality of *Gambusia hubbsi*, where *G. manni* (another Bahamian endemic) is believed to be absent (Breder, 1934). Other authors lump both species into a single species, *G. manni* or *G. puncticulata*. *G. hubbsi* is the subject of ongoing evolutionary studies by Downhower *et al* (1997) in the blue holes of North Andros.

On San Salvador Edwards *et al* (unpublished) found that nearly all blue holes (salinities brackish or marine) had only the two species, *G. puncticulata* and *Cyprinodon variegatus*, with *Atherinomorus stipes* occurring in one inland blue hole of marine salinity. Breder (1934) discusses the fish fauna of large freshwater lakes in North and South Andros (12 species), and mentions finding *Haemulon sciurus*, *Lutjanus griseus* and *Lutjanus apodus* in a blue hole in the interior of South Andros (it is not clear whether this was in a creek). Proudlove (1984) also found *L. griseus* in two blue holes of salinities 1 and 3‰ on North Andros. Both the crevice-living goby *Eliotris pisonis* and the blind cave fish *Lucifuga spelaeotes* are reported by divers to occur above the halocline as well as below (Palmer *et al*, 1998b).

Amphibians and reptiles

No amphibians or reptiles were found in blue holes. However, tadpoles occurred in a rock pool in the karst beside a cenote hole.

Birds

During brief visits to the interior cenote holes, no birds were seen using them. Around the fracture-line blue holes the following water birds were noted. Common Gallinule (*Gallinula chlorups*) and Belted Kingfisher (*Megaceryle alcyon*): singletons, seen only at School Hole/ Avalon and Battle Hole. Least Grebe (*Podiceps dominicus*): singletons, at Donkey and Gopher Holes. Green Heron (*Butorides virescens*) and Yellow-Crowned Night Heron (*Nyctanassa violacea*): widely distributed along both chains of holes, both seen at 8 holes each, but a total of 13 holes had one or other species, and usually several birds were present at each site; heron nests were present at Evelyn Green, Heron Hole, Battle Hole, Man Hole and Bolt Hole, but it was only at the latter where the Night Heron was definitely breeding. Extensive mangrove thickets must provide an abundance of other suitable aquatic habitat for these birds elsewhere on the island. See a later section for Cave Swallows and Barn Owls, two species utilising the caves and overhanging cliffs associated with the fracture-line blue holes.

EXPLANATIONS OF THE PATTERN OF DIVERSITY

This section considers the physical and biological factors that could influence the fauna associated with individual blue holes. Two general patterns in particular require explanation - the general paucity of the fauna, and the considerable variation in the fauna from hole to hole. Examples of the latter include the apparent restriction of the shrimp *Macrobrachium lucifugum* to School Hole, the two *Neritina* gastropods to Rat Bat Lake, and the hydromedusan *Ptychogena* to a set of adjacent blue holes. Quantitative sampling would probably have revealed further differences: Edwards *et al* (unpublished) studied molluscs from three adjacent and hydrologically very similar holes, where the relative abundances of species differed dramatically. Unfortunately many of the factors that might plausibly explain the faunal variation between holes co-vary, so it is not yet possible to draw definite conclusions about the main source of diversity.

Isolation and history

(i) The general freshwater and brackish fauna of Andros

Andros is an island and the blue holes are isolated habitats within this island, so one class of explanations for the species diversity considers the ease with which different taxa can colonise. These explanations depend not only upon the biology of each taxon, but also on the current and past geography of the Bahamas archipelago.

Andros is the largest island of the Bahamas, although it is split by marine creeks into several smaller islands. General expectation is that the larger the island the more likely it is that a species will have successfully colonised (MacArthur and Wilson, 1967). Andros' size also endows it with an extensive and thick freshwater lens and, in the interior, with large freshwater lakes (Breder 1934).

South Andros is 200km from Florida and 145km from Cuba, which seems close enough for wind transport of arthropods as well as resistant stages of other small aquatic organisms. Although the prevailing winds in both summer and winter bring air from the empty Atlantic, air masses from the south are not uncommon and these could transport biota from the Greater Antilles. But the past history of the archipelago is as important as current geography. From 120,000 years ago sea levels fell below their present level and 18,000 years ago they are estimated to have been upto 130m lower (Chappell and Shackleton, 1986; Smart *et al*, 1998)). This created a much larger island, the entire Great Bahama Bank, the edge of which lay close to Cuba. This can explain why the Bahamian flora, much of the terrestrial fauna, and the non-marine fish fauna share more species with Cuba than with Florida (e.g. Browne *et al*, 1993 and references therein; Rauchenberger, 1988).

A complication is the proposal that more recently (6,000 – 4,700 years ago) sea level may have been up to 4m higher than today (Fairbridge, 1990). Biogeographical studies are broadly supportive of such an inundation (Browne and Peck, 1996), but it appears not to be widely accepted. Much more definitely established is that 125,000 years ago, during the last interglacial, sea levels were upto 6m higher than today (Chappell and Shackleton, 1986). The cenote blue holes in the interior would then have been under the sea. The aeolian dune ridges along the east coast, through which the fracture-line caves run, are now up to 14m above sea level (higher in North Andros) and would have survived the inundation, although the ecological conditions must then have been rather different. None of the Bluff chain of fracture-line holes (the chain now with less-saline water) occurs in land above the 6m contour, and the islands left would have been so narrow that drainage would drastically thin the fresh/brackish water lens. Permanent freshwater above ground quite probably disappeared. Blak (cited in Breder, 1934) argued that the number of endemic freshwater molluscs described by Pilsbury (1930) from North Andros implied a great antiquity for this habitat on Andros, but the status of these taxa requires modern re-evaluation.

This probable extinction of most freshwater species (125,000 years ago if not c.5,000) contrasts with the survival of the endemic crustaceans found at depth in more saline conditions. Stock (1986) points out that the Bahamas and Turks and Caicos islands have few low-salinity stygobiont endemics, whereas most of the Antilles have numerous such species. One explanation is that any low-salinity endemics on low-lying islands such as Andros did not survive past sea-level rises. Perhaps surprisingly, the shallow water of anchialine ponds and blue holes seems generally not to have been re-colonised by the halophilic stygo-adapted fauna found just below (Stock, 1986). Instead re-colonisation could come either aerially from freshwater on Cuba and Florida or from species tolerant of marine salinities. The need for such re-colonisation will bias which species are now available on South Andros to occupy blue holes, and could impoverish the total number of species.

Certainly tolerance of high salinities characterises much of the freshwater and brackish fauna. Breder (1934) considered that the fish living in the freshwater (1.5‰) lakes of Andros are "typically marine or at least brackish water" species. *Gambusia* can even be transferred directly between sea water and freshwater (Krumholz, 1963). More generally, Barnes (1989) argues that in all brackish faunas most species can tolerate full strength sea water, the exceptions being species derived from freshwater ancestors, which are never found in salinities over about 10‰. So, since blue holes with more saline surface waters would anyway be expected to have only species tolerant of sea water, and since such species could have survived on, or readily re-colonised, Andros, the fauna of these holes should not necessarily be expected to be impoverished.

This need not be true of the less saline blue holes. The lack of fish restricted to freshwater is presumably because of the difficulties of colonisation. But the collections from other low-salinity habitats demonstrate that many species of insect and pulmonate mollusc restricted to low salinities have colonised or survived on South Andros.

The data described in this paper do not allow quantitative assessment of how depauperate the blue hole fauna is compared with similar habitats in Cuba, Florida or Mexico. A similar question that others might aim to answer is whether blue holes on the other Bahamian islands have a poorer surface fauna than those on Andros, and whether this can be related to the islands' size, distance from other islands, or height above sea level.

(ii) Dispersal between blue holes within Andros

Blue holes can be viewed as aquatic islands surrounded by dry land. But the possible dispersal routes between blue holes must be considered in deciding how isolated they really are. Difficulties of colonisation may restrict the distribution of some animals, but not that of animals able to use other dispersal routes. Very similar questions, concerning ease of dispersal and to what extent species composition is a matter of chance, have been asked about brackish lagoons in northwest Europe (Barnes, 1988).

Inter-hole dispersal will be particularly important if species periodically go extinct in some blue holes because of changes in sea level and water quality. Evidence for this kind of extinction in the last few thousand years is provided by Kjellmark (1996) for sediment-living bivalves and by Crotty and Teeter (1984) for ostracods. The probable reasons were climate-driven changes in salinity.

One possible dispersal route between holes is underground, since the fracture-line blue holes are connected by phreatic cave systems sometimes large enough to allow divers to connect separate entrances. Tidal flow along the fracture can transport material rapidly, but the rate is much slower in large diameter passage away from the sea (cf. dye tests in Cousteau and Diolé, 1973, and Whitaker and Smart, 1997a). Moreover, the connecting passages discovered between the South Andros fracture-line blue holes are beneath the halocline in saline water that mixes little with the overlying brackish water, at least in the Bluff chain. The high levels of hydrogen sulphide and low levels of oxygen in the halocline form an additional barrier. The fish *Lucifuga spelaeotes* and *Eliotris pisonis* occur both above and below the halocline (Palmer *et al*, 1998b), but generally this seems an unpromising dispersal route for the surface faunas, even though much of it is tolerant of high salinities. In contrast, when sea levels were lower in the Quaternary, the passages would sometimes have been at water level and could have acted as a highway.

In fact such a dispersal route within the freshwater/brackish lens probably still exists. Cores and the high permeabilities detected in pumping tests indicate that the limestone is permeated by interconnecting fissures up to a few centimetres across (Whitaker and Smart, 1997b). There is a fauna living permanently in this groundwater, some members of which may also utilise blue holes. For instance, the ostracod *Strandesia longula* is common in wells, pools, and the underflow of running waters in Haiti and the Bahamas (Broodbakker, 1984). Recently a live fish (probably *Lucifuga*) was pumped from a shallow well on New Providence Island, 4km from the nearest blue hole (N. Sealey, pers. comm.). For such organisms even the geographically isolated cenote blue holes may be linked.

Underground dispersal might account for the increased diversity of fish observed in the northern holes of the Congo Town chain, the most northerly of which is only about 1.7km from the marine connection at Driggs Hill Sinkhole. High surface salinities here suggest that the tidal flow is not so isolated from the surface water as in the Bluff chain, and thus that the underground route is more practicable. But their high salinities would anyway lead to an expectation of more marine fish, even if dispersal were not facilitated. The same factors may explain the highly diverse fauna of Sagittarius on Grand Bahama (Cunliffe 1985) and of the saline blue holes of San Salvador (Godfrey *et al*, 1994).

The alternative to the underground route between holes is overground. The fracture-line holes are commonly close to their neighbours, so that each can act as a stepping stone to the next. The cenote holes tend to occur either on their own or in isolated groups, but the low-lying honeycomb limestone in the interior can be covered with pits holding rainwater, and there are even large low-salinity lakes (1.5‰). At least on North Andros the narrower active creeks inland are also fresh (Smart, 1984). The freshwater "islands" are thus not so widely apart, facilitating aerial dispersal. Rare floods may even provide an overground aquatic connection: storm surges associated with hurricanes cause large areas to be inundated with sea water.

An additional means of dispersal for fully aquatic organisms is in vegetation caught on birds' feet. Shallow holes with overhanging vegetation are much more suitable for herons to feed and breed in, so ease of colonisation is one of several reasons why such holes might be predicted to be richer. (But a test of such a hypothesis in isolated brackish lagoons in England did not show a relationship between faunal similarity and use by birds - Barnes, 1988.) In contrast, some of the deep cenote holes of the interior, surrounded by treeless expanses of bare rock, seemed unattractive to bird life, and might thus be less liable to colonisation.

Perhaps there is a knock-on effect: once a hole has been colonised by one species of fish, herons are attracted and bring further aquatic life. More generally one could envisage that, following the last major extinction event driven by high sea levels (whether 120,000 or possibly c.5,000 years ago), blue holes showed a temporal succession driven by the slow colonisation of species, each of which could provide a niche for new colonists and cause the extinction of earlier colonists through predation or competition. An important open question is whether colonisation is sufficiently difficult, compared with the time since the development of the freshwater lens, that most blue holes are not yet saturated with species already present on Andros. Artificial introductions would settle the issue but would be controversial ethically. The following sections discuss several alternative explanations why different blue holes have different faunas.

Topography

(i) Size

The blue holes on Andros vary in size and shape. The cenote holes are circular with a typical width of 30 to 150m, some being much larger. The fracture-line holes are more variable in shape, typically less than 30m wide and a little longer, but the length of the water surface may be up to 200m (Nine Tasks Lake). Much of the organic input to blue holes must be from vegetation overhanging the holes, so large circular holes would tend to have relatively less. Larger holes are more exposed to winds, the effects of which are discussed below. Area may also be important in affecting the probability of colonisation and of chance extinction when population size is small (MacArthur and Wilson, 1967). The smallest populations are likely to be of the biggest animals, but the fish *Gambusia* and *Cyprinodon* commonly occur in abundance. However, fish predatory on these small fish, such as *Lutjanus griseus*, might quite plausibly be restricted to the larger holes. (Other predators high up the food chain, such as dragonflies, land crabs and birds can move readily between holes.) Also, commonly only small regions of each hole are shallow or vegetated enough to suit some species, whose populations consequently might be vulnerably small; total area of the hole would be a poor predictor of this.

(ii) Shallows

Some cenote holes are deep shafts with vertical or overhanging walls continuing up to 100m underground, but much shallower cenote holes are common on North Andros (Proudlove, 1984). For instance, one cenote hole visited on South Andros was nowhere more than 6m deep, lined with a pale marl sediment. Many fracture-line holes also have extensive shallow lakes adjoining the deep shafts, and these holes tended to be faunally richer, probably partly because they were richer in emergent vegetation.

In the shallows trees may grow, including the pond apple, *Annona glabra*, and mangroves at more saline sites. Many holes contained extensive areas of tall *Acrostichum* ferns, and smaller patches of sedges and rushes (the latter rather sparse). These plants provide shelter for surface-skimming arthropods and a source of organic input. In particular the emergent vegetation can recycle the nutrients locked up in sediment. Tree branches hanging low over the water are also where the herons nest.

Underwater much sediment in the fracture-line holes was overlain by mats of algae, which sometimes floated to the surface. In the cenote holes of North Andros, Proudlove (1984) identified similar mats as consisting of blue-green algae; he emphasised their enormous bulk and ubiquity (lining much of the sloping walls and present in all but one hole). The damselfly *N. cultellatum* was often observed ovipositing on these floating mats. Algal mats provide food, oxygen, and shelter, but their consistency made searching for animals within them difficult. In some holes, such as Evelyn Green, the substrate was instead covered by calcareous algae, different colours mapping out concentric zones of a particular depth. In this and other holes, extensive areas of soft pale sediment appeared bare of algae, and at least some of the cenote holes on South Andros appeared devoid of macroscopic algae. The microbial flora of the fully saline anchialine blue holes and hypersaline lakes on San Salvador sounds different again: Edwards (1996) describes "flocculent layers" of phytoplankton either lining the substrate or floating half a metre below the surface.

In Evelyn Green, the beds of calcareous algae are a likely source of the sediment, but the bivalve *P. maritima* living in the sediment also contributed noticeably. In other holes (e.g. Donkey Hole) the sediment was instead derived from hydrobiid snail shells and ostracod carapaces. These sediments provide a niche that in deeper holes is only present, if at all, on rock ledges around the vertical shaft (*P. maritima* did exist on narrow ledges in the otherwise deep Swimming Hole). If herons are to feed they will require at least such ledges upon which to stand.

In shallow holes dead organic matter remains potentially available to the ecosystem, whereas in deep holes it sinks down to float within the halocline, out of the range of surface dwellers. The shallower the water, the more likely that thermal convection, wind, and tidal disturbance can eliminate the stratification that loses the nutrients from the surface waters, and prevents oxygen reaching the sediment (see below).

Shallow parts of blue holes, if unshaded, felt noticeably warmer and no doubt show more diurnal fluctuations. Smart and Whitaker (pers. comm.) measured daytime surface-water temperatures in July 1986 at a range of holes. Although measurements were made at different times of day and on different days, a pattern seems to emerge. 33°C was the highest recorded, at School and Evelyn Green holes, which have extensive shallows. This compared with 29°C at the consistently deep but open Co-op Hole, and 26°C at Stargate (deep and overhung by cliffs). The water at depth was at 25°C. Temperature profiles at other deep holes in North Andros are given by Smart (1984), and their significance for stratification discussed below.

(iii) Subaerial cliffs

Blue holes vary in the extent to which the water surface is surrounded by subaerial cliffs. Cliffs several metres high are typical of most fracture-line blue holes, because these happen to occur along a line of lithified aeolian dunes. Nevertheless the shade was apparently insufficient to suit the rich fern flora associated in the Bahamas with the smaller "banana-hole" solution pits (Correll and Correll, 1982). The cenote holes of the interior lacked cliffs, as the water surface was only half a metre below the surrounding level plain.

Several cliffs around blue holes supported wasp nests and large honey bee colonies. The cliffs reduce wind at the surface, which should favour surface-skating insects, and clouds of mosquitoes, but also reduce aeration. Wind made the surface of the large exposed cenote holes quite choppy, and drove most dragonflies and damselflies away. In total contrast, Stargate is small and partly overhung with cliffs, which must significantly reduce not only wind, variation in temperature, and light (factors that in open holes reduce stratification and/or increase aeration), but also reduce the input of wind-blown organic detritus. This is presumably why its waters are particularly clear.

Surrounding vegetation

The fracture-line blue holes of South Andros occur along the coast, where the natural vegetation is a thick broad-leaved woodland or scrub. The proximity of the coastal villages has led to extensive clearing by burning, in order that crops like maize can be grown in the vacated solution holes. However, nearly all fracture-line holes still had trees around them. Tree leaves must be a major source of organic detritus, which supplies nutrients and affects the oxygen levels deeper underwater (see below). Woodland also reduces wind, and shields birds using the holes from casual disturbance from people working or walking nearby. In fact, the woodland can be so impenetrable that holes away from cultivation are unlikely to be visited.

In contrast, some of the cenote holes in the unpopulated interior were in a flat rockland landscape, devoid of trees and very thinly vegetated otherwise, which accentuated their exposure to wind. The low detrital input into such holes may make them nutrient-poor, and thus explain their rather sterile appearance (pale blue in colour and lacking the algal mats found in many fracture-line holes, which looked distinctly greener and darker). Most of the blue holes examined by Proudlove (1984) in North Andros are cenote holes situated in forest, and they did have thick algal mats. Both cenote and fracture-line holes also occur in mangrove thickets.

Having noted that the surrounding vegetation could well affect the biology of the blue holes, one might equally ask whether the blue holes have any affect on the surrounding vegetation, other than on those species already noted as growing in the water itself. Blue holes produce a permanent gap in the forest canopy, which seemed to enrich the epiphytic orchid and bromeliad flora in their immediate vicinity; but any such effect was minor, and unimportant given the frequency of artificial clearings.

Water quality

(i) Salinity

The surface salinity of the blue holes differed considerably, from 25.9‰ (74% of sea water) to potably fresh (<1‰), although the least saline fracture-line hole still had a salinity of 4.2‰. Brackish faunas world-wide are impoverished relative to those of adjacent fully marine or freshwater habitats, the minimum diversity occurring around 7‰ (Barnes, 1989). Salinity is thus likely to be the major reason why the surface waters of the fracture-line blue holes, and of some cenote holes, contain few species. This is especially true of insects, which globally decline dramatically in diversity as salinity increases, and which showed this pattern strongly along the Bluff chain of fracture-line blue holes (Table 1). In contrast, the diversity of fish and molluscs declined as salinity decreased. It would be interesting to sample molluscs from additional less-saline cenote holes, where perhaps diversity might increase again as strictly freshwater pulmonate species could colonise. Certainly the quarries and potholes with freshwater had freshwater pulmonates, as well as a dramatically increased diversity of insects.

Salinity varies not only between holes, but within blue holes in response to recent rainfall. Edwards *et al* (unpublished) showed surface salinity in Watling's Blue Hole on San Salvador varying from 10 to 30‰ at the surface and from 22 to 32‰ deeper down (<5m). Heath and Palmer (1985) reported that at least 25cm of almost potable water on the surface of the lakes in the Zodiac Caves on Grand Bahama disappeared within a month of no rain. However, local rainfall is only sufficient to affect salinity much if rainwater is funnelled from a wider area. This is likely only where there is suitable relief, or adjacent to tidal creeks to which the lens drains (Whitaker, pers. comm.). On Andros the fresher and deeper freshwater/brackish lens means that irregularities in rainfall will matter less than on other islands.

A change in climate or a greater rate of water abstraction by man might lead to longer-term changes in salinity that could cause local extinctions. Crotty and Teeter (1984) took sediment cores from a blue hole on San Salvador and, from three dramatic shifts in the ostracod fauna over the last 3,000 years, interpreted considerable changes in salinity. Furthermore the shifts corresponded to salinity minima (Teeter and Quick, 1990). Four ostracod species showed only quantitative changes in abundance, but two species occurred only in the most saline zones. Kjellmark (1996) argued that the bivalve shells from a core in sediment currently 27m underwater (15m below the halocline) could only have been living there when these depths were oxygenated, perhaps because low rainfall led to the disappearance of the freshwater lens 3,000 to 1,500 years ago.

(ii) Aeration and hydrogen sulphide

The smell of hydrogen sulphide (H_2S) that divers notice at, and sometimes below, the halocline, and that is also apparent on disturbing sediment close to the surface, is a product of the anaerobic metabolism of organic detritus in these anoxic environments. Whereas the blue-hole endemic crustaceans are adapted to anoxic conditions, the surface fauna will be able to survive only in oxygenated water. In particular the surface of the sediment is likely to have a very different fauna depending upon whether the water at that depth is anoxic. H_2S is itself highly poisonous, although it is not known how sensitive the surface fauna is to it.

In a 7m-deep brackish blue hole Crotty and Teeter (1984) reported 5.4 ppm of oxygen at the surface, dropping to 2.4‰ at -3m (where the water was more saline), then dropping suddenly again to 0.5‰ at -5m (where the water also contained H_2S). At another blue hole Yager (1987) measured oxygen concentrations of 4 ppm near the surface, but below 0.1‰ once the halocline was reached. Whitaker (1992) shows oxygen and sulphide profiles for some fracture-line holes on South Andros. The low oxygen concentrations are caused by oxidation of the organic detritus combined with a lack of mixing of surface layers. The low organic input to Stargate explains why its oxygen concentrations remain high to a great depth (H_2S levels also do not rise). For more open blue holes the factors controlling the depth of aeration include the mixing effect of wind, tidal movements, and temperature changes. Solar heating of the surface layers will lead to a daily overturning when the topmost layers cool down overnight. Temperature profiles further suggest a yearly overturning to depths of several metres (Smart, 1984). (Although average temperatures in Bahamas show little seasonal variation, occasionally winter temperatures drop to under 10°C for 2-3 days and ice has been observed on one Andros blue hole — N. Sealey, pers. comm.) Nevertheless on South Andros oxygen levels can fall to low levels well above the halocline (Whitaker, 1992). The halocline prevents deeper mixing of surface waters, and in most holes accumulates organic matter that consumes the remaining oxygen and/or generates high concentrations of H_2S. In blue holes too shallow for a halocline, organic detritus will instead accumulate on the bottom, where the depth of mixing will determine oxygen and H_2S concentrations.

Near the surface another potential source of oxygenation is photosynthetic algae, either single-celled species in the plankton, or species forming floating mats, or benthic species such as calcareous algae common in Evelyn Green and encrusting mats of blue-green algae.

(iii) Nutrients

In both North and South Andros water clarity in most blue holes was excellent, which suggests that they contain few planktonic algae. K. Nelson (unpublished) confirmed that in several blue holes productivity in the water column was indeed very low, under $3mg/m^3/day$. This is comparable with ultra-oligotrophic arctic lakes. Presumably the reason is a lack of one or more nutrients.

Since there is virtually no direct run-off into blue holes, input of nutrients must be limited and mostly be from fallen leaves. Conceivably at some holes the guano around heron nests may be a significant additional source. The surface water of many blue holes is stained dark, presumably owing to tannins. This implies that breakdown products of leaves enter the surface water, but other reasoning suggests that this is not so easy. In deep holes detritus sinks to the halocline, and is lost to the surface habitat. In shallower holes thermal stratification might similarly restrict nutrient availability. And, even in the shallowest holes, the sediment may lock up many of the nutrients. The strong smell of H_2S when disturbing these sediments implies that bacterial breakdown is occurring without oxygen being able to get in, and thus probably without nutrients getting out. One bivalve species was the only common burrowing animal in this sediment, so there is probably little mechanical disturbance that might help recycle nutrients, although wading herons might contribute.

However, the *Acrostichum* ferns and flowering plants that grow into submerged sediment will be able to extract dissolved nutrients and make them re-available, again mostly in the form of fallen leaves.

Proudlove (1984) observed that one hole in North Andros did have a rich plankton bloom. Comparing the nutrient concentrations in this hole with those in others would be the easiest clue to which are limiting. Phosphate is the limiting nutrient in most freshwater systems and is especially likely to be so in blue holes because carbonate is known to adsorb phosphate rapidly (Short *et al*, 1985). Concentrations throughout the water column in Elvenhome, Stargate and Evelyn Green's blue holes are low, below 0.1 mgL^{-1} (the minimum detectibility of the analysis kit used - Whitaker, pers. comm.). Anoxic conditions actually favour the release of phosphate, but if the surface of the sediment is not anoxic the high pH of the water will have the reverse effect (Payne, 1986).

Tidal disturbance

In the fracture-line holes tidal movements are often obvious: even at the inland end of the Bluff chain tidal range is 0.3m, half that of the sea (Whitaker and Smart, 1997a). On North Andros the tidal range of Ocean Hole was less (0.15m; Farr and Palmer, 1984) despite being beside the sea, but even a cenote hole 18km inland showed tidal fluctuations 6% those of the sea (Whitaker, 1992). In some fracture-line holes water obviously streams in and out from a shallow conduit in the wall. In other holes the inflow and outflow is imperceptible, and need not necessarily lead to much mixing if the connection to adjacent holes is deep and spacious. But besides its effect on mixing and aeration, a tidal influence may restrict which animals can colonise. Barnes (1988) noted that the species restricted to brackish lagoons in northwest Europe are not found in other habitats, not because they could not tolerate greater salinities, but because this is the only non-freshwater habitat lacking tides. As examples of the difficulties caused by tides for non-adapted organisms, young dragonfly nymphs left above water level during a low tide are exposed to predation, and when dragonfly nymphs deliberately leave the water to emerge as adults, they risk being covered by a rising tide just when their new wings are drying. In contrast most plants growing as emergent vegetation probably are adapted to fluctuating water levels even if their normal habitat is not tidal.

Human disturbance

Palmer (1989) discovered that Sanctuary, a deep hole with a narrow entrance, had been used by the Arawak Indians for human burial, and much more recently for the disposal of animal carcasses. This practice may have arisen simply as a solution to the difficulty of finding enough depth of soil to dig a grave, although the discovery of a canoe suggests that sometimes a ritual element was involved. Since some blue holes provide deep water-filled pits close to habitations, it is surprising that the only other South Andros blue hole where divers have noted rubbish is School Hole. Rubbish instead freely accumulates in the scrub behind each dwelling. Palmer (1989) commented that a sewage outfall also emptied into School Hole. In Sanctuary, carcasses appeared to have been weighted, and would then sink well below the halocline. In School Hole some of the rubbish has settled nearer the surface; this and the sewage could influence the surface ecology, but there is no striking evidence of this, except perhaps for the poor visibility underwater.

In 1987 Nine Tasks Lake and the associated High Creek Caves seemed to be used extensively for laundry, whilst Katrina's Cave had been used for this purpose in the recent past. Palmer (Palmer *et al*, 1998a) wondered whether this pollution was responsible for the absence of cave fauna at these sites. Blue holes are used because they provide less saline water that is not readily available otherwise. However, the water is still sufficiently saline that much soap is necessary, and bleach may be used to remove the smell of hydrogen sulphide. Regular laundry use may also be a source of disturbance, preventing herons from nesting at some holes.

Holes are used for swimming by local children, but generally the sea is preferred. Indeed the local inhabitants view blue holes as rather sinister places. This may still be connected with the local mythology of the Lusca, an octopus-like creature that is believed to inhabit blue holes and drag down victims (Cousteau and Diolé, 1973). The halocline is too deep on Andros to be disturbed by non-divers, and bathers would be expected to avoid the soft stinking beds of sediment that are otherwise probably the habitat most sensitive to disturbance.

No shotgun cartridges were seen around any blue hole, although some were noted around a fossil tidal creek in the interior.

THE DRY CAVES AND THEIR FAUNA

Many of the cliffs around blue holes overhang slightly, but at a few sites the overhang develops into a cave extending along the fracture. These caves are used as nest sites by two species of bird. In 1986 Cave Swallows (*Hirundo fulva*) were nesting in Twin Rifts Cave, the first breeding record for the Bahamas. No nests were in use there in 1987, but another two nests were found at Evelyn Green. The Barn Owl (*Tyto alba*) was observed around six of the fracture-line holes and disused nests were found on a shelf in one deep overhang. Of related interest are what were presumed to be nests of the extinct barn owl *Tyto pollens*, located underwater in a chamber beside Swimming Hole. The spoil included skulls of the hutia (*Geocapromys*), also now believed extinct on Andros.

Only two subaerial caves deep enough to have a dark zone were visited. The larger is Rat Bat Cave, a passage connecting two blue holes (survey in Carew *et al*, 1998). Except for one short section the passage is not constricted and continues some tens of metres, but much of this is lit by a diffuse light from the next hole. A much smaller cave was found along the fracture line just north of the north-east corner of Gopher Hole; it extends <15m along a moderately constricted rift.

Rat Bat Cave is so named because it contains a nursing colony of the bat *Erophylla sezekorni* numbering in the order of a hundred. This nectar-feeding species is relatively common throughout the southern Bahamas and will roost in areas of caves where much daylight penetrates (Buden, 1976). Surprisingly little guano was found, which may imply that the colony is not very old, or just that it is only used for a short period of the year. Elsewhere in the Bahamas guano is assiduously collected from caves for manure (Campbell, 1978), which is also a possibility here. The guano provides food for large numbers of the cockroach *Periplaneta americana* (now world-wide, but thought to be an introduction in America). Pitfall traps did not reveal further fauna in the guano. Also in this cave were the amblypygid *Paraphrynus viridiceps* and a cricket species of the genus *Amphiacusta*. This could be *A. bahamensis*, apparently endemic to Andros, but the specimens have not been compared with the type material. This was the only site where a large boa was seen (c.2m long, presumably a species of *Epicrates*); it lay over the most constricted section of cave, possibly snatching bats flying past.

The cave near Gopher Hole was visited at dusk, when about six small bats flew in. However no bat guano was apparent. The fauna consisted of lots of *Amphiacusta* crickets (mostly around the entrance), ambylpygids, a single small cockroach, spiders, two land crabs and two frogs under a boulder at the entrance. Such a fauna is probably typical of the many 1 to 2m-deep solution pits found in this area, offering cool and humid conditions. There was thus no evidence of the subaerial caves having any special fauna.

CONSERVATION

The rather impoverished fauna associated with the surface waters of inland blue holes cannot add much to the conservation value of the fauna found at depth. The rate of endemism in the Bahamas is typically about 16% for terrestrial taxa (e.g. Browne *et al*, 1993; Strohecker, 1953), so some of the fauna not identified to species level may be endemic. But the freshwater fauna may be too recent, and the brackish water fauna not sufficiently isolated, for their rate of endemism to be similarly high. A more important point is that the variety of other fresh and brackish water habitats on Andros means that most species found in the surface waters of blue holes are much more common elsewhere on the island. The shrimp *M. lucifugum* and the hydromedusan *Ptychogena* might be exceptions, but it cannot yet be judged either whether these species are truly absent elsewhere on Andros, or whether there are other species restricted to surface waters of blue holes.

Other arguments for the conservation of the surface waters are currently stronger:

1. The undoubtedly valuable fauna found at depth relies on organic input from the surface layers and ultimately from the terrestrial vegetation surrounding the hole. Any toxic pollutants in the surface layers are liable to diffuse slowly downwards to the halocline. The biota of the surface waters may thus serve as an advance indicator of some threats to the deeper fauna. It may also serve as an indicator of changes to the water quality of the freshwater lens, which is a vital resource for the human population.
2. The surface waters of the blue holes can serve as natural laboratories to answer general ecological and evolutionary questions. What makes them useful is that there are many isolated holes that can act as independent replicates, and rather few species. The environmental variation between holes that is stressed in this paper may or may not be an advantage. Currently at least two research teams are using the holes as natural laboratories (Downhower *et al*, 1997; Edwards, 1996). Another scientifically valuable aspect of blue holes is that their stratified sediments preserve a record of past biota in sequence. Interpreting the climate that produced this biota is facilitated by the current environmental variation between holes (e.g. Teeter and Quick, 1990).
3. The blue holes are aesthetically highly attractive, appearing as secluded oases ringed by shady cliffs in a landscape of hot sun, bare rock and thick woodland. There may even be a commercial value to preserving this beauty, since tourists and cave divers would be put off by holes full of rubbish or oil slicks.

Given that blue holes do have a conservation value, what are the threats to them? Potentially the most serious is the rise in sea level expected from global warming. Current estimates of the extent of sea-level rise have quite wide error bounds, but a 0.5m rise by the year 2,100 and a 1m rise by 2,200 are typical (Titius and Narayanan, 1996). Most of Andros is only a couple of metres above sea level, and even those holes not covered by sea are likely to be affected by a thinning of the freshwater lens and an increase in its salinity. The species most vulnerable are therefore those restricted to the surface waters of the least saline cenote holes.

Other potential threats may come from an increase in the human population, from a rise in the standard of living, and from industrial or tourist developments. The most serious consequence for blue holes may be pollution of the freshwater lens with sewage, salt water, or oil, and a thinning of the lens and an increase in its salinity through excessive extraction of freshwater. Such problems are documented by Edwards (1996) for San Salvador, and on the more developed islands water consumption has risen by 15% over 5 years (Whitaker and Smart, 1997b). Andros might seem less sensitive because it has a larger freshwater lens and the rather sparse human population is almost exclusively along the coast, but huge volumes of lens water are abstracted to be tanked to New Providence Island (Whitaker and Smart, 1997b). On Andros the increased provision of washing machines may increase water extraction and pollution of the freshwater lens generally, but the effect on the blue holes will probably be less than current laundry practises. Possibly with an increase in affluence agriculture and hunting will be practised less. Fortunately the Bahamas is free of malaria, but mosquitoes are a constant harassment, so attempts to control them by spraying open water near settlements is liable to affect the fracture-line blue holes.

More divers will visit the more accessible and spectacular of the blue holes. Deleterious consequences include disruption of the stratification and of the bacterial mats at the halocline (Palmer *et al*, 1998b), enrichment of oxygen levels, and perhaps introductions of fauna and flora. However, rather a small proportion of the holes are likely to be affected, and the publicity and revenue generated from visiting tourists is probably a positive measure towards the conservation of others.

CONCLUSIONS

This paper has demonstrated that individual inland blue holes differ considerably as physical environments. Consequently a diversity of factors could explain why their faunas differ. In the fracture-line holes salinity and depth are gauged as being the most important factors. In cenote holes the nature of the surrounding vegetation is likely also important. More rigorous answers will have to wait for more thorough sampling, but the presence of a large number of diverse blue holes in quite small an area will facilitate the disentangling of the various possible explanations. Indeed blue holes provide an excellent facility to further our understanding of brackish habitats generally.

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Habitat zonation in Bahamian Blue Holes

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Abstract: Underwater anchialine caves in the Bahamas and elsewhere contain a distinctive biota that changes with increasing distance into the cave. Four major habitat zones within such caves can be recognised and are defined by both physical and biological criteria. The following terminology is proposed for these zones: arena, entrance zone, transition zone and deep cave zone. They are defined as follows. The arena is the well-lit area surrounding the cave entrance that is affected in distinctive ways by the biotic community of the cave and by water movements associated with the cave. The entrance zone comprises those parts of the cave mouth and entrance passages that experience reduced light levels. The transition zone extends from the limits of daylight to the beginning of the deep cave. The deep cave zone is that part of an underwater cave in which only cave-adapted organisms can maintain populations. Conditions in these four zones in Bahamian blue holes are reviewed and compared with those in submarine caves elsewhere in the world. Many similarities exist, but important differences are due to the presence of tidally related currents in marine blue holes and to the absence in blue holes of sulphur springs that in some places provide an important food source for the cave fauna.

INTRODUCTION

Studies in Bahamian blue holes and other similar coastal underwater caves, commonly described as anchialine (coastal, with some marine influence, e.g. tidal, brackish, etc., Sket, 1996) have indicated the existence of a distinctive zonation with respect to their biotic communities. Research carried out in such caves confirms the presence of a marine fauna considerable distances into the dark areas, and supplies evidence for the existence of a cryptic deep cave environment, separable by a variety of biological and physical parameters from the more biotically diverse environments near the mouth of the caves (Iliffe *et al*, 1983; Warner and Moore, 1984; Cunliffe, 1985; Trott and Warner, 1986). To describe the range of habitats involved, four broad ecological divisions are suggested, progressing inward from the entrance: arena, entrance zone, transition zone and deep cave zone (Fig. 1). These four habitat divisions are described and discussed below and are compared, where relevant, with equivalent zones of submarine caves elsewhere in the world.

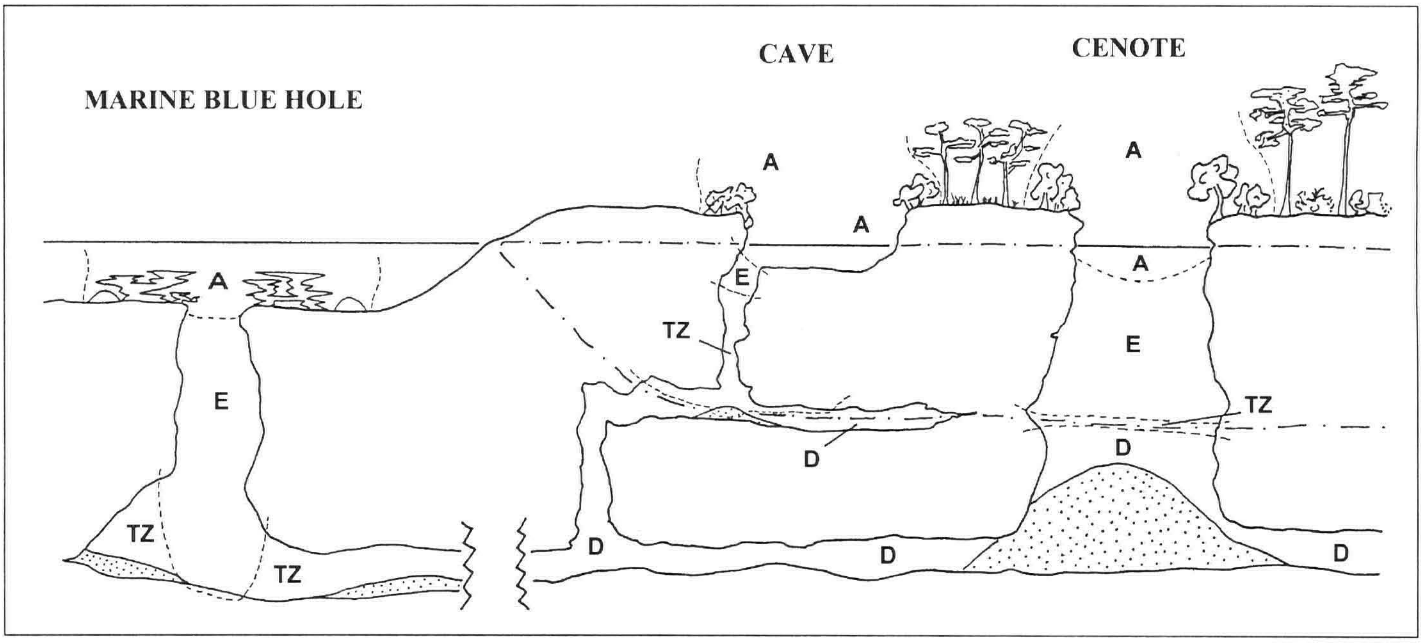

Figure 1. Diagrammatic representation of underwater cave habitat zonation (not to scale, see below).
A = arena, E = entrance zone, TZ = transition zone, D = deep cave zone. See text for definitions. Dotted lines indicate zone boundaries, while dashed lines indicate the boundaries of the freshwater lens. Stippling indicates accumulated sediments. The depth of the freshwater lens increases gradually with distance from the coastline, thus coastal saline and brackish lakes commonly lack a clear freshwater layer, while some kilometres inland the layer may be 30m or more in thickness.

REVIEW AND DISCUSSION OF HABITAT ZONES

The Arena

The arena consists of the brightly illuminated area surrounding the cave entrance that is affected in direct and distinctive ways by the biotic community of the cave and the water movements and other hydrological factors associated with the cave.

Cave entrances, whether air or water filled, provide shelter for a variety of organisms. Many members of such communities are highly mobile, using the cave mouth and entrance passages during rest periods, or during such times as their own predators are active. Such trogloxenes (cave visitors) emerge from the cave to forage, and have distinct spheres of influence outside the cave. In sub-aerial caves, animals such as bats may stray many kilometres from the entrance, but in marine caves, such influence tends to be considerably more localised. Fish that graze on sessile organisms (algae, sea grasses) surrounding the cave often remain within close range of the cave mouth, to which they can return quickly if danger threatens. Many marine blue holes in sea grass and algal beds have a distinct "halo" of overgrazed substrate surrounding the entrance (K Abbott, personal communication.). Similar halos, caused by fish and urchin grazing, have been observed round coral patch-reefs (Ogden and Zieman, 1977).

The presence of strong, tidally related currents within the Bahamian marine caves provides locally high fluxes of organic material at or near to the cave entrance during the inflow cycle (Warner and Moore, 1984). Such rich supplies of food can stimulate the growth of sessile suspension feeders (e.g. corals, sponges) and associated flora and mobile fauna. This results in a different halo: rings of coral growth that surround certain marine blue holes, e.g. "Doughnut Holes" (Benjamin, 1984). The currents may also be responsible for the shape of topographical features in the immediate surface vicinity of the entrance (e.g. sand bars and rock gullies) that offer additional environmental heterogeneity. All of these features can be regarded as lying within the arena of a marine blue hole.

In inland entrances to underwater caves, where the entrance lies within a freshwater or saline lake (Proudlove, 1984; Cunliffe, 1985), the arena may form the entire lake (if small), or only that part of it immediately surrounding the actual cave entrance. It has been noted (Bahamas National Trust, 1981) that the terrestrial environment immediately surrounding such inland blue hole entrances may be sufficiently distinctive to be regarded as an associated community. The presence of brackish or saline surface water may encourage the growth of mangrove communities in an otherwise barren area, or where the cave entrance contains fresh water, a halo of broad leafed woodland, often containing an unusual abundance of epiphytes and orchids, may develop within the surrounding Bahamian pine forest or scrub (Heath and Palmer, 1985; Hutchinson, 1998). Such cave-associated communities clearly belong within the arena of inland blue holes.

The Entrance Zone

The entrance zone is defined as that part of the cave mouth within the arena that experiences lower than normal light levels, and which extends to the limits of daylight within the cave.

In underwater caves with a daylight entrance, there is an identifiable biotic zone associated with the presence of reduced light levels. The entrance zone generally contains a greater density of mobile fauna than does the surrounding marine or lake environment (Trott and Warner, 1986). These organisms include entrance zone and arena feeding species, together with casual visitors sheltering within the enclosed and nutrient rich environment. Fish rarely proceed further into the cave than the entrance passages, though cardinal fish (*Apogonidae*) and squirrel fish (*Holocentridae*) have occasionally been recorded in the transition zone of marine caves (Trott and Warner, 1986).

Many of the sessile organisms found in the arena occur less frequently in the entrance zone. Algae and hermatypic corals that contain zooxanthellae are progressively reduced in numbers and size as the light level decreases (Trott and Warner, 1986). Other sessile organisms, however, increase their percentage cover on the rock surfaces as the light intensity drops. These include sponges, hydroids and ahermatypic corals. The cave walls in the entrance zone are commonly vertical, near vertical or overhanging. Such variations in substrate angle have distinct local effects on the composition of the biotic community, with the densest and most varied fauna being found on vertical surfaces, beneath overhangs and on the roofs of passages where cover by organisms may be >80%. Floors of entrance passages show high covers of sand or finer sediments (>60%) that inhibit the growth of sessile animals (Warner and Moore, 1984; Trott and Warner, 1986). Growth forms within the entrance zone can become elongated, perhaps in response to the currents or to reduced light, e.g. the hydroid *Thyroscyphus ramosus* grows to unusual lengths (Warner and Moore, 1984).

In inland blue holes and caves in fresh or brackish lakes, the entrance zone is generally dominated by algal communities. Where detritus is plentiful in the entrance passages, dense, colonial bacterial growth may occur close to the boundary with the transition zone (RJP, personal observation; Cunliffe, 1985). Filamentous bacteria, presumably sulphur-oxidising, may also be found in the entrance zone of marine blue holes that have a sulphurous outflow, such as Conch Sound II on Andros. The marine fauna in this cave appeared to have a lower than normal diversity, probably caused by the presence of hydrogen sulphide (Warner and Moore, 1984).

The environment offered by inland cenote blue holes is an interesting one. These cenotes are thought to have formed when the roof of a cave collapses creating a circular lake, the water in which may be deep enough to extend below the base of the freshwater lens (Fig. 1). The deep cave environment extending from the bottom of some cenotes can be considered a "relict" environment (see below) but the entrance zones of cenote sites have also been observed to contain species that may be Pleistocene relics, stranded in what are effectively, deep meromictic lakes by fluctuating eustatic sea-levels during the last glacial epoch. The presence, for example, of the grapsid crab *Sesarma angustipes* and a freshwater presence of the cave-adapted brotulid *Lucifuga spelaeotes* (more normally found in saline waters), both reported by Proudlove (1984) from a site on Andros, suggests that in such isolated inland blue holes the entrance zone may be of palaeo-ecological importance. In the case of decapod crustaceans, adaptations to cave life may have evolved in response to isolation of epigean ancestors at such sites (Hobbs, 1994).

The Transition Zone

The transition zone is defined as the zone extending from the limit of daylight to the beginning of the deep cave zone. It may extend for several hundred metres in marine caves with a strong current flow and suitable passage morphology, or may be strongly compressed in inland isolated anchialine caves and cenotes.

In marine blue holes, the transition zone beyond the limit of daylight penetration generally supports a fauna not unlike that of the darkest recesses of a coral reef (Vasseur, 1974) and similar to the darkest regions of the entrance zone. The constant darkness and directional current flows can encourage unusual growth characteristics, e.g. serpulids that form pseudostalactites (MacIntyre *et al*, 1982; Cunliffe, 1985). Some species of sponge are white or paler than in the arena and entrance zones (e.g. *Chondrosia* sp.) and the tasselled growth form of the sponge *Haliclona aquaeductus* is characteristic (Warner and Moore, 1984). The major part of the fauna of the transition zone can be regarded, in speleological terms, as troglophilic, i.e. able to live within a cave and to complete their entire life cycle underground but not exclusively confined to the cave.

There are no ordinary reef fish dwelling within this zone, but mobile invertebrates such as crabs, lobsters, cowries and shrimps may be found (Warner and Moore, 1984; Trott and Warner, 1986). Some of these invertebrates may be regarded as trogloxenes, cave visitors that preferentially inhabit this zone, but which may make regular or occasional visits outside the cave mouth. These larger crustaceans are amongst the most mobile of these animals and may be able to use current flow and/or water temperatures as a means of directional orientation. In a Mediterranean submarine cave, swarms of mysid shrimps that migrated out of the cave at night to feed and back again by day, proved to be important in horizontal transport of organic matter into the dark regions of the cave (Coma *et al*, 1997). In marine blue holes, animal movements are unlikely to be important in organic matter transport because of the overwhelming influence of the strong tidally related currents. The density of the sessile suspension feeding fauna in the entrance and transition zones of marine blue holes is certainly related to the high particle flux resulting from these currents (Warner and Moore, 1984).

100m or more from the entrance, as the currents weaken and become diffuse, sessile populations become increasingly sparse (Warner and Moore, 1984) and are generally limited to small sponges and sporadic serpulid polychaetes. In Mediterranean submarine caves where tidal current flow is absent, this decrease in faunal richness occurs within a much shorter distance (50m) and is related to a four-fold decrease in particulate matter flux (Fichez, 1990). However, in Mediterranean caves in which sulphur springs occur, chemoautolithotrophic (sulphur-oxidising) bacterial production provides a food supplement to counteract the decreasing importance of horizontally transported organic matter from the sea (Southward *et al*, 1996).

In inland cenote blue holes, the transition zone may be abrupt and chemical in nature (Smart, *et al*, 1988; Whitaker and Smart, 1998). This sharp transition occurs at the base of the freshwater lens (Fig. 1) and is a zone of sudden salinity increase with depth where bacterial decomposition of organic debris floating on the slightly warmer but denser saline waters below causes a sudden drop in oxygen content and an increase in hydrogen sulphide produced by sulphate-reducing bacteria. The sudden density change and the layers of detritus and sometimes of purple sulphur bacteria are often dense enough to stop light penetration into the seawater below (GFW, personal observation). Similar bacterial decomposition of organic matter may also take place throughout the water-filled micro-fissures of the surrounding limestone at the base of the freshwater lens, and bacterial production may provide much of the useable food material for the deep cave fauna (Stock, 1986). Marine blue holes that produce a sulphurous outflow, such as Conch Sound II, presumably draw water containing hydrogen sulphide from close to the base of the freshwater lens.

The Deep Cave Zone

The deep cave zone is that part of an underwater cave in which the environmental conditions are such that only cave-adapted organisms can maintain populations. The fauna is dominated by troglobitic organisms - species that occur only in caves, and which are often specialised accordingly. Temperatures are extremely stable at 24-26°C in the deep cave zone of Bahamian anchialine caves (Whitaker and Smart, 1993). Current flow is minimal or undetectable. Organic food is sparse, and input is likely to be mainly vertical, by percolation, rather than horizontal, by current flow (Cunliffe, 1985). Water salinity can vary from fresh to fully marine, and there may be further variations in water chemistry, particularly in oxygen content, which is commonly lower in cave water than in surface sea or fresh water (Iliffe *et al*, 1984; Sket, 1996). Environmental conditions that exist in the deep cave preclude the survival of populations of the less well cave-adapted members of the troglophilic fauna characteristic of the transition zone.

The evidence from the Bahamas suggests the existence of a well-developed deep cave fauna of small crustaceans for which the primary source of food is percolating detritus and bacterial production. The predatory cave fish *Lucifuga spelaeotes* is at the top of the food chain (Yager, 1981; Cunliffe, 1985; Stock, 1986). Hart *et al* (1985) have linked this fauna with that of the deep sea, and further suggested that such deep cave zones may have served as faunal refuges over very long periods of time. Both they and Howarth (1983) commented on the role of micro-fissure porosity of the host rock in the aquatic cave habitat, and its place in the biological structure and dispersal of cave communities. Marine, anchialine and freshwater caves are all likely to be influenced by the movements of small organisms (bacteria and small crustaceans) through such fissures, which may form more important habitats for them than the larger deep cave passages, providing better refuges from predation as well as more direct access to percolating food supplies. Elsewhere in the world, cave faunas have also been linked to those of the deep sea. Hexactinellid sponges may occur in the deeper regions of some Mediterranean caves (Vacelet *et al*, 1994), and a range of unusual cave-adapted and deep sea bivalve molluscs have been found in marine caves in the Philippines (Hayami and Kase, 1996).

The existence of sulphur springs in parts of some deep cave systems can provide an alternative and more abundant food source than the slow percolation of organic matter through micro-fissures. In some Mediterranean submarine caves, sulphur springs support mats of filamentous, sulphur-oxidising bacteria (Southward *et al*, 1996) that in turn support rich and unusual communities, adapted to these physiologically hostile conditions. Similar adaptations are required by the sparser fauna of Bahamian anchialine caves where picnoclines supporting decomposing detritus provide rapid transitions between environments differing markedly in salinity, oxygen concentration and hydrogen sulphide content (Cunliffe, 1985).

CONCLUSION

The four cave zones described above should be regarded as being general habitat types within Bahamian and other similar underwater caves. It is clear that they overlap to a significant degree. The wide difference in surface environments (Warner and Moore 1984; Palmer 1985; Trott and Warner, 1985), passage morphology (Farr and Palmer,1984; Palmer and Heath, 1985), hydrology (Warner and Moore, 1984; Heath and Palmer, 1985; Whitaker and Smart, 1997) and other factors in the cave environment make it unwise to attempt too sharp a distinction between the divisions. There may also be instances in which one or more of the zones may be absent, for example where caves have been infilled to the point where only the arena and entrance zone are available for colonisation. Similarly, inland caves may lack a recognisable arena or, where the submerged cave lies within a dark, air-filled cavern, may lack an entrance zone and even a transition zone. There may also be isolated pockets of one zone type enclosed within another, dictated by cave morphology and/or current movements.

Notwithstanding these reservations, we suggest that the nomenclature proposed here will prove useful to future workers, and urge that it be adopted as standard terminology in future discussion of the biology of such underwater caves.

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APPENDIX 1

Inventory of blue hole sites explored or visited on South Andros Island, Bahamas

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INTRODUCTION

Most of the blue holes visited on South Andros lie along a massive fracture system that runs sub-parallel to the Tongue of the Ocean and close to the east coast of the island. Sites visited on the Andros Project 1986-7 are described from south to north (see Whitaker, 1998 for location maps). This list has been updated to include observations from more recent work where applicable, and is followed by a description of marine blue holes visited after the Andros Project and inland sites (cenotes) that do not lie on the fracture system.

MARINE BLUE HOLES

The Andros Project focused on marine holes lying along the bank-marginal fracture system extending from Mars Bay in the south, northwards to Smith's Hill at the southerly end of the Bluff Series of inland holes. These are described briefly below, but not coded in the manner of inland sites because it is believed that many marine sites remain to be identified.

MARINE SITES ON THE EAST COAST OF SOUTH ANDROS

Mars Bay Blue Hole, Mars Bay
A spectacular circular cenote hole on the beach at Mars Bay, with a sand cone floor, a maximum explored depth of -84m, and no apparent side passages.

Shark Hole, Little Creek (DK5)
This lies between High Point Cay and the small islet of Bird Cay just to the north. A spectacular entrance shaft descends to a sandy floor with continuing narrow passages at -60m. Currents are very strong. Side passages at -16m and -22m emit water on the outflow that was 2° to 3°C warmer than the main cave outflow.

Bidet Hole, Little Creek
An ocean hole approximately 2km offshore of Little Creek, set on the eastern side of an attractive patch reef. The entrance leads to a large sloping chamber that descends to around -12m. The roof of this chamber is spectacularly covered with ahermatypic corals. A descent on the far side off the entrance chamber leads to an extremely tight, descending rift, only passable with sidemounts. 10m of vertical squeezing leads to an enlargement at a depth of -35m, where the cave continues, to emerge in the roof of a sizeable chamber at -46m. The floor of this slopes steeply down, through a low section at -60m, to enter a second chamber. Here the roof rises back up above -55m, and the floor drops to split into a double continuation. To the northwest a passage at -69m shortly becomes too low for further exploration. The passage to the northeast reaches -70m where it continues horizontally, about 0.25m high by 1m wide, with a sandy floor.

Barren Blue Hole, Little Creek
Approximately 300m north of Bidet Hole, this small entrance on the eastern edge of a patch reef was not explored. A descending passage slopes down under the reef, and tidal currents are strong.

Giant Doughnut, Deep Creek (DK4)
The largest entrance in the line, with a spectacular coral ring some 80m in diameter, surrounding a 30m-diameter sand-floored vestibule. Constricted passages lead off from the lowest point at the base of a low cliff on the on the southwest side, and these were explored in 1982 for 50 to 60m to an obstruction at -40m.

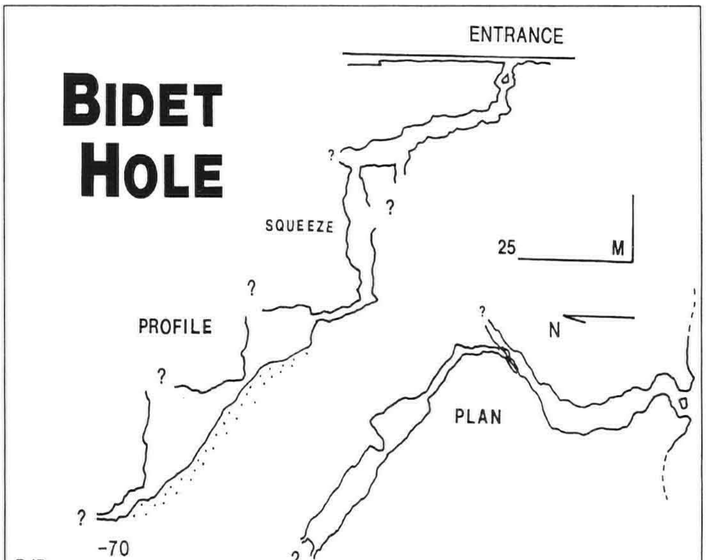
Unnamed Hole, Deep Creek (DK1)
This entrance lies directly off Deep Creek near Autec Marker 4 in 3m of water. The entrance passage was descended in 1982 to a depth of -17m, no floor being seen. Currents were weak and passages extending both north and south remain unexplored.

Coral Hole, Deep Creek (DK2)
Surrounded by a well-developed coral reef, this cave was first explored in 1982 to a point 50m in at a depth of -35m. Exploration was continued in 1987 to a depth of -58m a short way beyond the previous limit, at which point a passage constriction halted progress.

Question Mark Hole (Rubbish Pit), Deep Creek (DK3)
A small blue hole about 200m offshore on the south side of Deep Creek, well off the fracture line, and set in a seagrass bed. This was explored for about 200m to a final depth of -40m. There may be a way on down through very silty boulders at this point.

Virgin Blue Hole, Kemps Bay
This entrance, over 1km north of DK1, is a long, narrow crack in the sea floor that is partially infilled with coral debris from the surrounding reef. There are two main entrances, one at the northern end of the reef, and one at the southern end. Each appears to enter large vestibule chambers, though the northern entrance was not explored fully. The southern entrance leads into a large, sloping chamber at -6 to -7m depth, which abruptly enters the roof of a 3 to 4m-wide chamber developed along the fracture line. This closes down in huge boulders to the south, but stretches for over 30m to the north where it is 5 to 6m wide and over 10m high. The sand floor is at -20 to -22m depth. Deeper passages on the northern side were not examined, but a series of shallower passages holds the possibility of a link-up with the northern entrance.

Autec Blue Hole, Kemps Bay
The entrance to this lies about 15m south of Marker 13 on the Autec Channel and several hundred metres northwest of Virgin Blue Hole. A small reef surrounds a 7m-long and 3m-wide rift entrance, with a further small vent about 8m to the north. A shotline leads to -12m, then south for a further 5m to the limit of daylight. At this point a chamber approximately 3m wide, 5 to 6m long and 3 to 4m high leads to a choked rift directly forward. A descent can be made down a rift in the floor to a fissure passage and, by passing under a boulder, this can be followed south at -25m, rising to a choke at -20m a short way on. To the north, a descending slope leads to -35m, where a slot in the west wall discharges cold clear water with some force on outflow. Passages to the north were not explored completely. The walls of the cave are largely covered with serpulid worm tubes, many active, to the virtual exclusion of other forms of life, save



some sponge cover. Compared with other caves in the area, which have a more varied wall fauna, this is very unusual. The floor sediments appeared to be covered by a fine white bacterial film.

Porcupine Blue Hole, Kemps Bay
A very beautiful twin entrance a little north of the harbour at Kemps Bay. The two entrances meet in a chamber 9m down, beyond which a vertical rift descends to -35m. The north passage chokes after about 20m, but the cave continues to descend to the south, through an algal-floored duck at -45m, to emerge in a sizeable room, with the roof at about -42m and the floor at -60m. A continuation of the rift at -45m may be passable. The main way on lies at the floor of the chamber, where a descent through boulders leads to a slope at -75m. From here, the lip of a shaft can be seen ahead, at about -80m.

Smith's Hill Blue Holes, Smith's Hill
A group of five small entrances that lie just south of the point where the fracture zone crosses the coast. Of these, only Octopus Rift was explored thoroughly.
No 1. A small entrance 300m south of the main group. Unexplored.
No 2. Octopus Rift. Largest of the group and closest to the shore, the narrow entrance fissure to this cave is -15m deep. From this depth, narrow passages run both north and south. The north passage becomes impossibly constricted above a sandbank after 30m, but the south passage leads after 30m to a spiralling descent through a chamber, to a parallel fissure that continues down beyond the farthest point explored at -45m depth.
No 3. Barracuda Hole. A rift entrance, with unexplored but narrow cave passage appearing to continue below -6m.
No 4. Eel Hole. A small rift entrance with no apparent cave large enough to explore.
No 5. The most northerly of the group, this entrance lies farther offshore and parallels the others. The entrance slopes down to the south, to the limit of exploration at a depth of -20m, where it appears to continue to descend.

INLAND BLUE HOLES

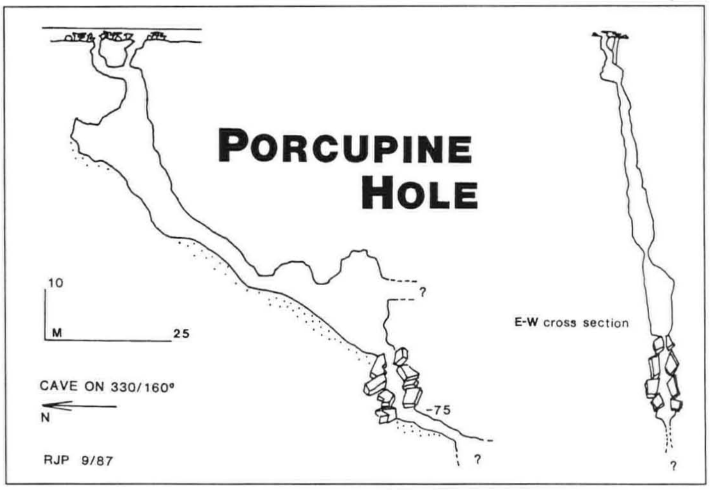
These sites lie along the onshore sections of the bank-marginal fracture, and are described from south to north. They are sub-divided into two groups, the more northerly northwest/southeast trending Congo Town group and the main north-south trending Bluff group, and are given a secondary numerical classification based on these divisions (e.g. B1, CT6). The Congo Town and Bluff systems are separated by a short marine excursion of the fault system just to the southeast of the airstrip at Congo Town. Local names are occasionally available for these caves, and where commonly accepted are used here. For other sites the names are those used colloquially by Project members and other previous explorers. The secondary numerical classification may help ease confusion in future work. Where appropriate, local grid references are given in the form (TB 411644).

BLUFF SERIES

B1. Mangrove Lake, Smith's Hill (TB 411644)
At the southern end of the Bluff system, this shallow lake lies between the road and the shore. Reached down an unusual gully, which appears to be the collapsed roof of a cave, the pool is entered on its western side, but is no more than 3m deep at any point, with flora similar to that of Evelyn Green's Blue Hole. Collapse on the western side may conceal a passage, but this site seems to be virtually infilled. Although the sea is only a few metres away, the water is brackish rather than saline. The main fracture line runs offshore a short distance to the south of this lake, towards Smith's Hill marine holes.

B2. Evelyn Green's Blue Hole, Smith's Hill (TB 410647)
Northwest of Mangrove Lake and a short distance west of the road, this blue hole is best entered at the southern end, where a 5m drop reaches water level above the entrance to the south passage. This is effectively a large daylight cavern descending through the mixing zone to the floor at -20m. Constricted passages can be entered for a short way on both sides of the final choke, and cave fauna was present in these. The floor of the chamber below the mixing zone contains a profuse shrimp population (*Barbouria* sp?), and a crevice at -6m (above the mixing zone) was home to a 1m-long green moray eel. Later exploration at the northern end of the lake by American divers revealed a passage that choked at a maximum explored depth of -30m. Extensive algal beds in the shallow central part of the lake, and regular sightings of eels, barn owls, cave swallows and herons, made this a significant biological site both above and below water.

B3. Gopher Hole, Smith's Hill (TB 409650)
Some 300m north of Evelyn Green's Blue Hole, Gopher Hole is biotically one of the most interesting of the inland sites. The lake has extensive algal beds, and several species of goby inhabit the lake and associated caves. The lake is 1 to 2m deep, and is most easily entered at the northwestern corner, where a 3m



descent can be made to small ledges at water level. At the northern end, a series of interconnected cave passages leads off at several levels between -3 and -12m. These run for about 30 to 40m to a choke at every level. They are populated by many gobies, including a few giants over 25cm long. There was a distinct current flow through the cave, evident also in a very small cave at the southern end of the lake. A profuse bird population in and around the entrance included green and night herons, least grebe, common gallinule and two barn owls, which appeared to be nesting in the cliffs surrounding the hole.

A few metres northeast of Gopher Hole is a small cave within a narrow fracture-guided rift. The rift slopes at 45°, about 4m down from the entrance to shallow puddles along the floor. Although less than 15m long the cave has a 'dark zone' and was visited by bats.

B4. Donkey Hole, Smith's Hill (TB 407654)
A further 400m north of Gopher Hole, Donkey Hole is fringed by low cliffs that reach a maximum height of 3m at the south end. Most of the hole is very shallow (less than 1m depth at low tide), and the bottom is a pale deposit full of mollusc shells, reeking of hydrogen sulphide on disturbance. There is one deeper spot beside a slight overhang on the west cliff, under which the floor may continue to slope downwards, though the site has not been dived. A strong current can be felt here as tides change.

As far as is known, the two entrances marked on the map between B4 and B5 have not been visited.

B5. Katrina's Cave, The Bluff (TB 405666)
The entrance is the most northerly of several small pools beneath an overhang on the main fracture just west of the Commissioner's Complex. A short passage between -16 and -22m depth leads south for 35m, to choke at -9m beneath the most southerly surface pool in a sand/rock inflow. North of the entrance, a steeply descending shaft falls to a sediment-floored chamber at -45m, beyond which a steep slope rises to a stalagmite grotto at -30m. There is no evident continuation and no cave fauna is present. The cave has been used as a laundry in recent memory, and this may have some bearing on the absence of cave life.

B6. Narnia, The Bluff (TB 405668)
A series of cave entrances and water surfaces in an enclosed depression just to the northwest of the Commissioner's Complex. Two of the western water surfaces were explored in 1984, and led to a linking passage 8m in diameter with a noticeable current flow. The base of the passage is at -22m, and the lower part of the cave lies within the mixing zone. There were few speleothems and the walls are extremely fretted. The passage chokes just before the large shallow lake at the northern end of the depression.

B7. High Creek Cave, The Bluff (TB 404671)
Immediately south of Nine Tasks Lake, this small blue hole has a silty passage leading off its northwestern end. This descends beneath a low air-filled cavern roof to a depth of -14m, at the top of the mixing zone, where it becomes impassably constricted. No cave fauna was seen, and the site is also in use as a laundry. A small cave under the south end is too choked to enter.

B8. Nine Tasks Lake, The Bluff (TB 404676)
A long narrow lake, used regularly as a laundry by local villagers. This hole has not been dived, but as it lies at the seaward end of a fossil tidal creek formed during an earlier high sea-stand, it would probably warrant further investigation.

B9. Round Lake, The Bluff (TB 404677)
An un-dived blue hole between Twin Rifts and Nine Tasks, set within trees, with a 3m cliff on its western side. The three blue holes may have a continuous water surface between them within the mangrove woodland.

B10. Twin Rift Cave, The Bluff (TB 404677)
This cave entrance lies at the northern end of the long enclosed depression that contains Nine Tasks Lake, and leads to two descending rifts either side of a rock island, several metres into the cave. The cave itself is 30 to 40m long, 20m wide and 10m high, and in 1986 contained nesting cave swallows. The rift on the west side closes down in boulders at a depth of -9m, with a well-decorated grotto at -3m depth at the far end. The eastern rift was descended to the top of the mixing zone at -17m, through a series of boulder constrictions. Cave fauna were present at this point, and much bacterial growth was evident on the walls.

B11. Stargate, The Bluff (TB 403680)
The entrance to this cave lies approximately 100m south of the Co-op road, beneath an overhanging cliff. There is a 4m drop to water level, and the overhang prevents significant input of organic matter, ensuring excellent visibility. The entrance shaft is spectacular, falling vertically through the mixing zone at -16 to -22m, beneath which visibility improves even further, and the cave descends to a maximum depth of -98m (reached in 1987 by Parker and Clough using heliox in Carmellan rebreathers).

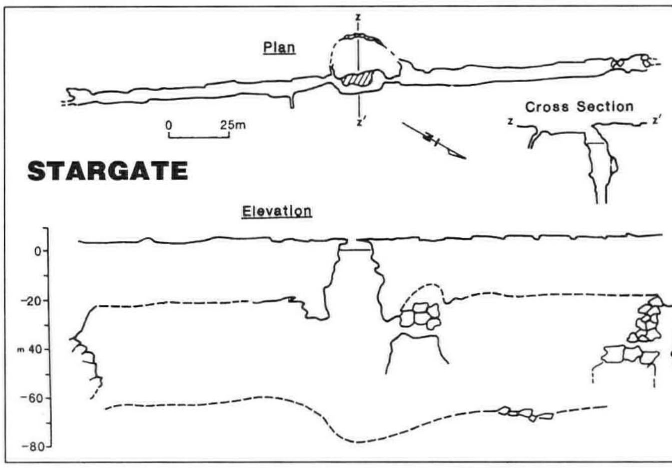
To the north, a 10m-wide passage, with its roof at -25 to -30m, runs for just over 100m to a choke. The floor of the passage varies between -45 and -65m depth, with possible continuations to greater depths. To the south, a similar passage is entered through a slot on the right-hand side of a massive boulder pile, and runs for 100m to another loose boulder ruckle. This can be passed with care on the western side at -37m, to reach an extremely loose boulder chamber, choking again after a further 30m. A delicate and committing penetration of this choke can be made for approximately 40 to 50m further to a depth of -67m.

The floor of the south passage approaching the final chokes reaches at least -80m and is composed of massive collapsed wall and roof wedged across the passage. The cave may continue to greater depths below. There is a secondary mild H_2S zone at -43m, which represents the base of the zone of actively circulating saline water. A profuse cave fauna inhabits the water between -22 and -43m, virtually ceasing above and below these depths. Palmer (on air) and Stone (on open circuit heliox) each reached a depth of -77m in the large chamber just before the end of the South Passage.

B12. Co-op Hole, The Bluff (TB 402683)
An 18m-deep cenote-type feature to the west of The Bluff settlement, just north of the road that passes the Co-op Store, this blue hole is surrounded by 3 to 4m-high cliffs with numerous ledges. Small passages exit to north and south, those to the north descending though boulders in the mixing zone from -16 to -23m, before ending at a final boulder constriction. Cave crustacea have been recovered from this final point.

B13. Heron Water/ B14. Elevenhome/ B15. School Hole, The Bluff (TB 400689/ 400690/ 400691)
These three inland blue holes are linked together through a connecting rift passage to make a traverse of approximately 200m with a maximum depth of -59m. School Hole is an elongate shallow lake (situated behind High Rock Primary School) that deepens at the north and south ends. To the south at the foot of a low cliff a passage slopes down over boulders containing plastic bags and other human rubbish. The passage is well-decorated, with some strangely-shaped formations on the eastern wall. The floor of the passage is at -45m, but directly beneath the entrance to Elvenhome falls away to -59m.

The Elvenhome entrance, a short way south of School Hole, is a 30m by 10m fissure, with a 3 to 4m drop to water level. Surface waters are turbid, with visibility of 2 to 3m, and there is a strong H_2S taste to the water between -9 and -22m. Beneath -22m depth, visibility is excellent and the water is saline. To the south, a canyon passage (Cavalier Canyon) with floor depths of between -15 and -50m, leads to another small cliffed entrance, Heron Water. The water below the mixing zone has a profuse fauna of micro-crustacea and other cave-adapted biota.



B16. Avalon, The Bluff (TB 399693)
The northern continuation of the School Hole lake. The entrance to the cave lies though an extremely constricted squeeze at the foot of an organic "mung" slope, in the mixing zone. Visibility is atrocious, and the cave is not recommended for more than one extremely experienced diver at a time.

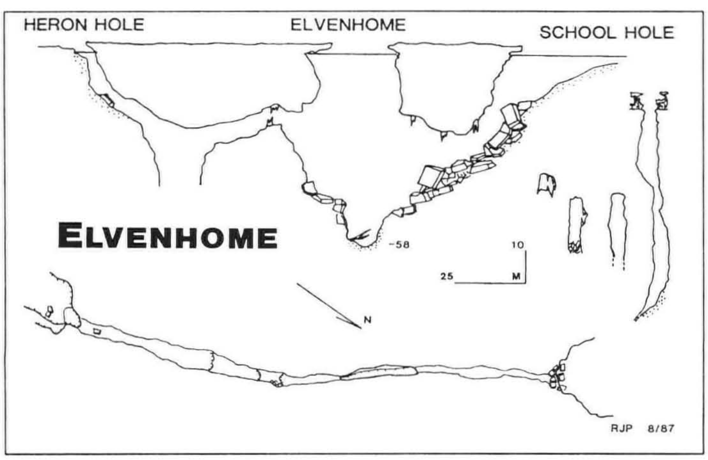
The constriction leads into a short length of passage at -25m, which emerges in the roof of a large canyon passage at -35m. This ends in a well-decorated choke after about 30 to 40m, where the line is tied off at -40m. Beneath this, a stepped shaft descends through a narrow section at -55m to emerge in the roof of a large hall, 20m long by 15m wide. At -77m, the floor below was seen to be covered with large gour pools at -80m, sloping down towards a tiny crack on the west wall, apparently too small to enter.

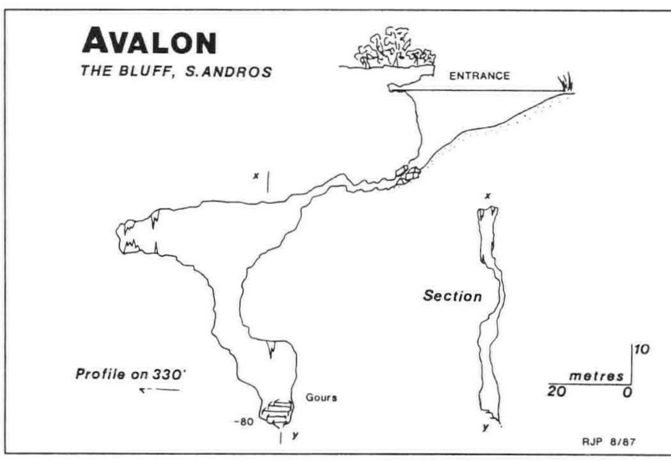
B17. Battle Hole, The Bluff (TB 397696)
An un-dived blue hole to the north of High Rock Primary School, proved to contain the freshest water in the southern chain, but was nevertheless still noticeably tidal. Surrounded by forest.

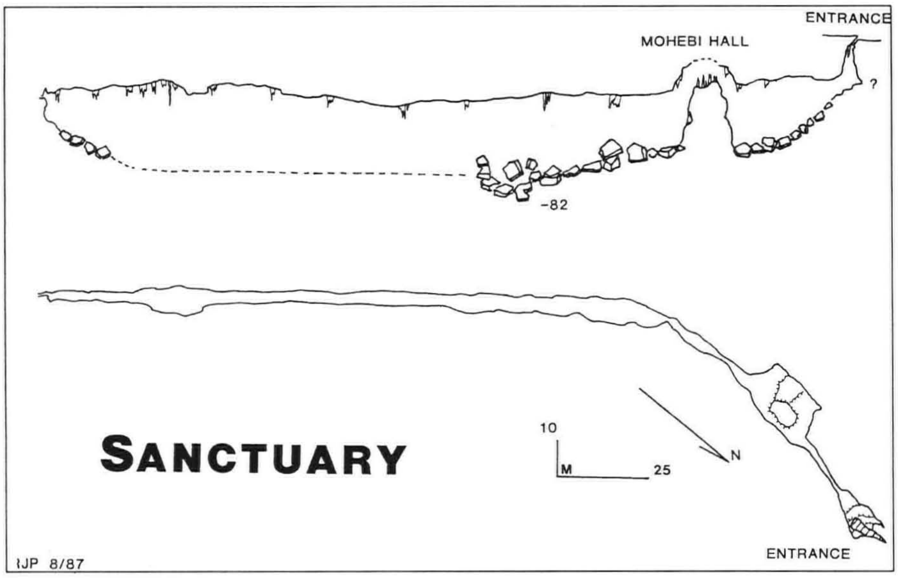
Sanctuary
The main new discovery of the Andros Project. A spectacular inland blue hole that stretches more than 250m south from the small hidden entrance, ending in a boulder choke at -45m. 70m into the south passage is the spectacular "Mohebi Hall", where a collapse pile peaks in an underwater ridge covered with stalagmites. Just beyond this, a maximum depth of -82m was reached by descending through massive boulders in the passage. The northern continuation was not explored. The exact location of this site is kept secret due to the discovery of Arawak Indian skeletons on the debris cone beneath the entrance. This marks the cave as a major Pre-Columbian archaeological site. The last underwater site so found in the Bahamas was raided by somewhat ghoulish souvenir hunters, who wrecked any chance of learning anything from excavation of the site. A joint operation between the Bahamas Department of Archives and Bahamas Archaeological Team in 1990 brought the fragments of 16 skeletons to the surface. This material, together with more recently discovered artefacts including a Lucayan canoe (thought to be up to 1000 years old) from Stargate, are still being studied.

CONGO TOWN SERIES

CT1. Swimming Hole (Jellyfish Lake), Congo Town (TB 370750)
The most southerly of the Congo Town chain, reached by a well-defined path from the school house at Congo Town settlement. Explorations in 1986 revealed







a shallow chamber containing formations at -7m on the north side of the Hole, and a cavern descending to -20m, again with formations, on the south side. Cliffs 3 to 5m high surround the entrance, and access is best at the SE end.

The surface waters are inhabited by huge numbers of small jellyfish, ranging in diameter from 3 to 200mm. The mixing zone lies between -16 and -20m depth, beneath which, at the southern end, a large daylight cavern ends in a narrow rift passage between -9 and -23m. This may be too constricted to pass. The rock walls above the mixing zone were clean and fretted, but massive bedding and planar collapse made dissolutional effects indistinct below the mixing zone. On the northern side of the lake, a very well-decorated passage, with many speleothems, ran for about 30m at a maximum depth of -15m, to a multilevel choke, perhaps passable with side-mounted tanks. The cave is notable as the home of one of the largest (over 25cm long) blind Bahamian cave fish (*Lucifuga* sp.) yet recorded.

Subsequent explorations by an American team found a deeper continuation to the north, through an awkward squeeze. This led for about 75m to a final constricted choke at several levels, with a maximum depth of about -40m. It was notable for the remains of what is assumed to be the nest of extinct giant barn owl (perhaps the "Chickcharnie" of Andros mythology). Beneath the nest site, which is somewhere above the halocline at less than -10m, the bones of small prey items are strewn down the slope to a depth of over 30m. Many of these bones are of the hutia, a small guinea pig-type rodent, now found only on a couple of small Bahamian islands, and thought to be extinct on Andros. A second nest site was found at -7m in the shallow upper chamber on the north side, and a 30m penetration along the east wall actually led to a small isolated airbell - an unusual find in the Bahamas.

CT2. El Dorado, Congo Town (TB 370751)
This deep site north of Swimming Hole was first explored by American divers in autumn 1986. They connected it to Rat Bat Lake, the third in the series and several hundred metres farther north again, at an average depth of -40m. The continuation to the south from this passage reached a depth of -67m on the roof of a large cavern, where a shotline was dropped to approximately 85m. In 1987 Palmer and Stone, using open circuit heliox, bottomed the passage at -85m and explored a short choked continuation on the east wall. To the west the passage was found to terminate in a boulder choke at a maximum depth of -89m.

CT3. Rat Bat Lakes and Cave, Congo Town (TB 369753)
A series of three separate water surfaces joined by a series of dry and flooded cave passages. At the northern end of the most southerly lake a dry rift cave system (Rat Bat Cave) connects the lake above and below water to the fourth blue hole in the chain. This in turn connects to the fifth, below an above-water arch, making the fourth and fifth blue holes identified from aerial photographs effectively a single lake.

The entrance to the largest cave (Rat Bat Cave) is a rift, at the northwest corner of the lake, that slopes down for about 10m to water level. After the large first chamber the roof of the dry cave drops in the second chamber and almost reaches the water surface. Just before this, a squeeze (beneath a 2m boa constrictor) allows access to the further continuation of the rift. Soon the cave opens out into a high, wide cavern, most dramatically lit by diffuse light from the northern entrance, which is still out of direct line-of-sight. Further progress out into the northern lake is only possible by swimming, though another short length of rift leads back towards Rat Bat Lake.

CT4. Hidey Hole, Congo Town (TB 361763)
Holes CT4 to CT9 are approached along a narrow but well-worn track that starts at NGR TB 401760, where there is a concrete-capped well opposite the church. After just over 1km, Hidey Hole is to the west of the path, shortly before it turns sharp left to avoid a steep hill. The hole is about 20m in diameter, completely encircled by 5m-high cliffs, which are easily descended on the western side. These cliffs continue vertically underwater, though the bottom in the centre appears no deeper than -9m. Passages may continue underwater to north and south, but the site was not dived.

CT5. Apes Cave, Congo Town (TB 360764)
Apes Cave lies off the track, over the steep hill to the north of Hidey Hole. At the southern end of a narrow depression overhung by 4m-high cliffs, a cavern extends for approximately 10m. The bottom of the depression is boulder-floored, with water covering only the lowest boulders. To the north, the boulder pile slopes gently down to the southern end of Bolt Hole, which occupies the same depression.

CT6. Bolt Hole, Congo Town (TB 359765)
Over 100m long, this hole is shallow over most, if not all, of its length, with a couple of islands in the middle. The surrounding cliffs are high, and the whole depression is an intriguing and attractive site. This hole had more heron nests (≥5) than any other visited, with the night heron as well as the more common green heron successfully fledging chicks. It contained fish not seen in the more southerly (and less saline) holes.

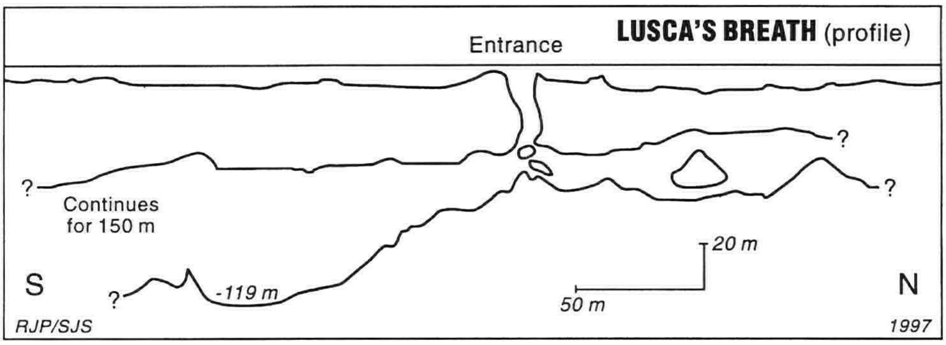
CT7. Plug Hole, Congo Town (TB 357767)
Holes CT7 to CT9 are reached by following the original path over the dune ridge complex to an elongate lagoon, probably a fossil tidal creek, that extends across the fracture system. The widest and deepest part of the lagoon lies on the line of the fracture, and on the north side water could be seen streaming into the lagoon (presumably from Plug Hole) as the water levels rose with the tide.

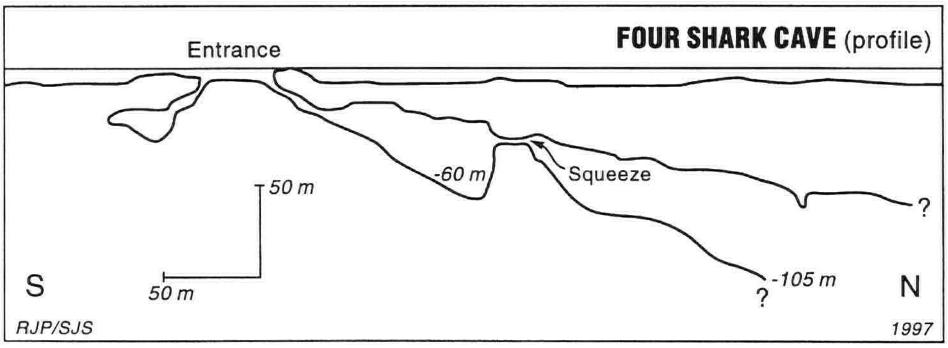
Plug Hole lies 50m north of the widest part of the lagoon, and is 20m in diameter and surrounded by cliffs only a metre or so high. Flow towards the lagoon with the rising tide was apparent from a crack in the southeast corner. From the shallow southern end, the water deepens progressively to the northern end, where it reaches 4m. The floor continues to descend under a broad high arch, and warrants further investigation but was not dived.

CT8. Man Hole, Congo Town (TB 356768)
From the northeast corner of Plug Hole, a fissure in the limestone leads to within 20m of Man Hole, which is surrounded by particularly dense scrub. The hole is about 20m in diameter, with encircling cliffs about 2m high. It did not appear shallow, but was not inspected closely.

CT9. Lug Hole, Congo Town (TB 355769)
This hole is about 50m long and 20m wide, surrounded by 1 to 2m-high cliffs. The depth increases steadily from the sides towards a rift in the floor a metre or two wide. This was plumbed to 13.2m, and offers some diving potential.

C10. Un-named Hole, Congo Town (TB 353771)
No attempt was made to reach this final blue hole in the chain.





C11. Driggs Hill Sink Hole, Driggs Hill
To the north of the Congo Town series the fracture system runs offshore at Driggs Hill Sink Hole, a 13m-deep cenote-type sinkhole that was not visited during the Andros Project. North of the sinkhole there are many small openings along the line of the fracture system.

OTHER MARINE BLUE HOLES

GRASSY CAY SITES

To the south of the area investigated by the Andros Project four major marine holes developed along the bank-marginal fracture in the area of Grassy Cay were explored in 1996-7 by the Blue Holes Foundation. These have been located precisely using GPS.

Atlantis, Grassy Cay
GPS co-ordinates 23° 50.100′ N 77° 27.760′ W. From a broad slit opening a large passage extends to the north at a depth of 60m. Within approximately 100m of the entrance an unexplored passage descends to depths in excess of 200m. The main north passage remains large but is blocked after some 250m by a huge sand slope, probably immediately below the infilled blue hole a few hundred metres north of the Atlantis reef. There are a series of upper passages that eventually lead back into the main chamber. This cave has a unique inhabitant Rose Coral (*Stylaster* sp. a branching, pink stony hydroid) lining the walls. Divers entering this section of the cave should take special care, so as not to destroy the colonies.

Lusca's Breath, Grassy Cay
GPS co-ordinates 23° 51.420′ N 77° 28.170′ W. At present the third deepest cave known in the Bahamas. The cave has some of the fiercest currents so far encountered, and a very impressive whirlpool develops at the entrance during inflow. From an entrance shaft descending to -45m depth, passages extend both north and south with continuing unexplored leads.

To the south a very large canyon passage has been explored for 500m to date. For most of the way the passage is 3 to 5m wide and for much of its length there is no floor in sight, but some 100m south of the entrance it has been plumbed to a depth of -119m. The walls are lined with marine growth and sporadic encrusted stalagmite-stalactite columns.

From the entrance shaft a passage leads to the north some 50 to 60m before dropping down into the darkness. A sloping floor of sediment met at about 75m continues steeply down over several small steps. The biota on the walls changes quite suddenly at a thermocline at -65m and only tubeworms and sporadic sponges are visible from then on. By a depth of 100m the walls become less fretted and very smooth and creamy. The floor here is composed of fine calcareous silt and scattered fragments of seagrass. At -119m the passage is joined by a slope from the other direction, and both lead down to a small hole in the eastern wall (exploration continues).

Four-Shark, Grassy Cay
GPS co-ordinates 23° 48.526′ N 77° 27.111′ W. An oval entrance approximately 6m across and 3m high with passages leading south to a closed chamber, and to the north into a very large cavern. The cavern floor slopes down from the entrance to a depth of -60m at the back wall. At this point, a very narrow constriction some 30m in length (referred to as 'The Crack') can be passed with side-mounted tanks. After the constriction the passage enlarges and continues with no end in sight. The floor here is over 100m deep. Unexplored passage continues to the north and exploration by the Blue Holes Foundation continues.

Funnel Cave, Grassy Cay
GPS co-ordinates 23° 47.854′ N 77° 26.816′ W. Funnel Cave lies just north of the Cays on the main fracture, and has been explored to both the north and south. A depth of -60m has been reached at both ends, which looked to be swinging back to join up directly below the entrance. A decent current of cool water emerges from this large depression, so there may well be more cave beyond.

SOUTH BIGHT (BENJAMIN'S) BLUE HOLES

To the north of the Congo Town Series of inland sites, the fracture continues across South Bight to Mangrove Cay. Here it is marked by a series of 7 entrances, some leading to extensive and spectacular passages that were explored and documented by George Benjamin *et al* from 1968 to 1975 (Benjamin, 1984). These are coded SB1 to 8 and are described here briefly.

SB1 and SB3. Small opening, most likely above the main passages of SB2. Entered for 30m to a depth of -25m, but no connections have been found.

SB2. From an entrance 6m by 9m, a vertical pit descends to -30m. To the south a passage at -43m depth was explored towards SB1, passing a 30m-high dome with stalactites some 45m from the entrance, for a total distance of 125m. To the north of the entrance the passage continues at a depth of almost 50m for nearly 250m. Half-way along this passage a beautiful grotto hosts numerous stalagmites and stalactites up to 6m in length.

SB4. Described by Benjamin as "the greatest of all Andros Blue Holes", with over 1.6km of passage explored, superb clarity and strong tidally-driven currents. There is a spectacular stalagmite grotto 325m inside the south passage, with an extension close to the north passage of SB2, but no connection has been found.

SB5. Narrow fissure with extremely strong currents. Constriction at -37m depth prevents diver access but no bottom is visible and great potential exists.

SB6 and SB7. Small openings with many fish, entered for 15m.

Additional inland blue holes are reported on Mangrove Cay along the fracture line, which continues north, taking in a series of deep ocean holes offshore from Mangrove Cay before crossing the Middle and North Bights towards North Andros. The full northern and southern extent of the fracture are not presently known, but may be significant, with bank-marginal fracturing along the entire length of the Tongue of the Ocean.

OTHER INLAND SITES

Iguana Holes, Deep Creek
Two circular inland holes about 5km up Deep Creek, taking the large northern branch of the creek. The first hole (TB 358580) was dived to a sand/mud base at -6m, and its waters were potably fresh. The second (TB 362575) was not dived, but appeared shallower, and was considerably more saline.

Quartet Holes, Little Creek
A series of four closely-spaced blue holes in the centre of South Andros, approximately 15km inland on the north side of Little Creek (a long hot Zodiac ride). The nearest of the holes to the creek (Quartet One: TB 295426) was dived to -50m where a silt floor could be seen at about -70m. The remote location of this cave, and the unlikelihood of horizontal passage, made deeper exploration pointless at the time. Quartet Two (TB 290426) was visited but not dived, though it appeared deep.

James Barr Blue Hole, Grassy Creek
GPS co-ordinates 23° 54.216′ N 77° 31.851′ W. An inland cenote explored recently by the Blue Holes Foundation and named after James Barr (aged 87) who located this hole, after chopping his way through the bush for 7 hours. The upper 2m of the water column is brackish but hot (34°C summer temperature). Immediately below this upper layer the water becomes cooler (24°C) and smells very strongly of H_2S. Extensive search did not find a passage; however lights were not carried and the cave warrants further exploration.

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APPENDIX 2

Brief reports of additional scientific investigations carried out during the Andros Project

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AQUATIC BIOLOGY OF INLAND BLUE HOLES

The inland hole biology programme was unfortunately curtailed due to the last-minute withdrawal of the researcher concerned, but over the two field periods of the Project (1986 and 1987), a number of important observations were made.

The subaquatic flora and fauna of the inland caves can be divided loosely into three regions, surface to mixing zone, the actual mixing zone, and the saline cave below.

Above the mixing zone

Along the fracture-orientated inland blue holes, the water above the mixing zone was brackish in varying degrees, this saline influence increasing towards the coast. There was little direct marine influence of the shallow fauna, however, other than the occasional presence of small moray eels in the caves nearest the coast. Freshwater eels were occasionally observed at sites farther inland on the fracture, and were widely reported by locals.

Saline-tolerant species common to inland lakes and brackish caves were common. Fish such as *Gaubusia manni* (the mosquito fish) and small gobies being present, often in considerable numbers, in shallow, algal-floored entrance areas. *Eliotis pisonis* (the spiny-cheeked sleeper) and *Lucifuga* (the blind Bahamian cave fish) were both commonly observed above and below the mixing zone, some individuals in excess of 20cm length. *Lucifuga* was also commonly observed in the inner passages of the marine blue holes.

At least one species of crustacean (*Machrobrachium lucifugum*) was present in the brackish upper layers of School Hole. No determined effort was made to sample micro-planktonic or -nektonic communities in the open water, though such were observed by divers. The inland blue holes north of Congo Town contained a species of minute jellyfish (*Ptychogena*), and these were observed down to the level of the mixing zone and occasionally well into the dark zone of caves where the depth of the mixing zone allowed. Some specimens were observed in Rat Bat Cave, in a guano-lined pool.

Algae and bacterial mats were present on the daylit walls of caves, with green, calcareous algae growing profusely on shallow (1 to 2m-deep) sediment banks in the open lakes. Below this depth, red algae predominated. Occasional encrusting sponges occurred on the walls of caves down to the level of the mixing zone, more notably those closest to the influence of the sea.

The mixing zone

Colonial bacterial mats are common along the length of the mixing zone, in and out of the dark zone. Such bacterial mats are extremely fragile; divers' bubbles are enough to disturb them from cave roofs and bring them down into the sub-mixing zone cave waters. What effect this has on food-budgets within the cave, or on continuing mat growth, is unknown at present.

These mats are probably formed by anaerobic sulphur-reducing bacteria, and as such are responsible for the removal of oxygen from the lower mixing zone making this area of the cave waters anoxic. Almost paradoxically, it is the lower mixing zone, and the upper part of the deep cave waters immediately beneath it, that appear to be most populous, with a wide variety of troglobitic micro-crustacea.

Below the mixing zone

The deep cave waters are extremely clear. They contain little obvious detritus, other than that which falls vertically from surface openings and is heavy enough, or decayed enough, to penetrate the buoyant waters of the mixing zone. The cave crustacean food chain is based upon the bacterial mats and suspended organic matter within the mixing zone, and the crustacea appear to be able to tolerate extremely low levels of oxygen within the water column in order to penetrate this region to feed.

A well-developed food chain is present, with ostracods (including the newly identified *Deeveyae bransonis* from Stargate), copepods and thermosbanaceans as base-level detritivores, probably preyed upon by cirolanid isopods, amphipods, small shrimps, remipedes and polyonid polychaetes. The latter two are interesting. Remipedes appear to be one of the more common high-level predators of such anchialine communities elsewhere in the Bahamas, but they seem to be curiously rare on South Andros. To date, only two individual specimens have been observed, one possibly *Speleonectes sp.*, and one possibly *Godzillius sp.* Their place as major predators seems to have been taken by the polyonid polychaete *Pelagooacellicephala iliffi*, previously known only from one site in the Turks and Caicos Islands, but common throughout South Andros caves. Populations of all the troglobitic species seem to be densest in the 10 to 20m immediately below the mixing zone, with an abrupt cut-off point at about -40m, at the base of the marine current flow throughout the fracture system. Most species have been observed below this depth, but more infrequently, with a preponderance of the larger species Near entrances, occasionally very large populations of the shrimp *Bahadzia* are found though less frequently where there are also large populations of gobies or *Lucifuga*.

Rob Palmer

MARINE BIOLOGY

The marine biological programme was two-phase, a study being made during the 1986 Reconnaissance to:

a) characterise the macro biota and major communities existing on and around the arena and vestibules of previously identified blue hole sites and, by comparing these to nearby patch reefs, to highlight any possible influences created by the presence of a blue hole;
b) to identify further marine blue hole sites suitable for specific detailed studies on the vestibule and transition zones during the main Project in 1987.

The 1987 team concentrated further on the inner passages of the caves, working on species within sessile communities not examined in 1986.

1986

In total, nine marine blue holes from north of High Point Cay to Smith's Hill were described. Biological investigations concentrated on the diversity and abundance of fish, and on quadrat studies of coral, alcyonarians, algae and other substrates and macrobiota. Despite the desirability of sites lacking blue hole influence, few were found. The majority of patches existing on or near the blue hole fault line were found to contain vents (patches that have openings to the cave systems beneath, but which are not penetrable by a diver). For this reason, a compromise was forced, and only three true patches were investigated, the remaining three sites being vents.

With the exception of the two inshore holes (Octopus Rift and Question Mark), that were located in algal beds and sand with no distinctly raised patch and very low hard coral cover, all of the sites examined in detail occurred on a raised rock coral platform ranging from 850m^2 to at least 4,000m^2 in area. The relative abundance of coral species, as well as the dominance and composition of other groups such as algae and gorgonians, varied widely, and preliminary analysis of substrate data suggests that on this coarse scale no significant difference between blue hole sites and others will be detected. However, blue hole outflow water (and thus presumably the major part of its influence) appears to be channelled fairly narrowly at the majority of sites, and detailed study focusing on the finer differences across these channels may be fruitful.

Of the 93 species of fish identified at offshore sites, 14 (15.1%) were common to all sites, and a further 13 (total 29%) were common to three-quarters of the sites. With the exception of Autec Hole (37 species), blue hole sites did support a higher number of species (range 45-61) than either vent (41 species) or patch sites (range 38-42 species). Of perhaps greater interest were a few species that were encountered only at blue holes, but the incidence of some'Blue Hole' species was so low that their absence at non-blue-hole sites may have been random. However, though several of these species may be common on the outer reef, it is possible that blue hole sites offer them suitable habitats in the lagoon that would not otherwise be available. The data are still under analysis, and the significance of the preliminary results remains to be determined.

The outer vestibules of each blue hole were described, with preliminary investigation of the the first chamber of three of the holes for wall biota.

Examination of fauna and flora has laid a sound foundation of knowledge on which to build during future research programmes, and has raised a number of questions that will be examined in further detail.

Mary Stafford-Smith

1987

The rich encrusting fauna of the walls of marine blue holes had been noted by previous expeditions. Pulsing currents in and out of the caves generated by tidal rise and fall bring food-rich moving water to attached animals inside the caves. The 1987 project aimed to make collections of these attached animals for identification and estimate the relative abundance of different species in different parts of the caves, as well as comparing the species present at different caves.

Virgin Blue Hole and the largest of the Smith's Hill caves were investigated thoroughly, with photographic transects being made at both sites. Other sites visited included Shark Hole, Coral Hole, Autec Hole, Question Mark Hole and a series of newly-discovered holes, including Porcupine Hole, along the fracture between the Autec Channel at Deep Creek and Smith's Hill.

In order to interpret the photographic transects, it is first necessary to identify the external appearance of the principal organisms present. These were predominantly sponges, and therefore can only be identified by internal skeletal characters that are only visible after sectioning and examination under a microscope. Specimens of individual sponges were therefore photographed and collected in separate, numbered polythene bags for later identification. This will then allow the external appearance, which is commonly distinctive, to be linked with the specimen after sectioning and identification.

The hydroids present on the cave walls were also collected, but are apparently less diverse than the sponges. They have not yet been examined, but appear to represent less than ten species. Similarly, a number of tunicates are also present, including some didemnid and polyclinic species, but these are no more diverse than the hydroids.

One species of particular interest was observed and photographed on a night dive at one of the smaller entrances at Smith's Hill, This is the cerianthid anemone *Arachnanthus nocturnua* Den Hartog, 1977. This species was previously known only from Curaçao in the Netherlands Antilles, just off the Venezuelan coast. Its presence in the Bahamas suggests that it is a widespread species in the Caribbean and tropical West Atlantic. The several specimens observed were very sensitive to light, curling their tentacles and withdrawing into the seabed within a minute or two of being illuminated by a torch. They were all living in the floor of the entrance chamber of the cave, and were not extended in the daytime.

The predominant environmental factor that appeared to determine the colonisation of the cave walls was the quantity and distribution of sand in suspension. In caves with horizontal or gently shelving entrance passages in shallow water, such as Question Mark and Smith's Hill, large quantities of sand have settled on the floor of the chambers. The effects of abrasion from movement of this sand are evident in a marked zonation on the walls of the cave, with only the most scour-tolerant species living near the floor. Horizontal ledges also tend to accumulate sediment, preventing growth of sessile organisms, whereas overhanging surfaces are kept clear of silt by gravity, and are richly covered by attached animals.

The velocity of the currents in the caves is another factor that appears to have major effects on the species growing on the walls. Coral Hole, with a steeply-sloping entrance passage with strong currents, has more hydroids and a more scoured appearance with less sponge growth than the quieter Virgin Blue Hole. Comparative collections of sponges were made from the outer reef front, in depths of 20 to 25m. The dominant sponges in this habitat were large vase-shaped, massive, or ramose types. Thin encrusting sponges could be found beneath overhangs, but these were apparently different species to those found in the caves. The outer reef at Andros consists of separate coral heads rising two or three metres above a gentle, sloping sandy platform. This platform finishes abruptly at -30 to -40m, where the vertical drop-off at the 1,800m-deep Tongue of the Ocean begins. The sponges seen near the top of the drop-off were apparently more diverse and of different species from those present on the outer reef, but no time was available for more than a brief appraisal of this habitat.

Bernard Picton

SEDIMENTOLOGY

During the sedimentology studies, the most important aspect was the recovery of eight cores of sediment from eight blue holes. The localities sampled spanned most of the aquatic environments of South Andros, cores being obtained from Virgin, Giant Doughnut, Mars Bay, Mangrove, Elvenhome and School Blue Holes, and the southernmost of the Iguana Holes (No.l) inland. The first two of these are entirely marine, Mars Bay lies in an intertidal coastal area, and Mangrove is just above the high tide position. Elvenhome and School Hole, though inland, lie on the fracture, and are subject to considerable saline influence. Moreover, School Hole has a thick sedimentary infill, with marshland on its northern region. Iguana Hole No.l has water of drinkable quality and its sediments are accumulating in a virtually completely freshwater environment. In addition to these sites, a core was taken from sediment inside the entrance to Rat Bat Cave, which has a prominent bat fauna.

Sediments were sampled at depths down as far as -58m, and the cores were columns, usually of 1.5m. Superficial sediments were collected from other sites, including Stargate and Evelyn Green's Blue Hole. The sediment cores were collected by divers using sections of plastic drainpipe with end caps placed on underwater immediately after insertion into the sediment. The pipes were capped and withdrawn carefully, remaining in a vertical position in the water column. The cores were maintained in vertical position while being drained slowly and partially dried. Finally, the sediments were extruded and wrapped in aluminium foil for transhipment to the UK.

Banana holes are extremely numerous near the eastern coast of South Andros. An area of $50m^2$ near the Government Offices at the Bluff was mapped and the average density found to be one banana hole/m^2. Banana holes near the Bluff, Stargate and Deep Creek were surveyed and superficial sediment collected. Most show lateral development at the sediment level and there is extensive fretting in some localities. It has been tentatively concluded on field evidence that plant roots play a prominent role in the development of these banana holes. Standing water was discovered in small saucer shaped depressions lined with humus, developed on the bare bedrock surface.

Banana holes farther inland were investigated, those studied being fringed by, or lying within, woodlands of Caribbean pine. These banana holes appeared to be less abundant in a given area compared to those in more coastal sites. The banana holes of this region commonly have deeper soil layers and less pronounced lateral development than the coastal sites.

At Swimming Pool/Jellyfish Lake, three fragile fossil skulls of the large rodent *Geocapromys*, now extinct on Andros, were found, together with a considerable amount of post-cranial material, in what has been presumed to be the 'lair' of an extinct giant 'chick charnie' owl. Bones of modern rodents were discovered in the lair of the extant barn owl in a cave at the northern end of Avalon Blue Hole. These bones cascaded down the scree slope and taphonomical investigations were made of the deposits. Although a thorough search was made for remains of vertebrates in banana holes, none were found. Lizards were, however, present in great abundance in and near the cavities.

Work is currently progressing on the detailed analysis of the cores and superficial sediments. Records of the fauna, lithology and, if possible, palynology will be produced.

David Whiteside

RESEARCH FUNDS AND GRANTS

THE BCRA RESEARCH FUND

The British Cave Research Association has established the BCRA Research Fund to promote research into all aspects of speleology in Britain and abroad. Initially, a total of £500 per year will be made available. The aims of the scheme are primarily:

a) To assist in the purchase of consumable items such as water-tracing dyes, sample holders or chemical reagents without which it would be impossible to carry out or complete a research project.
b) To provide funds for travel in association with fieldwork or to visit laboratories that could provide essential facilities.
c) To provide financial support for the preparation of scientific reports. This could cover, for example, the costs of photographic processing, cartographic materials or computing time.
d) To stimulate new research that the BCRA Research Committee considers could contribute significantly to emerging areas of speleology.

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant must be the principal investigator, and must be a member of the BCRA in order to qualify. Grants may be made to individuals or groups (including BCRA Special Interest Groups), who need not be employed in universities or research establishments. Information about the Fund and application forms Research Awards are available are available from the Honorary Secretary (address at foot of page).

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a minimum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Hurst Farm Barn, Cutler's Lane, Castlemorton, Malvern, Worcs., WR13 6LF, UK. Closing dates for applications: 31st August and 31st January.

THE E.K.TRATMAN AWARD

An annual award, currently £50, made for the most stimulating contribution towards speleological literature published within the United Kingdom during the past 12 months. Suggestions are always welcome to members of the GPF Awards Committee, or its Secretary, David Judson, not later than 1st February each year.

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

CAVE & KARST SCIENCE - published three times annually, a scientific journal comprising original research papers, reviews and discussion forum, on all aspects of speleological investigation, geology and geomorphology related to karst and caves, archaeology, biospeleology, exploration and expedition reports.
Editors: Dr. D.J. Lowe, c/o British Geological Survey, Keyworth, Notts., NG12 5GG, UK and Professor J. Gunn, Limestone Research Group, Dept. of Geographical and Environmental Sciences, University of Huddersfield, Huddersfield HD1 3DH, UK.

CAVES AND CAVING - quarterly news magazine of current events in caving, with brief reports or latest explorations and expeditions, news of new techniques and equipment, Association personalia etc.
Editor: Hugh St Lawrence, 5 Mayfield Rd., Bentham, Lancaster, LA2 7LP, UK.

CAVE STUDIES SERIES - occasional series of booklets on various speleological or karst subjects.
No. 1 *Caves & Karst of the Yorkshire Dales;* by Tony Waltham and Martin Davies, 1987. Reprinted 1991.
No. 2 *An Introduction to Cave Surveying;* by Bryan Ellis, 1988. Reprinted 1993.
No. 3 *Caves & Karst of the Peak District*; by Trevor Ford and John Gunn, 1990. Reprinted with corrections 1992.
No. 4 *An Introduction to Cave Photography;* by Sheena Stoddard, 1994.
No. 5 *An Introduction to British Limestone Karst Environments;* edited by John Gunn, 1994.
No. 6 *A Dictionary of Karst and Caves*; compiled by Dave Lowe and Tony Waltham, 1995.
No. 7 *Caves and Karst of the Brecon Beacons National Park;* by Mike Simms, 1998.

SPELEOHISTORY SERIES - an occasional series.
No. 1 The Ease Gill System-Forty Years of Exploration; by Jim Eyre, 1989.

CURRENT TITLES IN SPELEOLOGY - from 1994 this publication has been incorporated into the international journal Bulletin Bibliographique Speleologique/Speleological Abstracts; copies of which are available through BCRA.

BCRA SPECIAL INTEREST GROUPS

SPECIAL INTEREST GROUPS are organised groups within the BCRA that issue their own publications and hold symposia, field meetings etc.
Cave Radio and Electronics Group promotes the theoretical and practical study of cave radio and the uses of electronics in cave-related projects. The Group publishes a quarterly *technical journal* (c.32pp A4) and organises twice-yearly field meetings. Occasional publications include the *Bibliography of Underground Communications* (2nd edition, 36pp A4).

Explosives Users' Group provides information to cavers using explosives for cave exploration and rescue, and liaises with relevant authorities. The Group produces a regular newsletter and organises field meetings. Occasional publications include a *Bibliography* and *Guide to Regulations* etc.

Hydrology Group organises meetings around the country for the demonstration and discussion of water-tracing techniques, and organises programmes of tracer insertion, sampling, monitoring and so on. The group publishes an occasional newsletter.

Speleohistory Group publishes an occasional newsletter on matters related to historical records of caves; documentary, photographic, biographical and so on.

Cave Surveying Group is a forum for discussion of matters relating to cave surveying, including methods of data recording, data processing, survey standards, instruments, archiving policy etc. The Group publishes a quarterly newsletter, Compass Points (c.16pp A4), and organises seminars and field meetings.

Copies of BCRA publications are obtainable from: Ernie Shield, Publication Sales, Village Farm, Great Thirkleby, Thirsk, North Yorkshire, YO7 2AT, UK.
BCRA Research Fund application forms and information about BCRA Special Interest Groups can be obtained from the Honorary Secretary: John Wilcock, 22 Kingsley Close, Stafford, ST17 9BT, UK.

Rob Palmer : 1951 - 1997